Calorimetry

"everything not tracking" (in CMS)

David Yu (LPC/Nebraska)

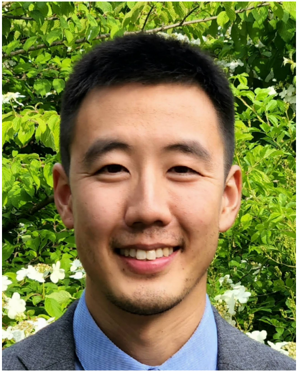
on behalf of the ECAL and HCAL groups

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

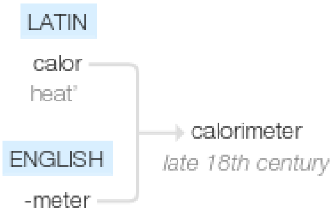
CMS Induction Course, July 8, 2024

Who am I?

- LPC support staff, focus on US contributions to CMS operations.
- Research scientist at University of Nebraska; soon to be assistant professor at University at Buffalo.
- Current research:
  - Searches for exotic particles (especially dark matter), Higgs measurements, calorimetry
- What am I excited about in the next 10 years?
  - Phase-II upgrade detectors, especially HGCAL.
  - The Next Collider (muon collider?).
- Outside of work:
  - Running, cycling, photography

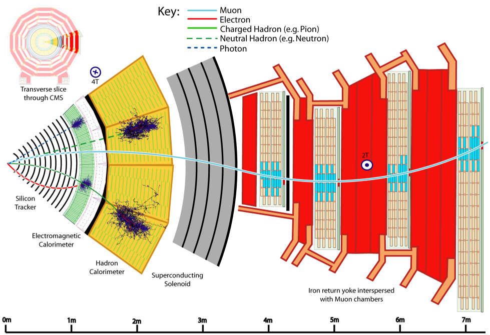


What is a calorimeter?



What is a *particle physics* calorimeter?

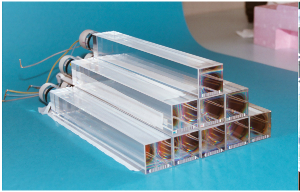
- Calorimeters are particle detectors that measure the energy of incoming particles by absorbing them and converting the energy into some measurable signal.
  - Electrons, photons, and hadrons (e.g., pions, kaons, protons, neutrons, ...).
- Basic idea: bash the particle into dense material, creating a “shower,” and then measure the secondary particles in the shower:



What is a *particle physics* calorimeter?

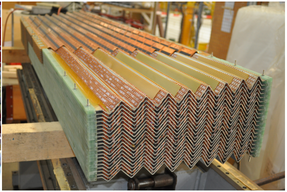
Key features:

- Stochastic process⇒better at high energies (opposite of tracking).
- Incoming particle is destroyed.
    - Calorimeters are also the shielding for the muon detectors! Only muons make it through to the muon detectors.
- Two fundamental processes: electromagnetic showers (simpler) and hadronic showers (more complex).
    - The different physics behind the two types of shower drive the art and science of calorimetry.



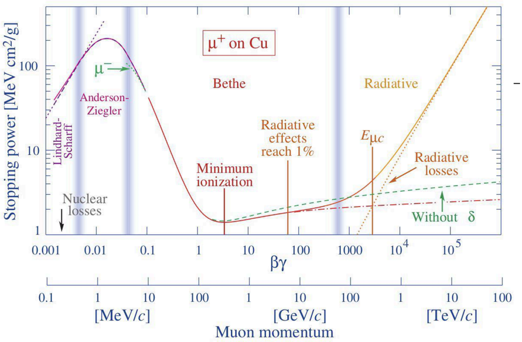
(a) CMS ECAL crystals

(b) CMS HCAL barrel



(c) ATLAS LAr slice

Electrons vs. photons vs. muons



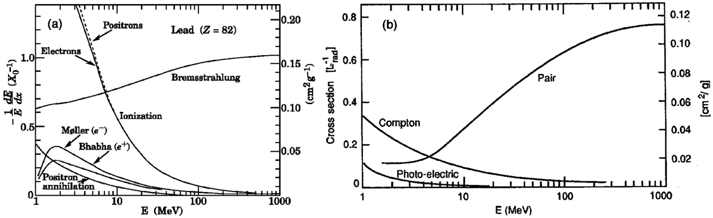
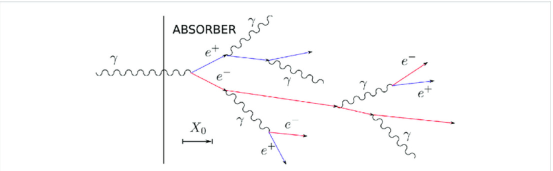


FIG. 1. (a) Fractional energy lost in lead by electrons and positrons as a function of energy (Particle Data Group, 2002). (b) Photon interaction cross section in lead as a function of energy (Fabjan, 1987).

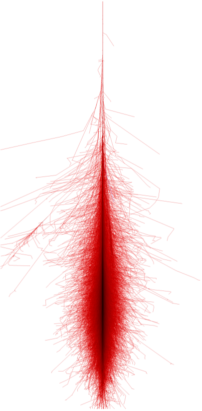
The "simple" case: electromagnetic showers

- At high energies ($\gtrsim 20\,\mathrm{MeV}$), only two processes matter:
  - **Bremsstrahlung** ($1e^{\pm} \to 1\gamma$) and
  - **Pair production** ($1\gamma \to 1e^{+} + 1e^{-}$)
- At low energies ($\lesssim 20\,\mathrm{MeV}$): ionization, photoelectric, Compton.
- critical energy, $E_c \approx 610\ \mathrm{MeV}/(Z + 1.24)$: 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)

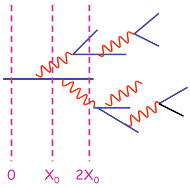


e.m. shower example



EM showers

Radiation length, X_0: average distance for $e^{\pm}$ to reduce energy by factor of $1/e$ (similarly photons, $\frac{9}{7}X_0$).

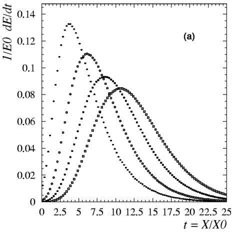


A simplified model:

- Electron with $E > E_c$: travel one X_0, emit photon with $0.5E$.
- Photon with $E > E_c$: travel one X_0, split into e^+e^-.
- Electron with $E < E_c$: deposit energy via ionization.

