Achieving the optimal calibration and performance of the CMS Electromagnetic Calorimeter in LHC Runs 2 and 3

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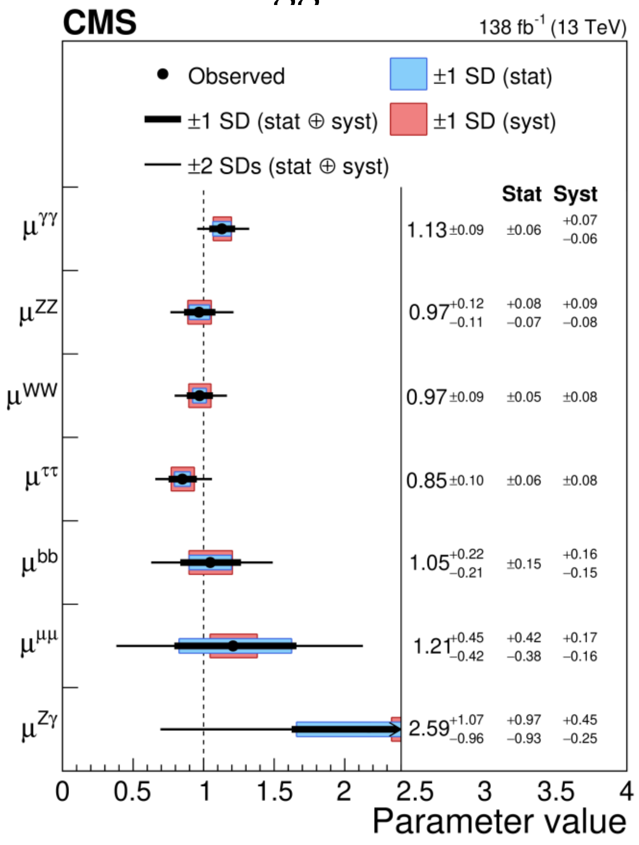
On behalf of the CMS Collaboration

Introduction

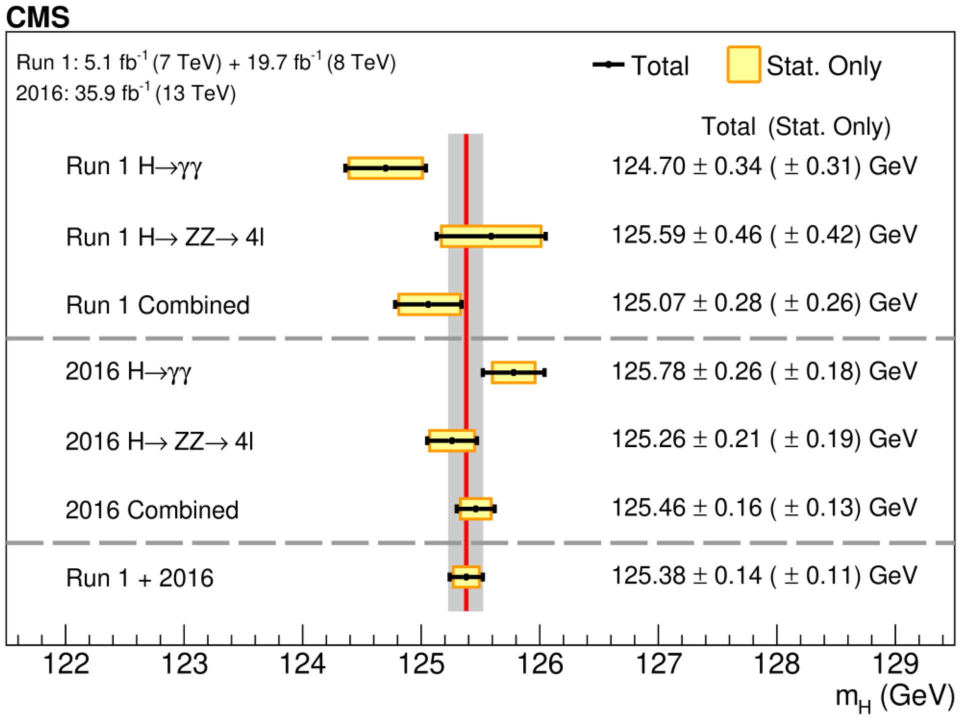
The Electromagnetic Calorimeter (ECAL) performance is crucial for precision measurements involving electrons and photons, and for the reconstruction of the jets and missing transverse (MET) energies.

