Ten years of operations of the CMS ECAL

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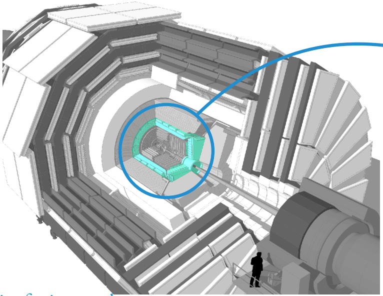
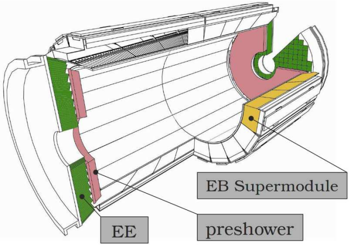
The CMS ECAL: a scientific "gift"

- **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, ≈ 80% of scintillating light in ≈25 ns, refractive index 2.2; weight of one barrel crystal 1.1 kg, total weight of the barrel crystals 67.4 t for 8.14 m^3 of crystal volume
- **Barrel (EB)**: 61200 crystals in 36 super-modules, **Avalanche Photo-Diode (APD)** readout $|\eta| < 1.48$
  - $2.2 \times 2.2 \times 23$ cm^3, $\approx 26\,X_0$
- **Endcaps (EE)**: 14648 crystals in 4-Dees, **Vacuum Photo-Triode (VPT)** readout $1.48 < |\eta| < 3.0$
  - $2.6 \times 2.6 \times 22$ cm^3, $\approx 25\,X_0$
- **Preshower (ES)** (endcaps only): $3X_0$ of Pb/Si strips $1.65 < |\eta| < 2.6$
  - 1.9×61 mm^2 x–y view



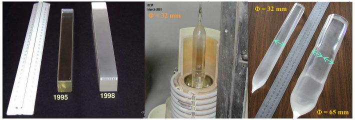


Designed for 14 TeV
10 years of running,
10^{34} cm^{-2}s^{-1}, 500 fb^{-1}

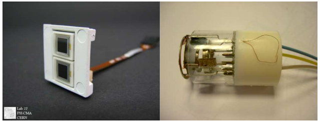
- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- Tracker coverage: $|\eta| < 2.5$

Timeline: from idea to (a new boson) discovery in ≈ 20 years

$PbWO_4$ R&D and prototyping (1993–1998)



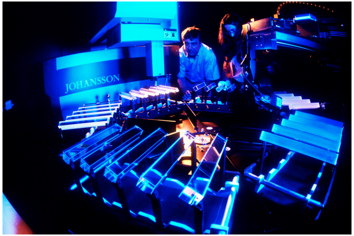
- Increase light yield (LY) (to 4.5 pe/MeV)
- Uniform longitudinal light transmission ($d\text{LY}/dX_0 < 0.35\%$)
- Define light readout APD (barrel) and VPT (endcap)



equivalent surface × Q.E.

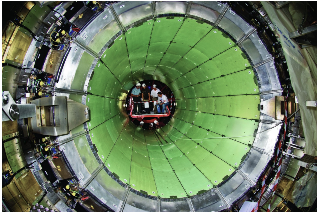
Mass production and quality control (1998–2008)

- Specs on: dimensions, LY + uniformity, optical transmission (T_λ), absorption induced by irradiation (μ_{ind})



- Two machines (CERN & Rome)
- From LY measurements: EB intercalibration (IC) @ 4.5%

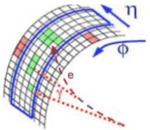
Installation and operation: (2009–now)



- From intercalibration at startup...
  - test beam: @ 0.3% on 1/4 of EB
  - cosmic rays: @ 1.5–2.5% on all EB
  - beam splashes: @ 5% on all EE (combined with LY&VPT info)
- ...through commissioning, operation, full calibration...
- ...to Higgs boson discovery in 2012!

Ingredients for precision physics: energy reconstruction

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



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

Response uniformity

- Crystal light yield (LY) spread $\approx 10\%$
- Endcap VPT response spread $\approx 25\%$

$\longrightarrow$ **intercalibration,** c_i, with $\langle c_i \rangle = 1$

Response stability

- LY variation with temperature: $-2.2\%/\,^\circ$C
- Gain variation (EB APDs): $-2.4\%/\,^\circ$C, $-3.1\%/$ V
- Transparency change with radiation dose-rate

$\longrightarrow$ **environment and response corrections,** $s_i(t)$, with $s_i(t=0) = 1$