	LAr	Fe	Pb	U	C
X_0 [cm]	14.0	1.76	0.56	0.32	18.8

Longitudinal shape (1, 10, 100, 1000 GeV):

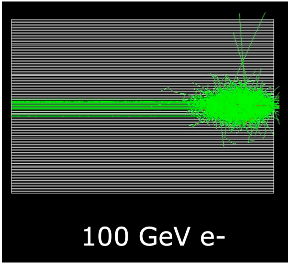


- Shower max: $t_{\max} \approx \ln \frac{E}{E_c} + t_0$, ($t_0 = -0.5$ for $e^{\pm}$ and $+0.5$ for γ).
- Containment: $t_{95\%} \approx t_{\max} + 0.08Z + 9.6$. Rule of thumb: $25X_0$ for 99% containment up to $E = 300$ GeV.

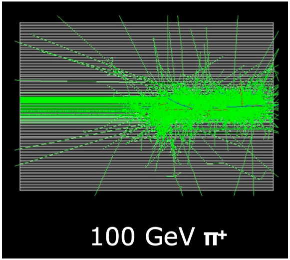
Transverse shape:

- Moliere radius $R_M \approx X_0$

The complex case: hadronic showers



(a) EM shower



(b) Hadronic shower

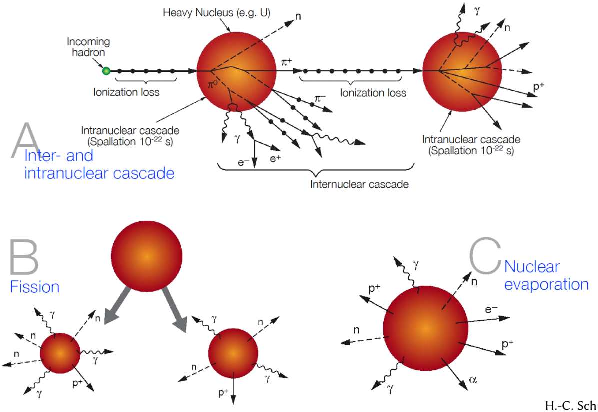
Hadronic showers are much more complicated than EM showers:

- Relevant processes: strong interaction and nuclear physics.
  - Production of secondary particles in hadron-nucleus collisions.
  - Development of EM shower inside hadronic shower! ($\pi^0 \to \gamma\gamma$)
  - Nuclear reactions: protons and neutrons released from nuclei.
  - "Invisible energy": undetectable energy from binding energy, target recoil, slow processes.
- Fluctuations and "compensation":
  - Because of invisible energy, a $e^{\pm}/\gamma$ leaves a bigger signal than a $\pi^{\pm}$.
  - $\Rightarrow$ fluctuations in the "EM fraction" change the observed energy! Leading contributor to energy resolution, and a driving factor in calorimeter design ("compensation").
  - Shower shape also has large fluctuations.

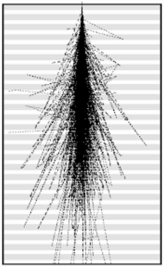
Thanks to N. Akchurin

The complex case: hadronic showers

- multi-particle production, typically mesons ($\pi^{\pm}$, π^0, K, ...)
- Important: $\sim \frac{1}{3}$ of secondaries are π^0s, which decay immediately via $\pi^0 \rightarrow \gamma\gamma$. $\Rightarrow$ 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

The non-EM component

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

- Energy deposit and composition of non-EM shower component, in Pb and Fe.
- Lower table: particles per GeV of non-EM energy.

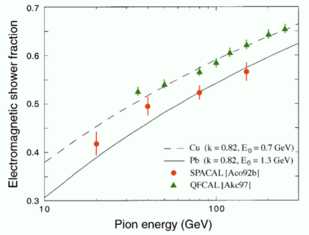
The EM fraction

Key fact: neutral pions decay immediately to two photons, $\pi^0 \to \gamma\gamma$.

- On average, $\approx 1/3$ of particles produced are π^0s.
- The π^0 energy goes into an EM shower; one-way street, that energy remains EM.

Simple stepwise model of hadronic shower:

- First generation (incoming hadron hits a nucleus): $f_{\text{em}} = 1/3$.
- Second generation: $f_{\text{em}} = 1/3 + (1/3 \text{ of } 2/3) = 5/9$.
- Third generation: $f_{\text{em}} = 1/3 + (1/3 \text{ of } 2/3) + (1/3 \text{ of } 4/9) = 19/27$.
- ...$f_{\text{em}}^N = 1 - (1 - 1/3)^N$.
- Stop when available energy can't create more pions; depends on how many pions produced per generation, $\langle m \rangle$.



$\langle f_{em} \rangle = 1 - (E/E_0)^{(k-1)}$

Compensation (oversimplified^n)

- **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.

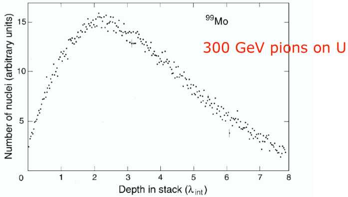
CMS approach: clearly separate e.m. and hadron calorimeters, and be clever at analysis level (Global Event

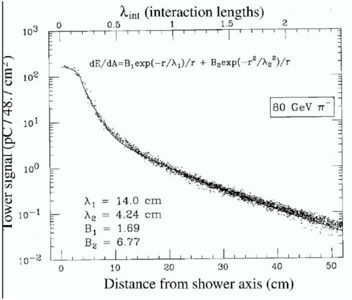
Hadronic shower shapes

- Key parameter: interaction length, λ_{int}, the average distance a hadron travels before a nuclear interaction.

	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

- Containment rule of thumb: aim for $9\lambda_{\text{int}}$. Hadronic calorimeters have to be big!
  - Fun fact: the CMS HCAL doesn't meet the rule of thumb! Only $\sim 5\lambda_{\text{int}}$ at $\eta = 0$.
- Tranverse shape: narrow EM core, wide had. tails.





Hadronic shower fluctuations

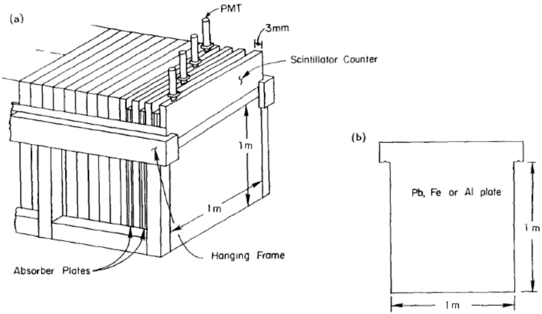
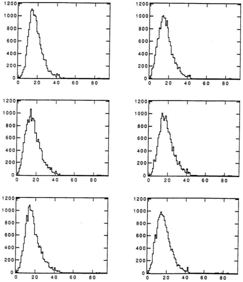


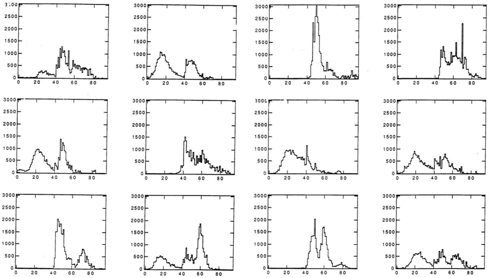
Fig. 1. (a) Schematic overview of the hanging file calorimeter (HFC). There was no transverse segmentation. The maximum depth of the calorimeter can be configured up to 2.2 m with a maximum number of 105 read-out planes. Each scintillator counter was read out separately. (b) Schematic drawing of the absorber plate.