The agreement with the SM predictions for decay channels of Higgs boson



[Nature 607 (2022) 60-68]

Summary of Higgs boson mass in H→γγ and H → ZZ→ 4*l* decay channels

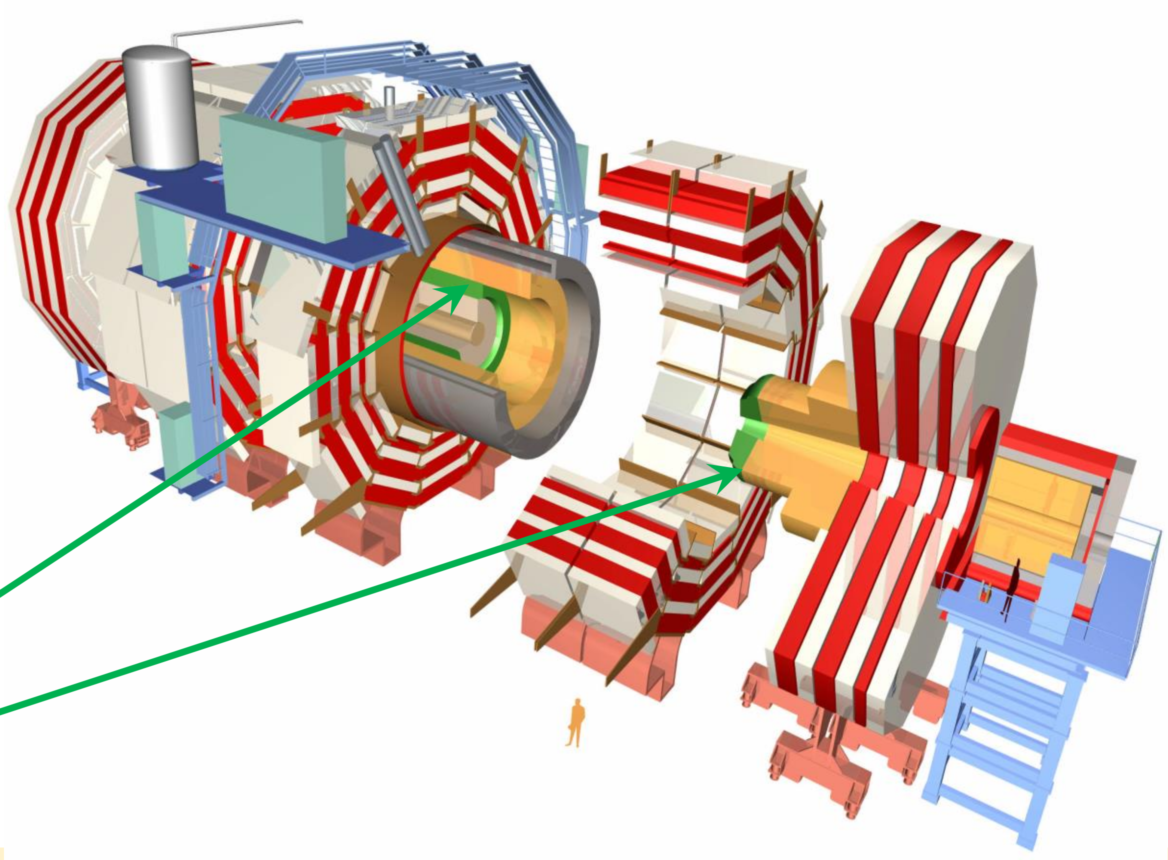


[PLB 805 (2020) 135425]