- Pileup and electronic noise

$\longrightarrow$ **filtered amplitude reconstruction,** $\mathcal{A}_i$

Geometry, Tracker material, B-field

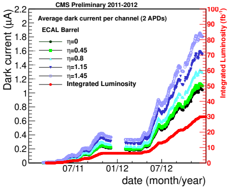
- Photon conversions, electron bremsstrahlung
- Energy spread along φ at $\approx$ constant η

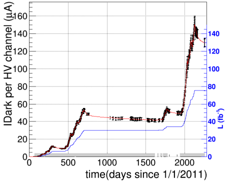
$\longrightarrow$ **clustering and energy corrections,** $\mathcal{F}_{e,\gamma}$ + global scale $\mathcal{G}$

- (Inter)Calibration with physics: $\pi^0, \eta^0 \to \gamma\gamma$ mass, φ-invariance of energy flow, electron E/p, $Z \to ee$
- Resolution, efficiency, and particle ID with $Z \to ee$
- Cross-checks with $Z \to \mu\mu\gamma$, but limited phase space
- Alignment is done relative to tracker with $Z \to ee$ events (or tracks for ES)

Expected & less expected challenges

- Crystal transparency changes
  - detector calibration is a continuous effort…
  - …that increases with luminosity, but so does physics data to refine the calibration
- APD dark current increase (i.e. electronics noise)
  - as predicted, in agreement with models





- Pileup (although ×3 w.r.t. design)

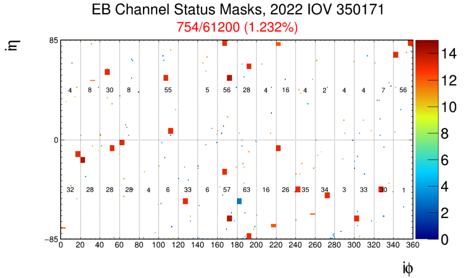
- Direct ionization signal in the APD ("spikes")
- Tracker material
  - e/γ reconstruction is complicated
  - γ/π^0 discrimination with ES is less effective (the showers broaden in the tracker)
- Monitoring sensitivity to laser pulse variations
  - fixed by using a solid state laser (more stable)
- Ageing of the laser monitoring components (reference PN diodes, fibers)
- Drift of pedestals with luminosity
- Crystal pulse shape changes, radiation-induced

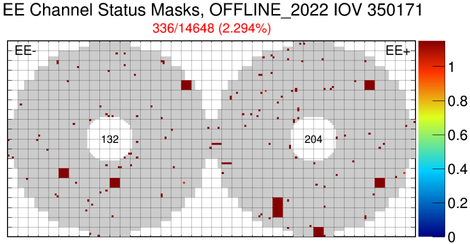
- Design choices for the ECAL barrel upgrade driven by all these challenges (compatibly with the hardware constraints)

more on ECAL upgrade on C. Cooke's talk on Thu

Boundary conditions

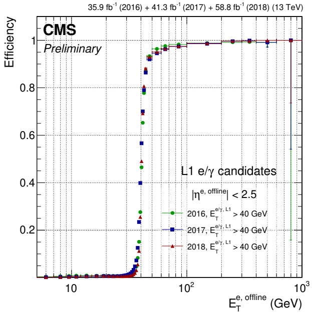
- Temperature stability at 18 °C: a factor of two better than required (< 0.05 °C for EB, <0.1 °C for EE)
  - thanks to the oversized cooling system, suitable to reach the working point at 9 °C for High-Luminosity LHC
- High-voltage stability is better than the measurement sensitivity and well below the required 60 mV
  - regular (now automatic) calibration of the channels to adjust the APD bias, if necessary
- Number of active channels remained stable and is today: > 98.7% (EB), > 97.8% (EE), 99.9% (ES)
  - EB, EE: very few single bad channels, most of the masked 5 × 5 regions can be recovered through trigger signal
  - ES: had alternate issues, with larger numbers of channels temporarily not working





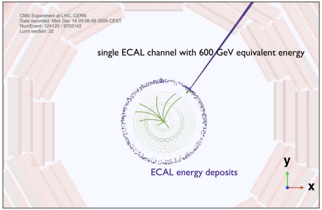
Running experience

- DAQ extremely reliable (and it kept improving with time); efficiency for offline data validation ≈ 99%
  - automatic recovery from single event upset, reduced configuration time, better monitoring programs, improved L1 trigger, automatic masking of noisy channels, improvements for spike detection (Run3)
- Efficient and stable e.m. trigger and turn-on curves well suited for the CMS physics program
  - dedicated high-rate calibration data streams with reduced event content
  - laser monitoring corrections applied, to stabilize trigger rate and turn-on curves (initially not foreseen)