- Hanging file calorimeter: measured showers with fine longitudinal granularity.

Hadronic shower fluctuations



(a) 170 GeV electrons

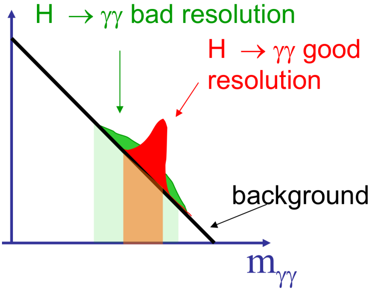


(b) 270 GeV pions

- EM showers are pretty uniform, had. showers have huge variations.

What are we aiming for?

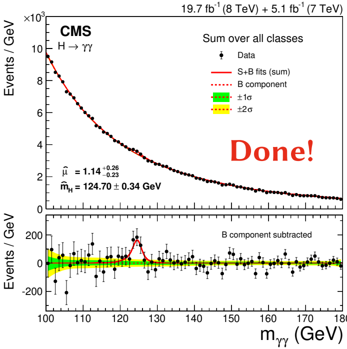
Best possible energy resolution σ_{calo} (compatible with the LHC environment).



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

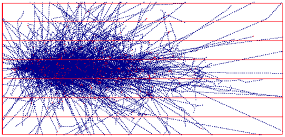
Design goals:

- 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

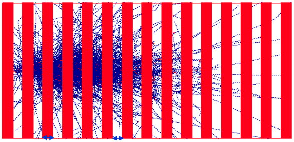
Two main possibilities (oversimplified[1]):

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

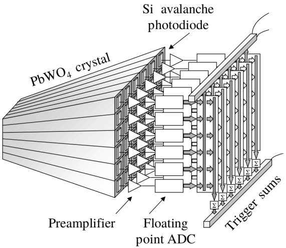
Designing a calorimeter - a HOW TO guide

Two main possibilities (oversimplified[1]):

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

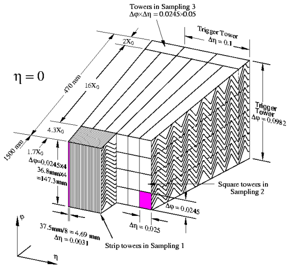
Sampling calorimeters: the shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z)

CMS ECAL choice



- Excellent energy resolution

ATLAS ECAL choice



- Longitudinally segmented

Designing a calorimeter - a HOW TO guide

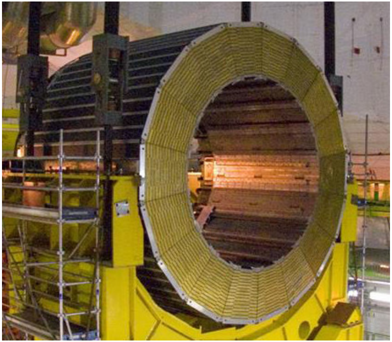
Two main possibilities (oversimplified[1]):