The CMS Detector and the ECAL

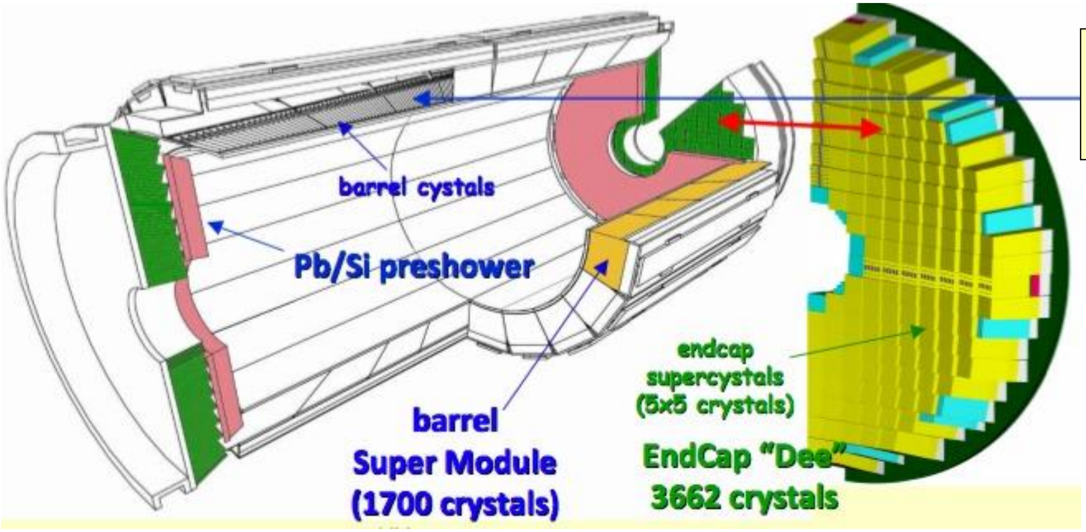
CMS

Length :21.5m
Diameter: 15m
Weight 14kt
Magnetic field:3.8T

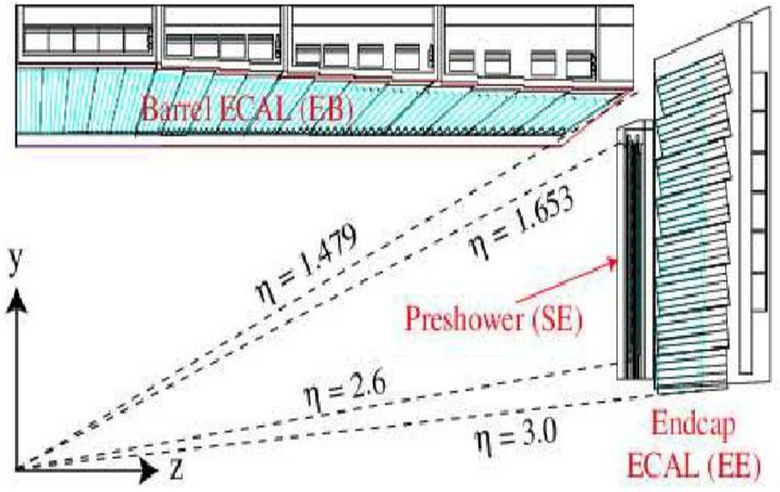


ECAL is crucial for precision measurements involving electrons and photons, and for reconstruction of the jets and missing transverse energies (MET).