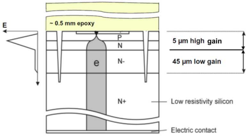


- Very limited failures over time, mainly in HV and LV power supplies, promptly repaired
  - ON/OFF cycles larger cause of issues than steady running
  - redundant configuration paths for online electronics proved in few cases to be a useful option
  - a campaign was necessary during the Long-Shutdown 1 (LS1) to fix ES LV connectors (required ES on surface)
  - ES cooling system affected by issues during LS2, due to Al joints reaching end-of-life (then simply refurbished)
- No system upgrade required before High-Luminosity LHC!
  - Detector Control System changed to improve reliability and prepare for HL-LHC

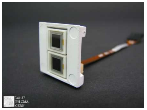
Trigger challenges: “spikes” (quite unexpected)

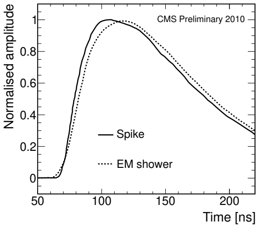


- Large signal in one single channel
- Direct ionization of the APD silicon

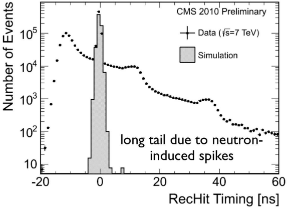


- Cure: dual readout



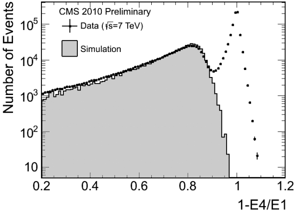


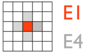
Early pulse...



- due to the absence of scintillation

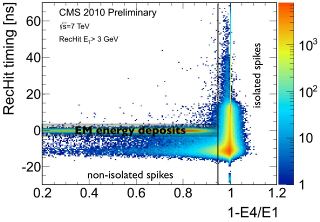
...on a single isolated channel:





Swiss cross variable:
spikes ≈ 1; $e/\gamma \lesssim 0.9$

can combine time and topology



- at HLT: full combination
- at L1: coarser topology and (>Run3) timing

Online rejection of spikes, i.e. at L1 trigger

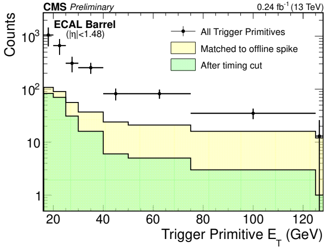
- Rate of spikes dominant component of the 100 kHz CMS L1 trigger rate bandwidth
  $\Rightarrow$ need reduction to maintain the lowest possible unprescaled e/γ triggers for physics

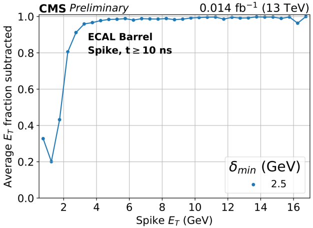
- The strip-Fine Grain Veto Bit (sum of 5 crystals in a trigger tower, programmable threshold) allows for a coarse shower shape:

  at least two contiguous strip over a threshold $\Rightarrow$ e.m. OK

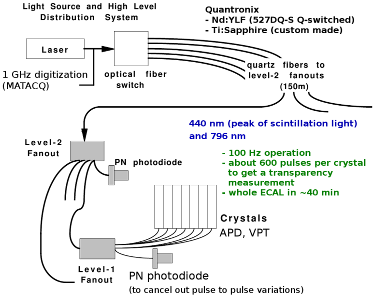
- Measured to reject > 95% of spikes with transverse energy greater than 16 GeV with a negligible impact on real e/γ

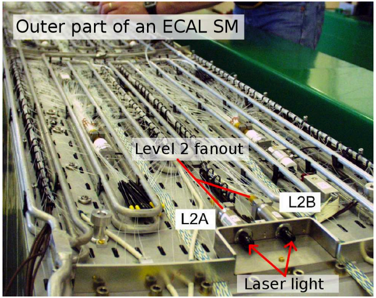
- In LS2: further improve the rejection by flagging out-of-time signals
  - exploiting an unused feature of the FENIX chip (for Trigger Primitives)
  - can serve for spikes below the sFGVB energy threshold (16 GeV)
  - the potential gain is promising
  - more detail on S. Pigazzini's talk

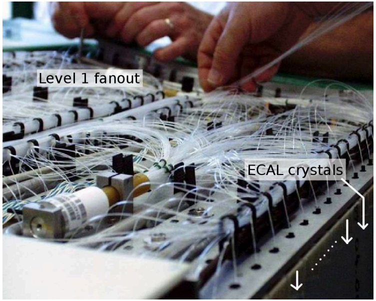


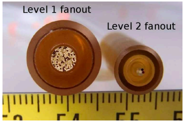


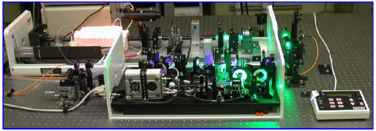
Laser monitoring system: hardware...