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

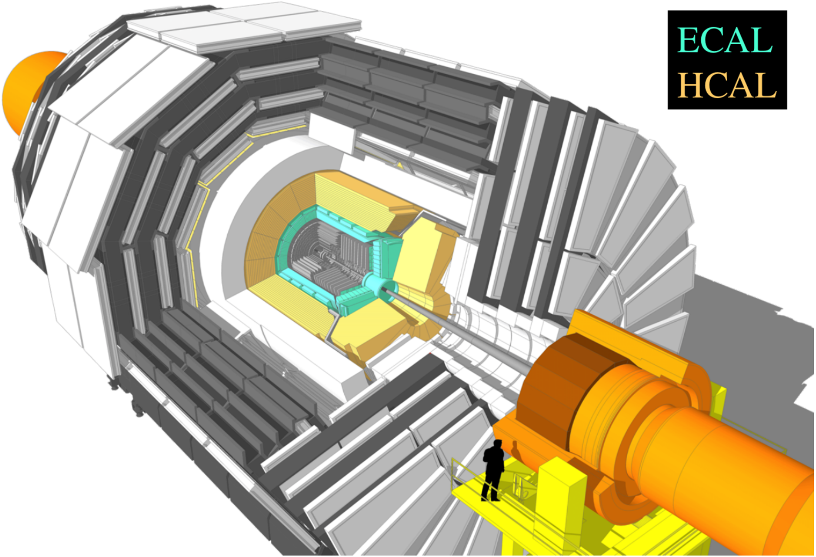
CMS HCAL choice



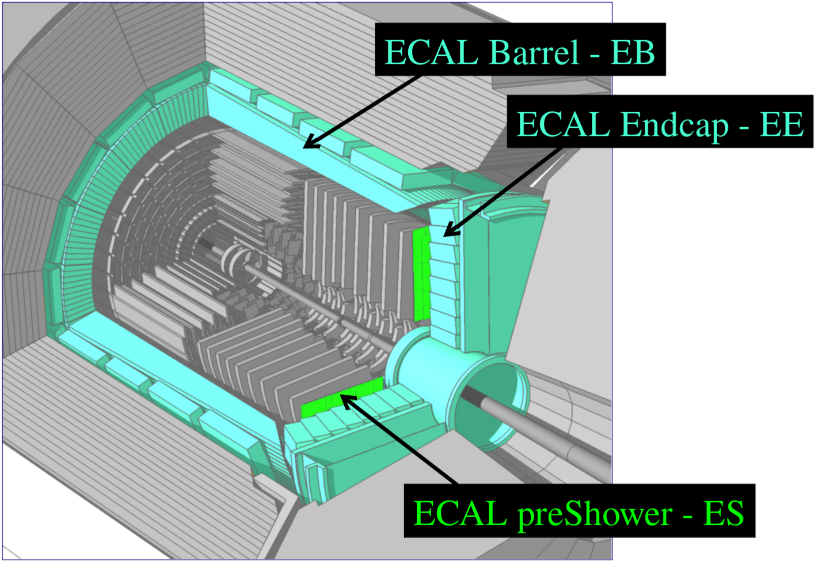
Building a calorimeter - a HOW TO guide

- **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

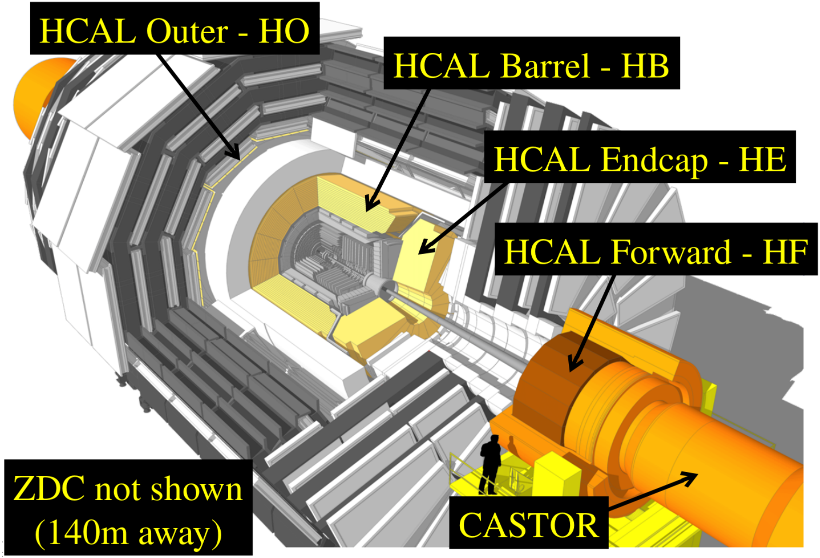
The CMS calorimeters



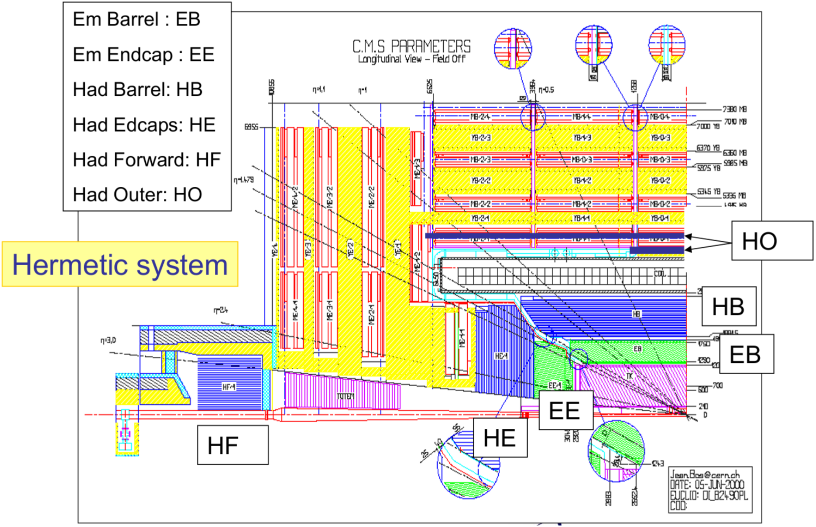
The CMS calorimeters



The CMS calorimeters

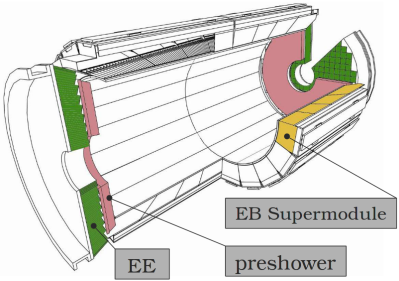


The CMS calorimeters



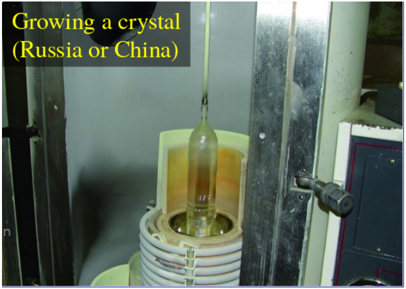
The CMS ECAL

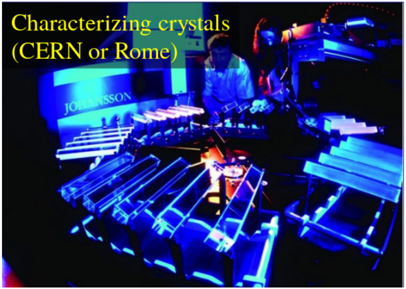
- **Homogeneous, hermetic, high granularity $PbWO_4$ crystal calorimeter**
  - density of 8.3 g/cm^3, radiation length 0.89 cm, Molière radius 2.2 cm, $\approx$ 80% of scintillating light in $\approx$ 25 ns, refractive index 2.2, light yield spread among crystals $\approx$ 10%
- **Barrel**: 61200 crystals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

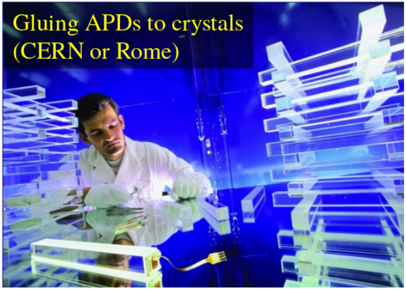


- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- CMS tracker coverage: $|\eta| < 2.5$

Production of the ECAL crystals (75848)







The CMS HCAL

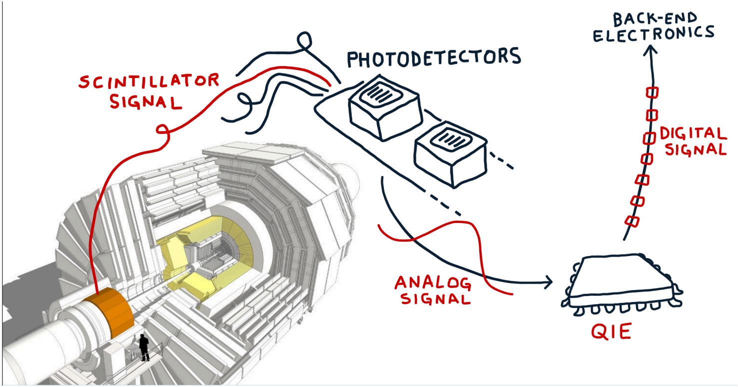
Barrel (HB)

- 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

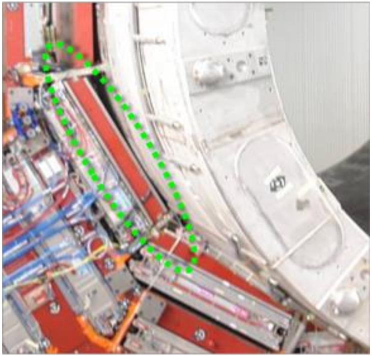


SCINTILLATOR SIGNAL
PHOTODETECTORS
BACK-END ELECTRONICS
DIGITAL SIGNAL
ANALOG SIGNAL
QIE

The CMS HCAL

Outer (HO)