The CMS Electromagnetic calorimeter



Tapered crystals to provide off-pointing of ~ 3° from vertex

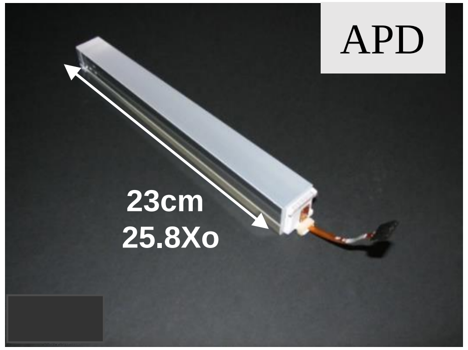


Barrel
36 Supermodules
(18 per half barrel)
61200 crystals
Total crystal mass 67.4t
$|\eta| < 1.48$, ~$26X_0$
$\Delta\eta \times \Delta\varphi = 0.0174 \times 0.0174$

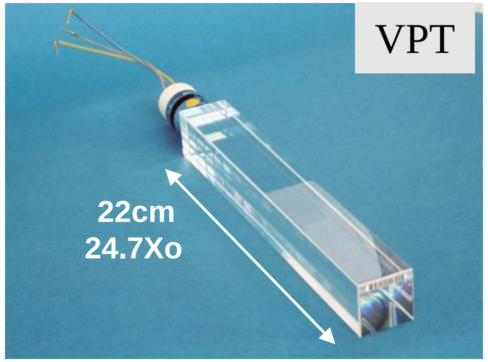
Endcaps
4 Dees (2 per endcap)
14648 crystals
Total crystal mass 22.9t
$1.48 < |\eta| < 3$, ~$25X_0$
$\Delta\eta \times \Delta\varphi = 0.0175^2 \leftrightarrow 0.05^2$

Endcap Preshower
Pb ($2X_o$,$1X_o$) / Si
4 Dees (2 per endcap)
4300 Si strips
1.8mm x 63mm
$1.65 < |\eta| < 2.6$

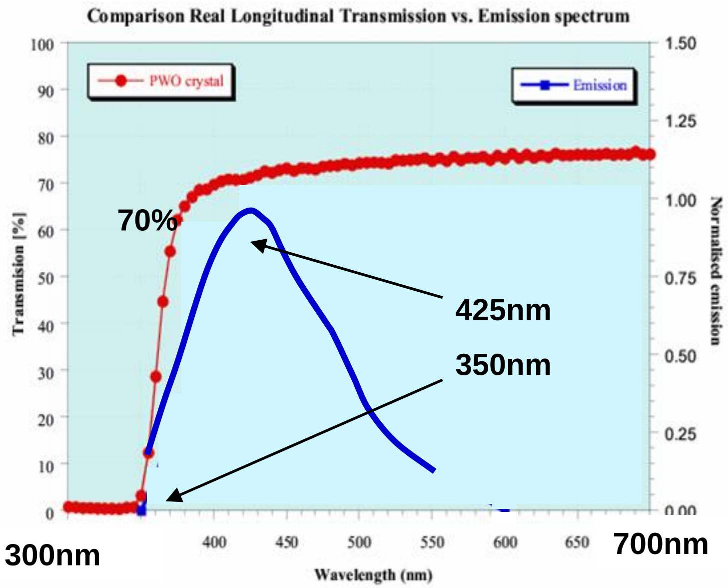
Lead tungstate crystals ($PbWO_4$)



Barrel crystal, tapered
34 types, ~2.6x2.6 cm^2 at rear



Endcap crystal, tapered
1 type, 3x3 cm^2 at rear



Emission spectrum (blue)
and transmission curve(red)

Reasons for choice

Homogeneous medium

High density	8.28 g/cm^3
Short radiation length	X_0 = 0.89 cm
Small Molière radius	R_M = 2.19 cm
Fast light emission	~80% in 25 ns
Emission peak	425nm

Reasonable radiation resistance to very high doses

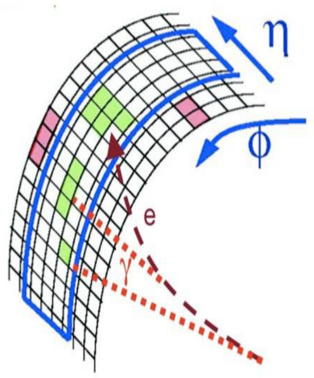
Challenges

LY temperature dependence (-2.2%/^{O}C) + APD gain temperature dependence
- Stabilise to ≤ 0.1^{O}C