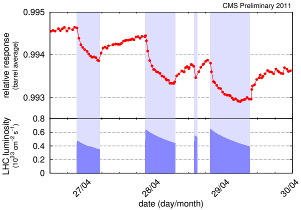


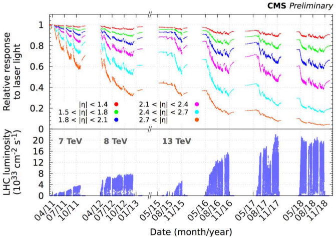


- Pulse energy: 1 mJ at the source, dynamic range up to 1.3 TeV equivalent
- Pulse width: <30 ns to match the ECAL readout
- Pulse jitter: <2 ns (30 min), <4 ns (24 hours)
- 100 Hz @ beam abort gaps, 3 µs every 89 µs of beam cycle, 1% used

- Corrections for CMS data reconstruction to be delivered within 48 h
- Redundancy (×2) in the PN reference diode proved to be useful, will be increased for HL-LHC (×4)

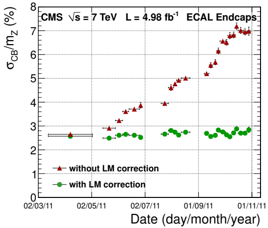
...and measurements: $E_{e,\gamma} = \mathcal{G} \cdot \mathcal{F}_{e,\gamma} \sum_i c_i\, s_i(t)\, \mathcal{A}_i$



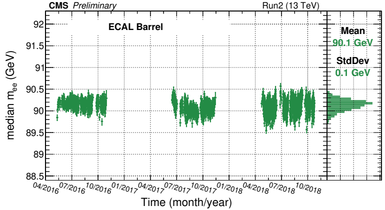


- Response to laser light R/R_0 and to e.m. showers S/S_0 related by a power law, at first order: $S/S_0 = (R/R_0)^\alpha$
- Photodetector response changes entangled to transparency measurements
- Corrections also deployed every few days at L1 trigger level (hardware configuration) and HLT (database conditions)
- System 100% reliable over Run1 and Run2, single measurement precision much better than 0.2%

- Clear impact on resolution:

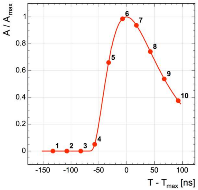


- Z mass stability over Run2



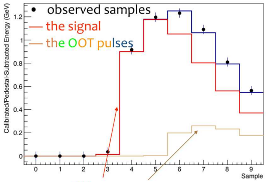
Pileup: $E_{e,\gamma} = \mathcal{G} \cdot \mathcal{F}_{e,\gamma} \sum_i c_i \, s_i(t) \, \mathcal{A}_i$

- Relevant from Run2 onwards: new amplitude reconstruction algorithm developed
  - Run1 algorithm: standard digital filtering technique (3 pedestal samples + 5 around the maximum)



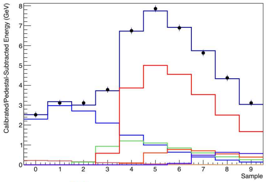
- LHC collisions at 40 MHz
- Pulse digitization at 40 MHz
- 12 bit ADCs, 3 gains
  (1, 6, 12; ...160...250...GeV)

example fit on a barrel hit



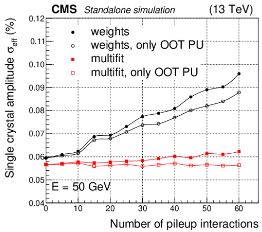
BX=0 and +2 fitted

example fit on a endcap hit



BX=0,-4,-1,+1,etc. fitted

- Multifit: template fit with fixed pulses and floating amplitudes
- Fit up to 10 pulses, need prior knowledge of the pedestals
- In-time pileup is irreducible; can be removed on average from the energy density in an event

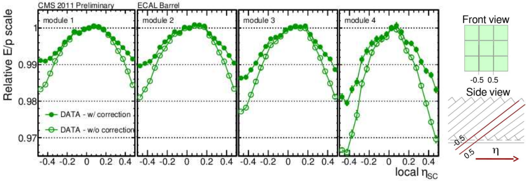


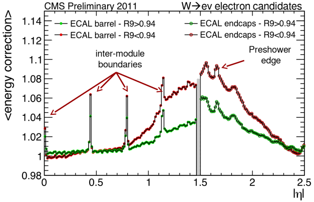
Examples of refinements: $E_{e,\gamma} = \mathcal{G} \cdot \mathcal{F}_{e,\gamma} \sum_i c_i \, s_i(t) \, \mathcal{A}_i$

more on ML techniques on P. Simkina's talk on Thu

Local containment corrections

- Dependence of the reconstructed energy on the supercluster position along η, referred to the local position of the crystal with maximum energy
  - derived from simulation, insufficient to correct data