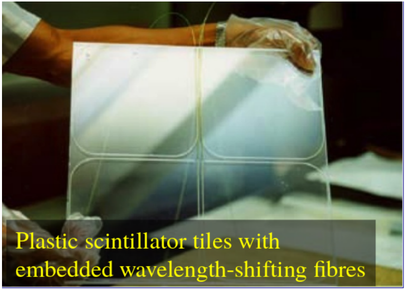
- Scintillator tiles (outside magnet yoke)
- 1 or 2 longitudinal layers, 10 mm scintillator
- $|\eta| < 1.3$

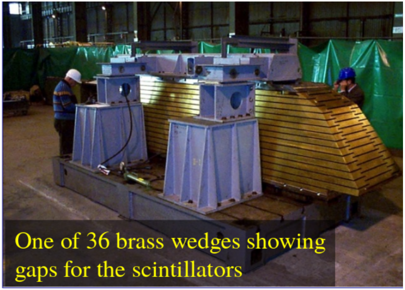


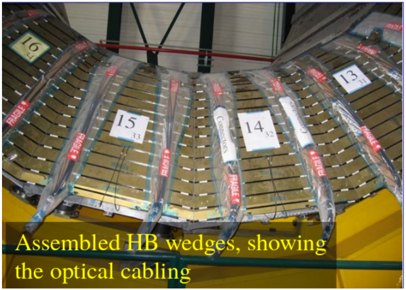
Forward (HF)

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

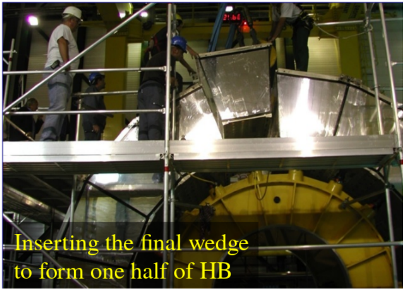
Assembly of HCAL barrel (wedges + megatiles)


Plastic scintillator tiles with embedded wavelength-shifting fibres


One of 36 brass wedges showing gaps for the scintillators



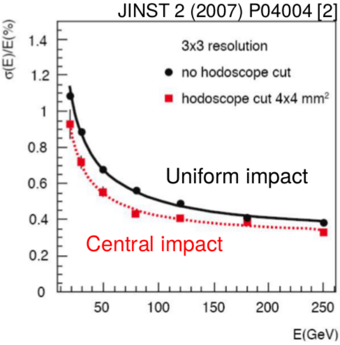
Assembled HB wedges, showing the optical cabling


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 $\approx$ 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

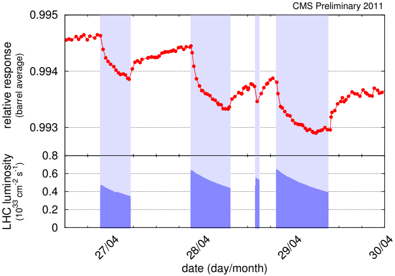
Photo-detector response:

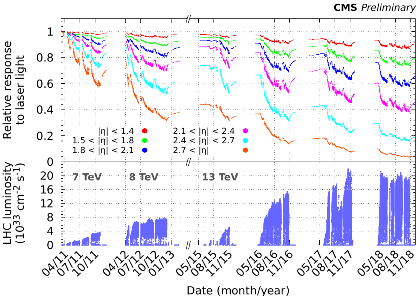
- APD → gain temperature dependence: $\Delta G/G \sim -2\%/^{\circ}\mathrm{C}$
  gain High-Voltage dependence: $\Delta G/G \sim 3\%/\mathrm{V}$
  direct ionization effects, a.k.a. "spikes"
- VPT, HPD, PMT → response dependence on the incremental charge at the cathode
- HPD → discharges, noise effects,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

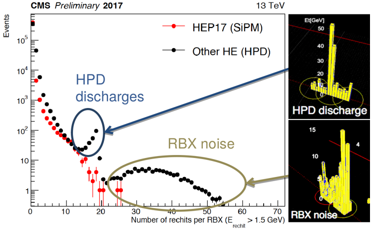
A glimpse of the challenges

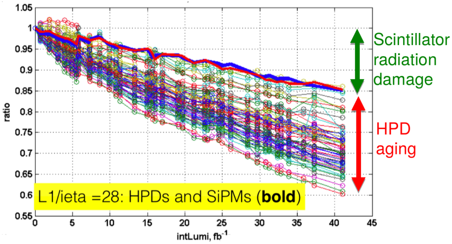
ECAL response: dose-rate variation... ...over 6+ years





HCAL: selected features





ECAL APD spikes analogous to HPD discharges

Not only calorimetry-induced fun

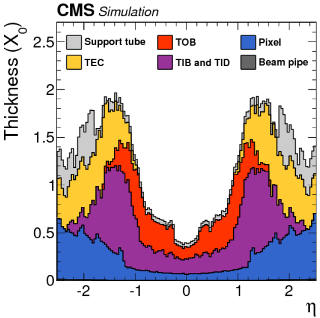
Tracker material in front of ECAL:

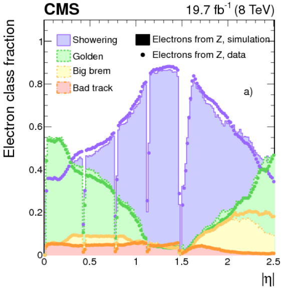
- photon conversions
- bremsstrahlung losses for electrons

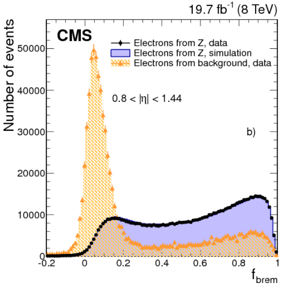
3.8 T solenoidal magnetic field:

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

$\longrightarrow$ Specific energy reconstruction algorithms and corrections

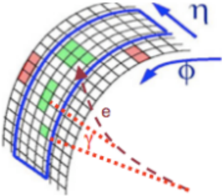






Ingredients for precision physics (ECAL example)

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



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

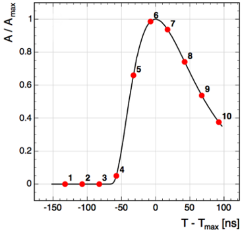
- $\mathcal{A}_i$: single channel amplitude, pulse fit in the time domain
- $s_i(t)$: single-channel time-dependent response corrections, via a dedicated laser monitoring system
- c_i: inter-calibration of the single channel response, using physics: φ- and time-invariance of the energy flow in minimum-bias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

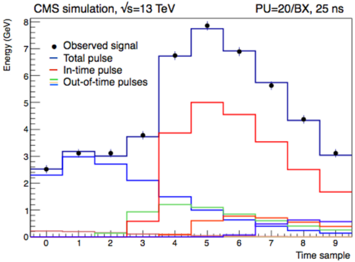
Resolution, efficiency and particle ID: $Z \to ee$