Irradiation affects crystal transparency
- Need precise light monitoring system

Low light yield (1.3% NaI)
- Need photodetectors with gain in magnetic field

e/γ energy reconstruction



Clustering

- Crystal transverse size is ~ R_M so EM shower spread over several crystals
- Clusters are extended in φ direction to form "superclusters" to recover energy radiated via bremsstrahlung or conversion

Cluster correction obtained from a regression method

Intercalibration: equalize signal response for the same η

Reconstructed signal amplitude

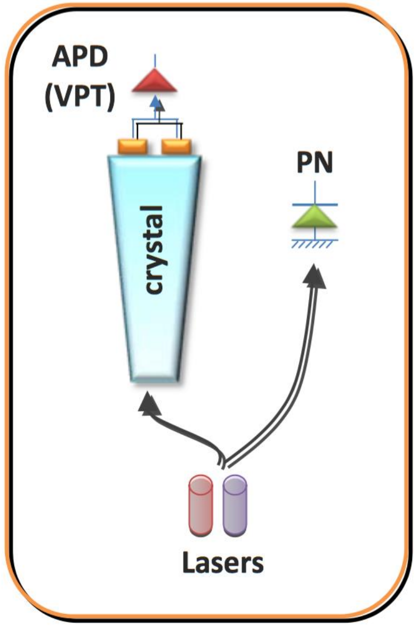
$$E_{e,\gamma} = F_{e,\gamma} \times \left[G(\eta) \times \sum_i C_i(t) \times S_i(t) \times A_i(t) + E_{ES} \right]$$

Global scale factor for the ADC-to-GeV conversion

Laser corrections: for signal transparency loss

Preshower energy

Crystal transparency monitoring



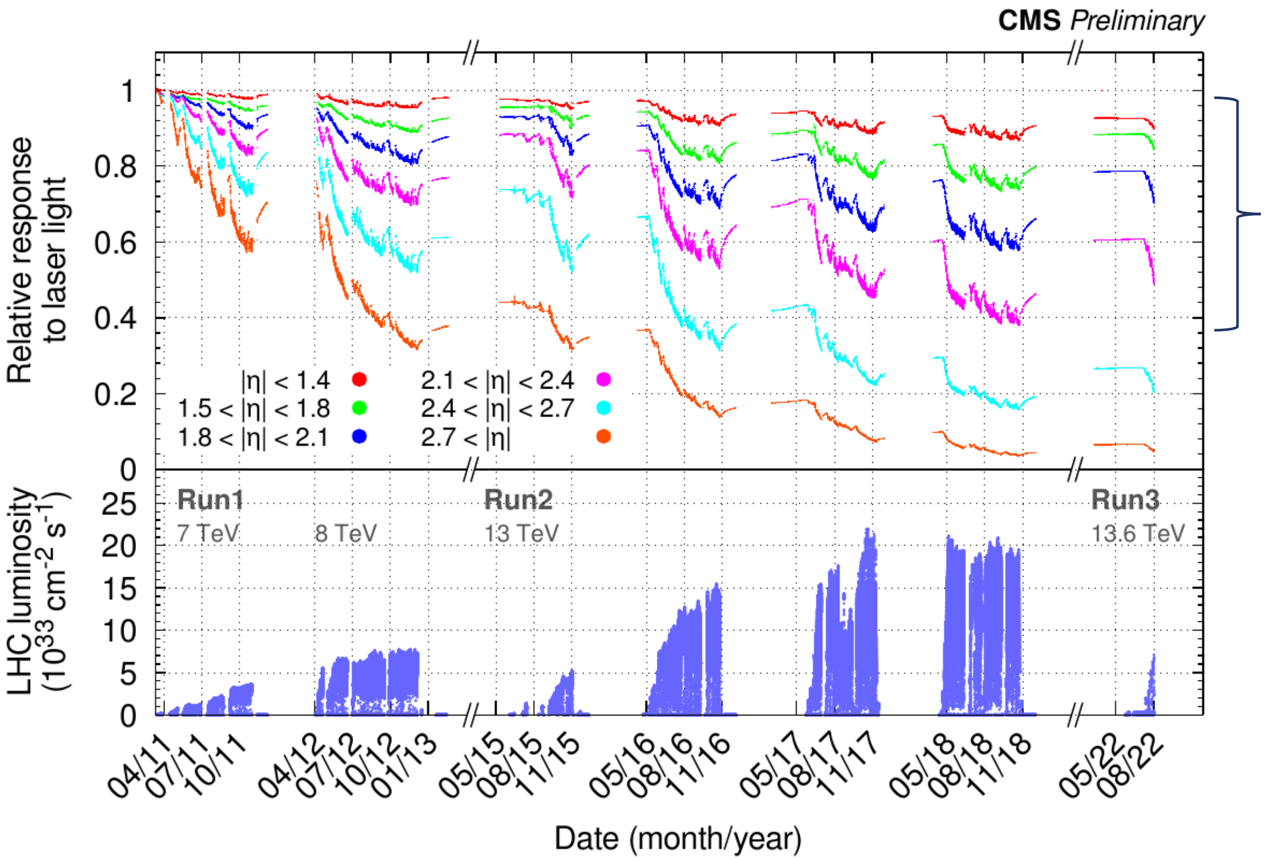
APD: Avalanche Photodiode (EB)
VPT: Vacuum Phototriode (EE)
PN: Reference diode