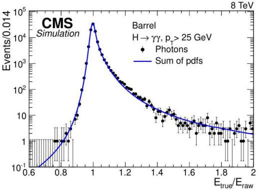


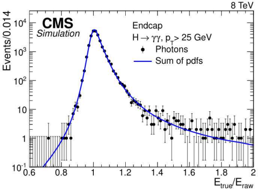
Energy corrections along η

- Corrections derived from simulation, several flavours of MVA analyses over time
- Based on shower shapes, shower location, and global event variables
- Tested and tuned *in situ* with $Z \to ee$ invariant mass and E/p uniformity vs η

Energy regression

- Used in the estimate of the mass resolution of individual diphoton systems (e.g. $H \to \gamma\gamma$)
- Excellent performance although hints for small systematics: still room for improvement



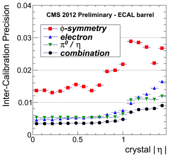


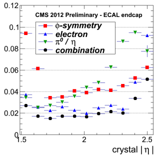
ECAL calibration in a glimpse: $E_{e,\gamma} = G \cdot \mathcal{F}_{e,\gamma} \sum_i c_i \, s_i(t) \, \mathcal{A}_i$

more on S. Pigazzini's talk on Thu

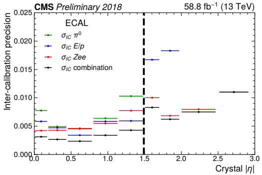
- Several calibration methods combined
- Precision and methods evolved during Run1 and Run2 due to ageing and pileup

→ different precision vs. η →





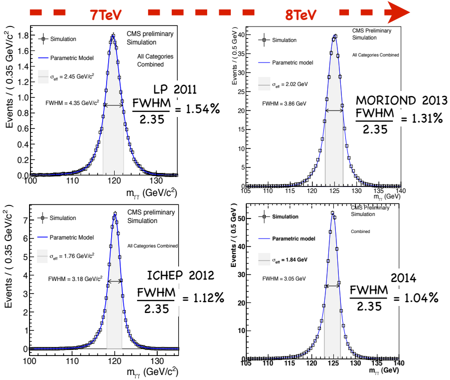
↓ different methods vs. year ↓



- Resolution measured in data with $Z \to ee$ events used to model in simulation the expected $H \to \gamma\gamma$ signal
- Steady progress and excellent results: conditions improved along the year and for end-of-run reconstructions
- Aim at having most of the experience built during Run2 embedded in automatic procedures for Run3

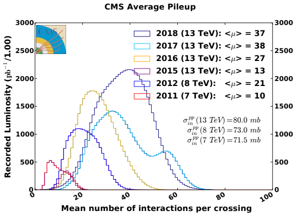
PROMPT reconstruction within 48h from data taking

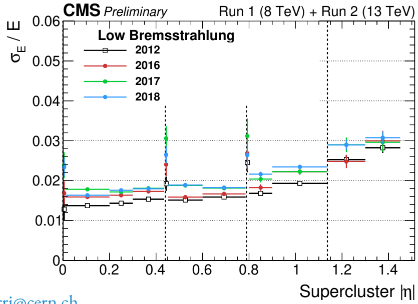
RECONSTRUCTION with improved conditions

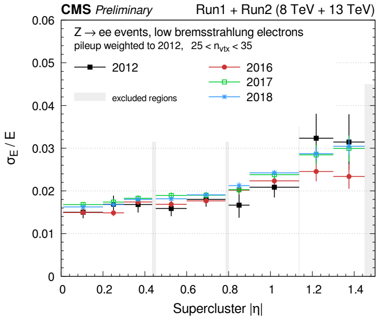


ECAL long term performance: comparison across runs

- Main differences compatible with the increase of noise (APD dark current) and pileup
  - pileup weighted events show a difference compatible with noise increase
  - caveats: different Run1 and Run2 pulse reconstruction, different years implies different regressions (with similar but not identical trainings and techniques)