Amplitude reconstruction

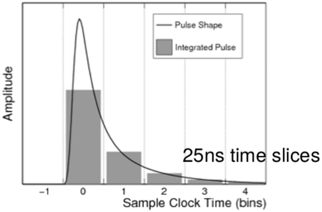
$E_{e,\gamma} = \mathcal{G}\ \mathcal{F}_{e,\gamma} \sum_i c_i s_i(t) \mathcal{A}_i$

ECAL algorithm

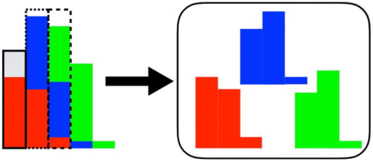




HCAL algorithm



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

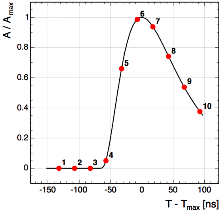
HCAL

- 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

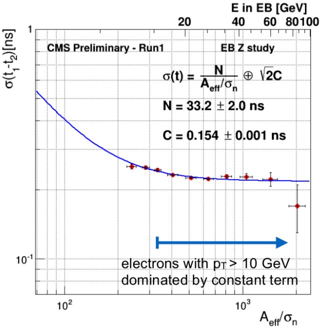
Many more subleties and challenges, **calibrating a detector is an art ;-)**

Gift: time resolution performance (ECAL)

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

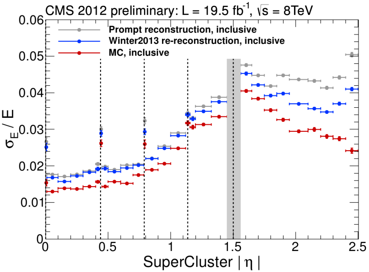


- From the time difference between the highest energy crystal of each of the two electrons from a $Z \rightarrow ee$
- **Noise term consistent** with Test-Beam
- **Constant term of ≈ 150 ps, much better than design**, uniform and stable in time
  - residual differences with Test-Beam qualifications ascribed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



Energy resolution performance (ECAL)

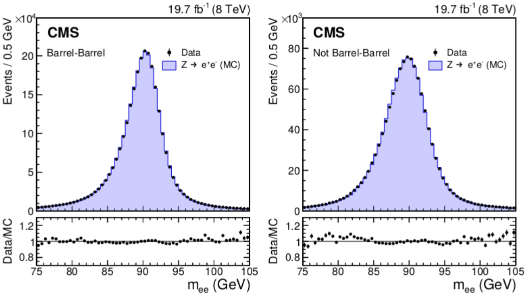
With electrons from Z



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

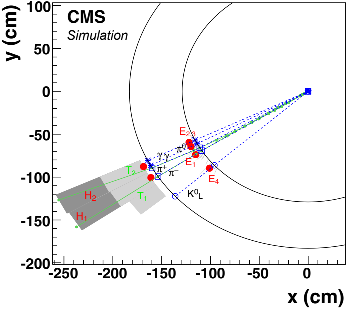
→ Simulation tuned to match performance observed *in situ* with $Z \to ee$ events

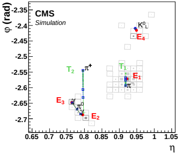
- scale: data → simulation
- resolution: sim. → data

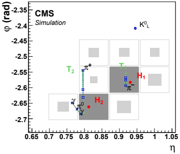


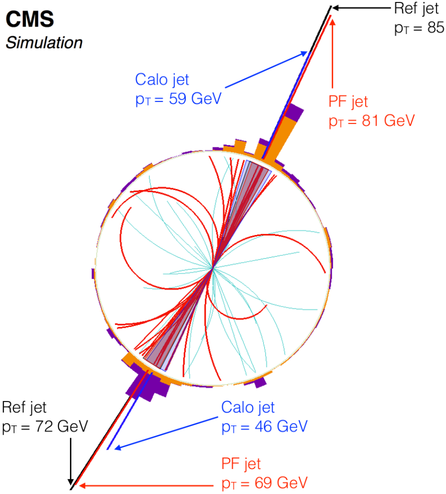
Team spirit: combine information

Particle Flow, or Global Event Description, in pictures

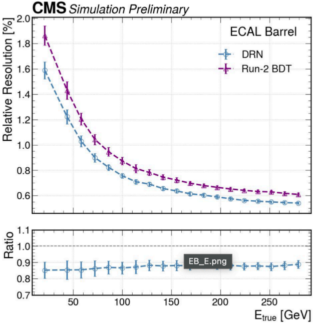




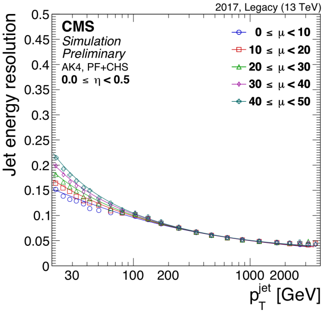




Final results: energy resolution



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

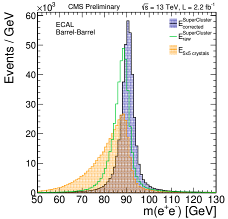


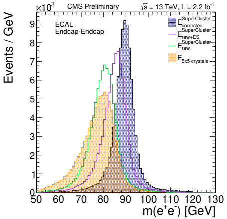
(d) Jets

Satisfied? Can improve further...

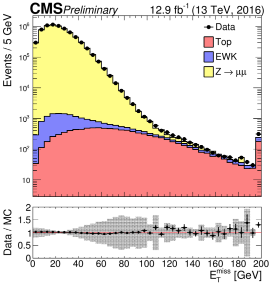
...with multivariate techniques (MVA, BDT, NN, etc.)

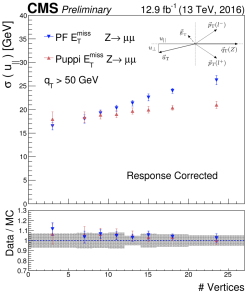
- Reconstructed Z mass in data with different levels of energy reconstruction and corrections (regression)





- 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

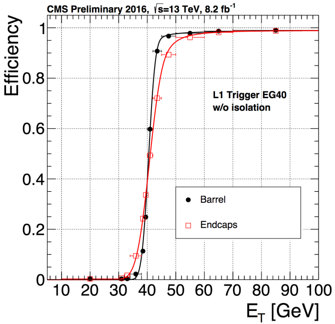
i.e. With the hope for the better, the good is lost

Trigger: another combined effort...