- ECAL channel response varies with time due to radiation-induced effects
  - Crystal transparency changes overtime
  - Photocathode aging with accumulated charge

- A dedicated laser monitoring system is designed to provide necessary corrections
  - Injects laser light with a wavelength of 447nm into each crystal
  - Measures the calibration point per crystal every40 minutes
  - Obtains and applies corrections within 48 hours for the prompt reconstruction

- Relates ECAL channel response variation to changes in the scintillation signal

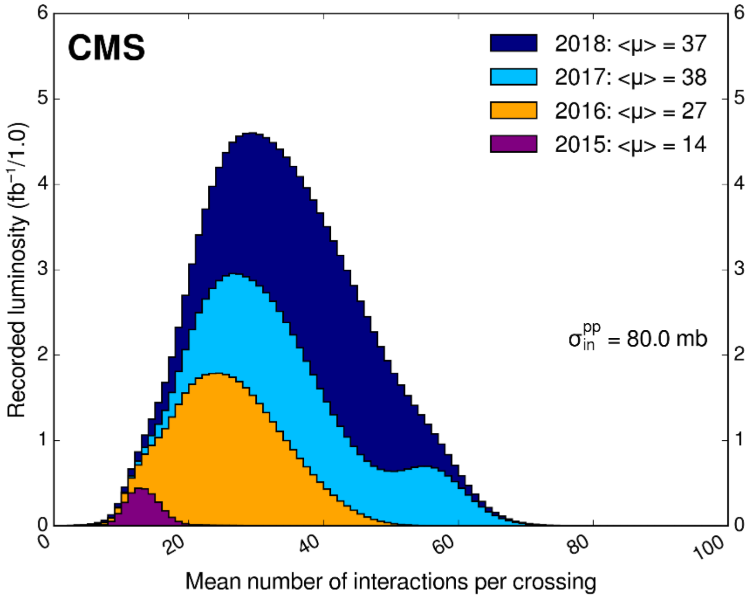
Crystal transparency monitoring



DP-2022/042

- Aging:
  - Barrel has up to 17% loss
  - Endcaps reaches up to 62% at η ~ 2.5 and up to 96% in the region closest to the beam pipe.
- The recovery of the crystal response during the period without collisions is visible but it is not complete.
- It is crucial to maintain stable ECAL energy scale and resolution over time