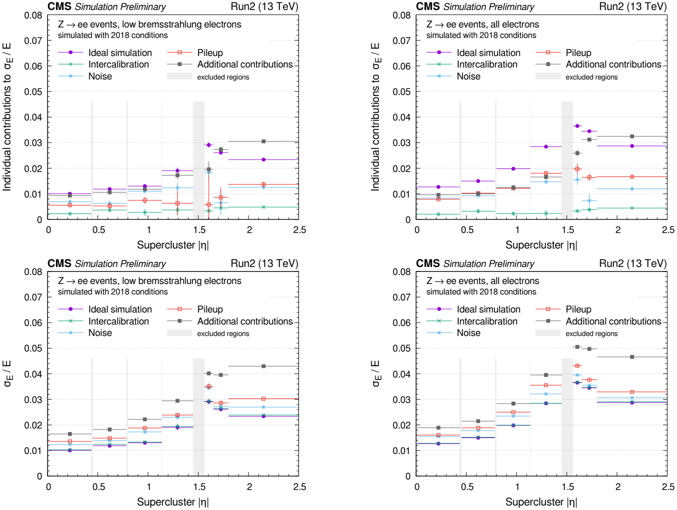






ECAL performance: resolution breakdown (from 2018 data)

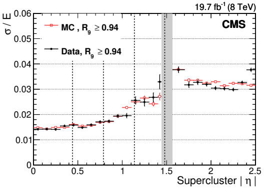
- Simple idea but complex realisation
- Effects enabled on top of the ideal detector geometry and shower simulation (w/ photostatistics)
  - different simulations (GEANT-based), with dedicated regressions
  - Intercalibration contrib. from data
  - Additional contributions: 2018 data ⊖ simulation
- Noise and pileup starts to be comparable (hint for Run3)
- Intercalibrations have small impact
- Effects not modeled from first principles are significant
  - well described by a Gaussian smearing

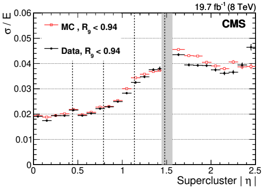


Simulation includes noise with sample-correlations and channel-to-channel variations, transparency variations for realistic light-yield (and fotostatistics), inhomogeneities in ϕ of services, intercalibration accuracy, geometry, pileup

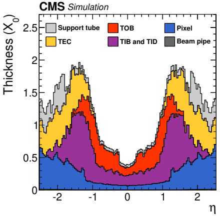
Example of (not too) imperfect simulation

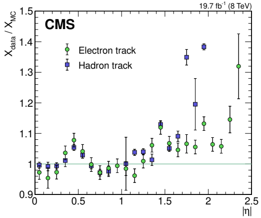
- Gaussian smearing computed in wide categories of η (and R_9) holds also with fine binning



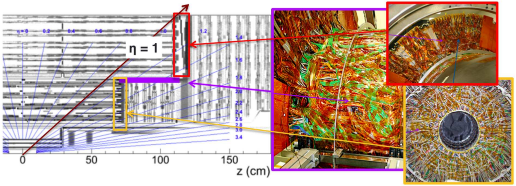


- Data/MC Tracker material thickness in X_0
  - bremsstrahlung of electrons: $1 - p_{\mathrm{vtx}}/p_{\mathrm{out}}$
  - multiple scattering of low p_T pions

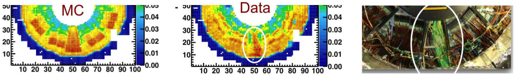




  - TIB/TOB support structure at $|\eta| = 0.5$
  - services in the Tracker/ECAL transition regions



- E-flow in the preshower in $Z \to ee$ events
  - cables and connectors at the back of the Tracker

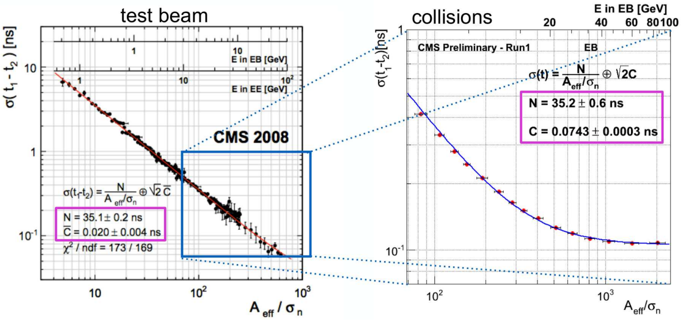


An average material density is not the same as a localized concentration of matter!