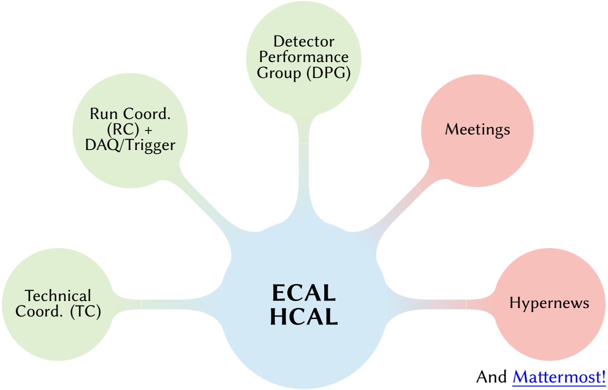
...which I leave to the data taking talk (speaker's team spirit ;-))

- At **L1** custom hardware processors 40 MHz $\rightarrow$ 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 $\rightarrow$ 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])

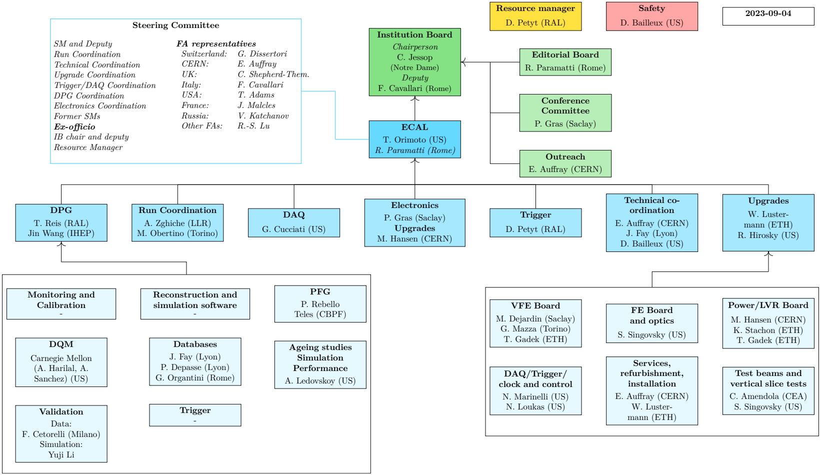


And Mattermost!

+ 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

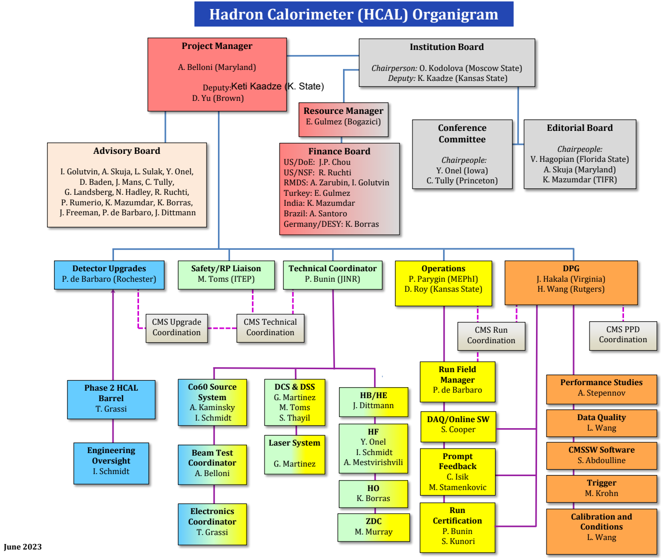
Main suspects for ECAL



- Organigram + DoC & DGL (2023; see twiki)

Main suspects for HCAL

To give you the feeling of the organization (2023; see twiki).



Already convicted

ECAL

Project manager

Toyoko Orimoto (Northeastern)

Deputy

Riccardo Parmatti (Roma)

HCAL

Project manager

Alberto Belloni (U. Maryland)

Deputy

David Yu (Nebraska/LPC)

Deputy

Keti Kaadze (Kansas State)

HGCAL

Project manager

Karl Gill

Deputy

Marcello Mannelli

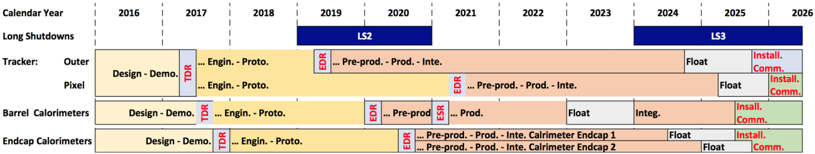
Deputy

Jim Strait

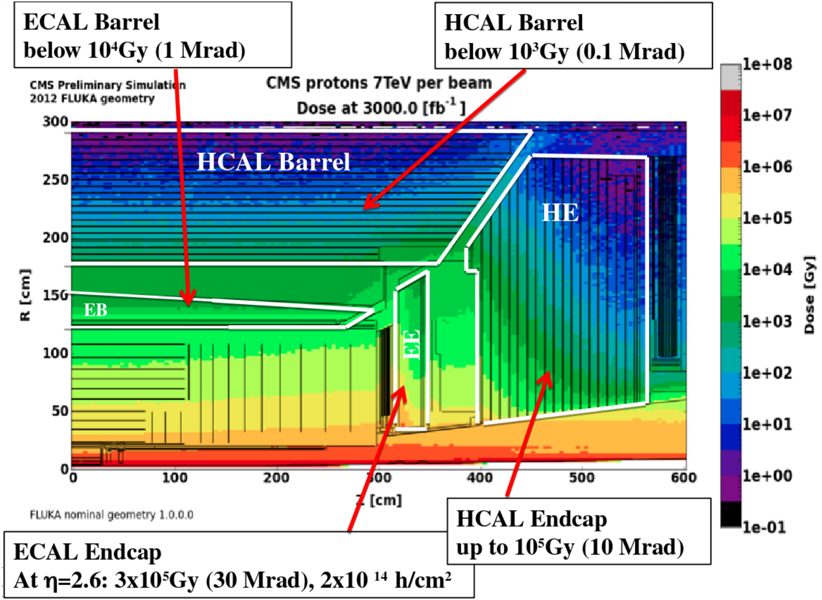
The future...

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

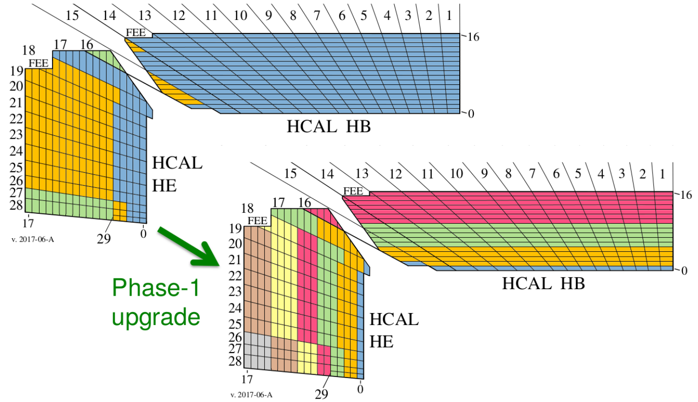
MTD: m.i.p. timing detector - not a calorimeter, but worth mentioning

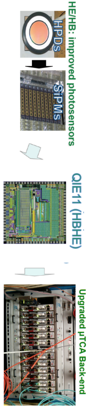
- new device between the tracker and the calorimetry, both in barrel and endcap, providing the arrival time of charged particles with a $\approx 30\,\mathrm{ps}$ resolution

Longitudinal segmentation in the readout

Phase 0 vs. Phase 1

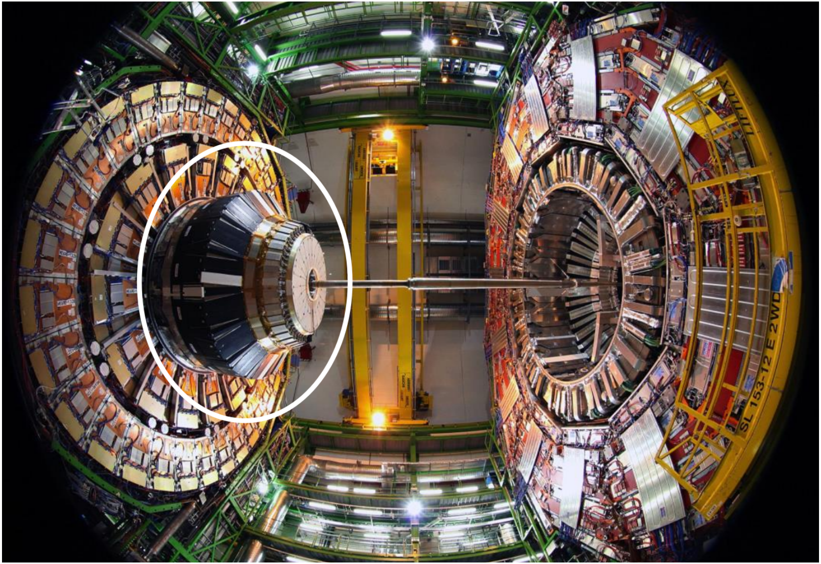
- Occurs with the photodetector transition HPD → SiPM
  - Phase 1 done (winter stop 2017/18): endcap segmentation fully exploited
  - Phase 2 during LS2 (just done!): barrel segmentation fully exploited
  - new opportunities to improve the offline reconstruction!
- and with an improved front-end electronics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





Forward calorimetry (for Phase 2)

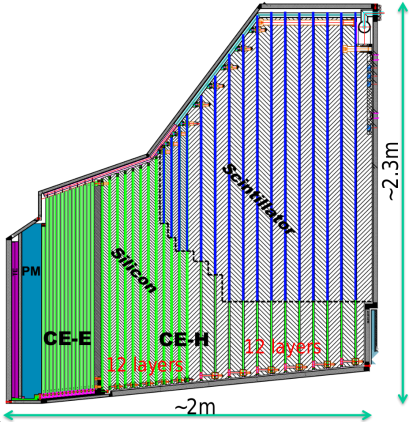
High **G**ranularity **CAL**orimetry (HGCAL)



Forward calorimetry (for Phase 2)

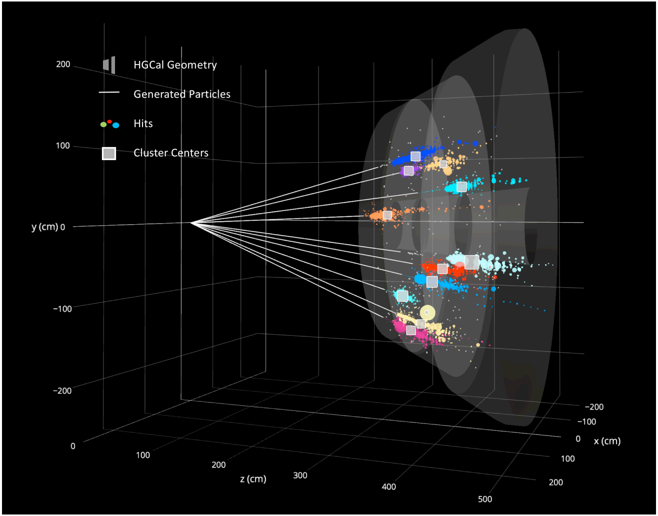
High **G**ranularity **CAL**orimetry (HGCAL)

- 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)**

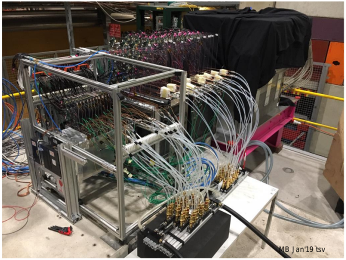
HGCAL reconstruction

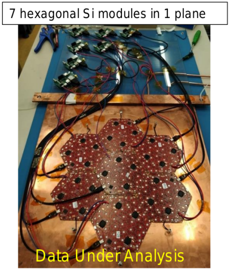


HGCAL: construction starting now!

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

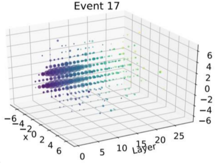
- Test beams in 2018 (CERN, DESY)
- 28 layers CE-E, 12 layers CE-H-Si
- Testing noise, mip calibration, electron and pion reconstruction

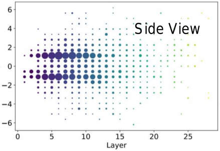


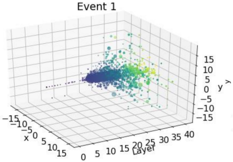


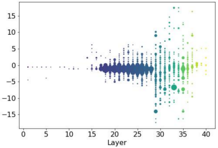
Electron(s? ;))

Pion









Wrapup

Main take-aways:

- Calorimetry is a fun subject with a lot of underlying physics!
    - Tons of technology and design choices ⇒ artistry and science in detector design.
- Electromagnetic and hadronic showers behave quite differently.
    - EM showers: only a few processes, see full energy.
    - Hadronic showers: many processes (including internal EM showers), large fluctuations, and non-compensation: the different response to EM and hadronic components.
    - CMS currently has separate EM and hadronic calorimeters; however, HGCAL will do both!
- Fundamental parameters:
    - Radiation length (X_0) and interaction length (λ_{int}) govern shower shape.
    - Energy resolution: $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E(GeV)} \oplus c$
- **ECAL and HCAL are fundamental** ingredients to achieve new physics discoveries as well as excellent measurement
- This was a fast and practical introduction to calorimetry at CMS. Many other, more in-depth resources are available!
    - E.g., R. Rusack et al's 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!