Timing

- Initially not at the core of the design requirements: better than 1 ns not to affect energy measurement
- Electronics shaping time ($\approx$ 40 ns) and sampling rate (40 MHz) allows for excellent time resolution
  - from TB results (2008 and 2016-2018 with Phase2 electronics), time resolution better than 50 ps and asymptotic to 20 ps at high energy
- Several effects worsen the precision *in situ*: clock distribution, impact point on the crystal, radiation, geometry (staggering), B field, tracker material, ...
  - already good for physics, needs further understanding to fully profit from it in HL-LHC

- *in situ* measurement from the Δt between two crystals of the same e.m. shower in $Z \rightarrow ee$ events
- if Δt between the two electrons (i.e. different e.m. showers), resolution of $\approx$ 150 ps



Lessons learnt (or at least attended): measurements

Relative precision:

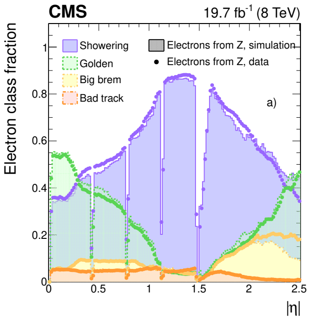
- $O(10^{-1})$ can be achieved by eye
- $O(10^{-2})$ is a standard textbook measurement
- $O(10^{-3})$ is where most of the "negligible" effects cannot be neglected anymore, and sooner or later come back to you

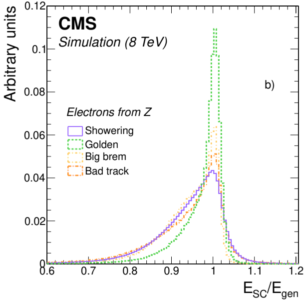
Lessons learnt (or at least attended): calorimetry

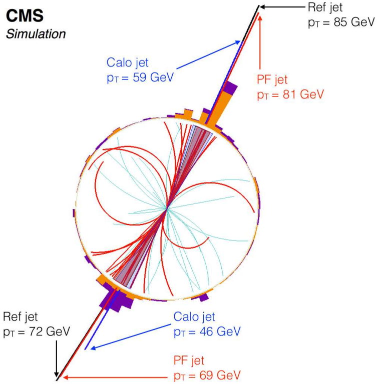
- If you want to build another crystal calorimeter in a harsh radiation environment, do it at your own risk! ;–)
  - more seriously: find the good balance between stability and ultimate performance, also considering limited personpower
- The detector ageing is paramount, radiation dose-rate and topology should drive the design, monitoring, and readout
  - e.g. radial slices for the endcap readout should definitely be avoided in favour of concentric circular crowns
  - modular and changeable parts may be a good enough solution to compensate for ageing
- Writing DAQ firmware is an art and debugging it a nightmare, having a flexible DAQ/Trigger is an incommensurable treasure
  - size the hardware properly in terms of memory and computing power
  - never ever deploy FW and develop features after data taking starts, it will finally work when it is about time to upgrade, i.e. to change the whole electronics and start all over again

Lessons learnt (or at least attended): calorimetry

- Building a fantastic calorimeter is only half of the job
- The other half is embedding it in a proper environment: early showers compromise the performance especially in a strong magnetic field
  - which, however, some time might happen to be at 0 T





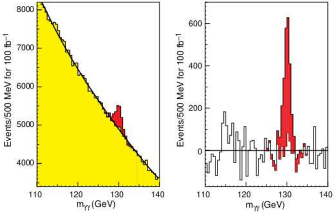


- Particle-flow reconstruction: combination of all the available information!

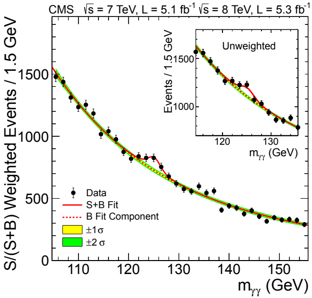
Higgs boson: fairy tales come true

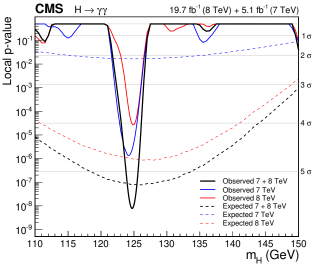
ECAL TDR, CERN/LHCC 97-3, 15 December 1997, p. 26:

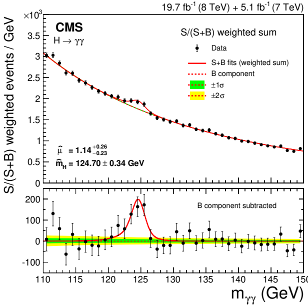
> *Figure 1.17 shows the two-photon signal from a 130 GeV Higgs after collecting 100 fb^{-1} at high luminosity before and after background subtraction. […] [F]or 30 fb^{-1} taken at low luminosity, the signal significance is above 5 over the entire Higgs mass range where the $H \to \gamma\gamma$ decay mode provides a distinctive signature for its discovery at the LHC.*



Conceptually simple measurements may reveal **quite a complex challenge**, but are definitely rewarding

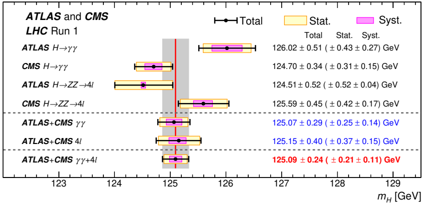


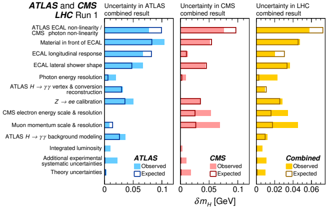




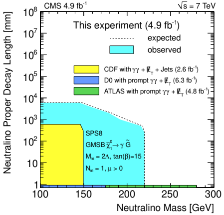
After all, how good were these past ten years?

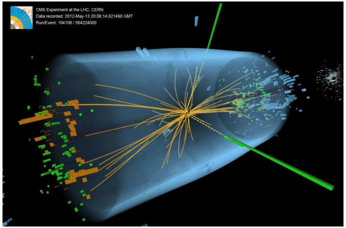
From precision physics of the Higgs sector…





…to searches for long-lived particles





Designed for 14 TeV
10 years of running,
10^{34} cm^{-2}s^{-1}, 500 fb^{-1}

Actually run at 7, 8, 13 TeV
for 10 years already, 15 more to come,
2×10^{34} cm^{-2}s^{-1}, 150 fb^{-1},
forecast: 5 to 7.5 $\times10^{34}$ cm^{-2}s^{-1}, 3000 fb^{-1}

well… not too bad actually, including plenty of physics with electrons, jets, MET.

And the LHC “bright” future coming seems promising!

more detail on ECAL on the Thursday sessions!

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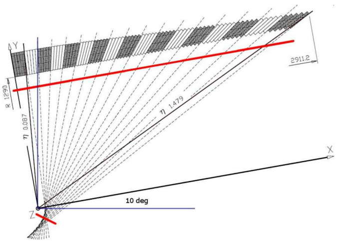
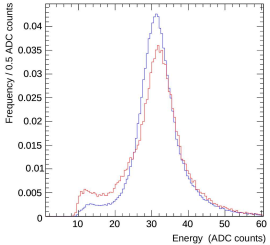
Spares

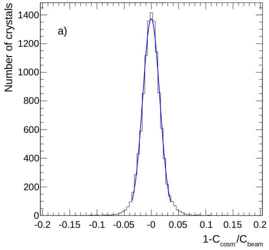
Intercalibration with cosmic ray muons

- Reference signal: 250 MeV from μ m.i.p. through 26 X_0
- $S/N \approx 25$: equivalent noise of 10 MeV if APD gain 200 ($\times$4 nominal)
  - Laser light to transport constants from APD gain 200 to APD gain 50
- Pointing trigger via crystal geometry to enhance co-axial muons
  - 10 deg tilt to partially compensate for $\cos^2 \vartheta$ dependence of muon flux
- Fit to reference distributions (from xtals at same η), fixed shape, normalization and scale as free parameters
  - 300 to 200 calibration events in one week of data taking

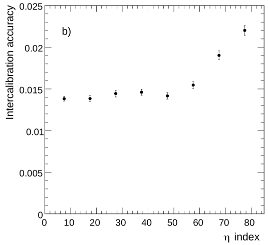




Module 1 and 4, OK w/ expectations



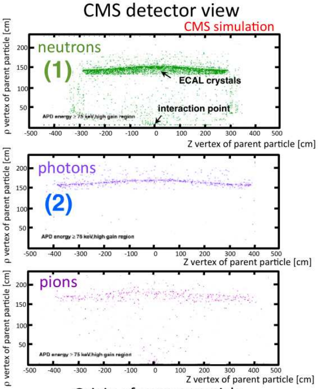
Accuracy validated with beam IC



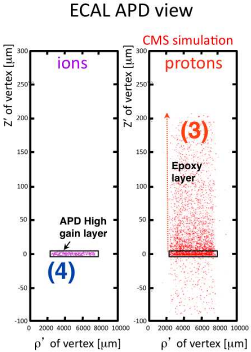
Upper limit for EB at startup (25% IC on e-beam)

Simulation studies: location of spike progenitors

- Detailed simulation of the APD structure implemented in the GEANT-based full simulation of CMS



Origin of parent particle
z - distance along beam axis
ρ - distance perpendicular to beam axis



Origin of particle hitting APD
ρ' - distance along APD
z' - distance perpendicular to APD axis

- (1) neutrons produced in the ECAL crystals
- (2) photons produced close to the APD layer
- (3) anomalous signals produced by np scattering in the protective epoxy coating of the APD.
- (4) Ions (silicon nuclei) directly ionize the APD active volume.