Pulse shape reconstruction

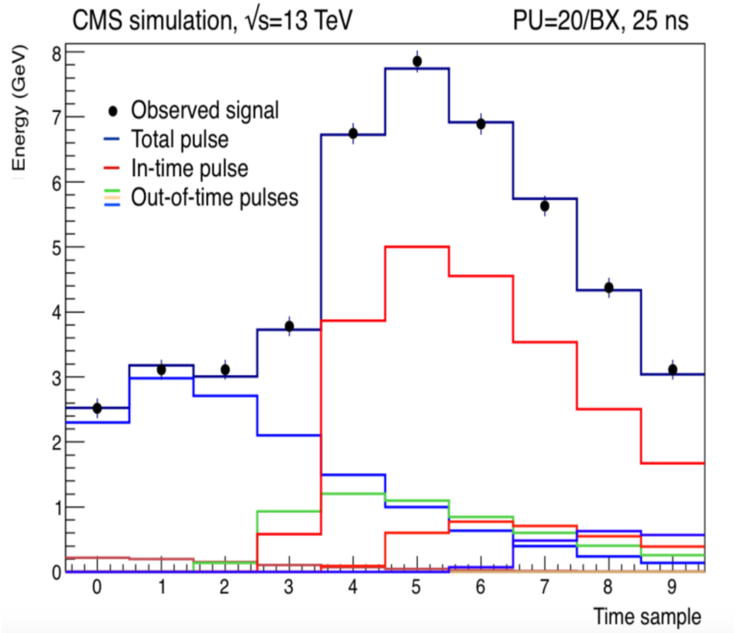


- High pile-up during Run 2
- Dedicated multi-fit method was developed to subtract contribution of pile-up in the ECAL pulse shape

- Pulse shape is modeled as in-time pulse plus up to 9 out-of-time (OOT) pulses
- Minimizing χ^2 to get best estimate of in-time pulse amplitude
- Contamination from OOT pulsed is affectively removed

$$\chi^2 = \sum_{i=1}^{10} \frac{\left(\sum_{j=1}^{M} A_j \times p_{ij} - S_i\right)^2}{\sigma_{S_i}^2}$$

- S_i : digitized amplitudes
- A_j(≥0): amplitudes from pulse at bunch crossing *j*
- p_{ij}: the template pulses , all identical and shifted by jx25ns
- σ_{S_i}: noise covariance matrix



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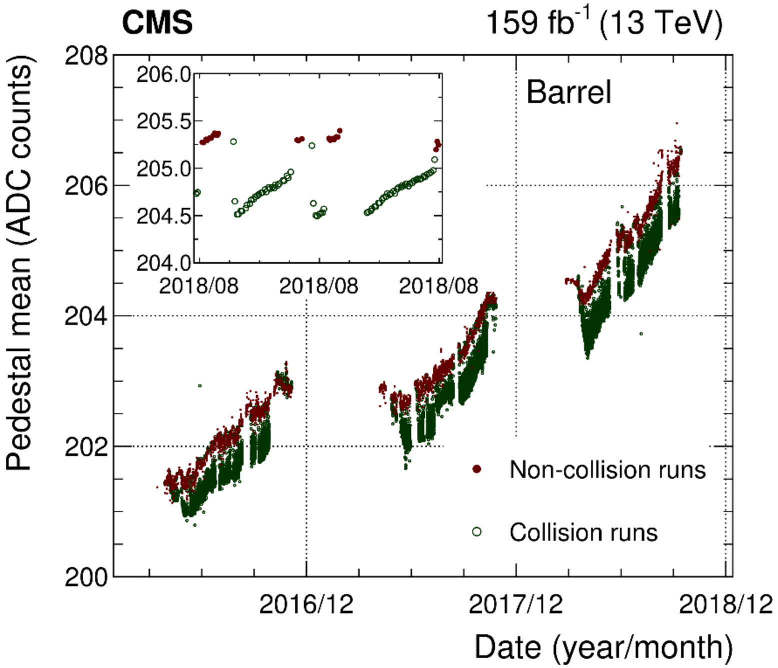
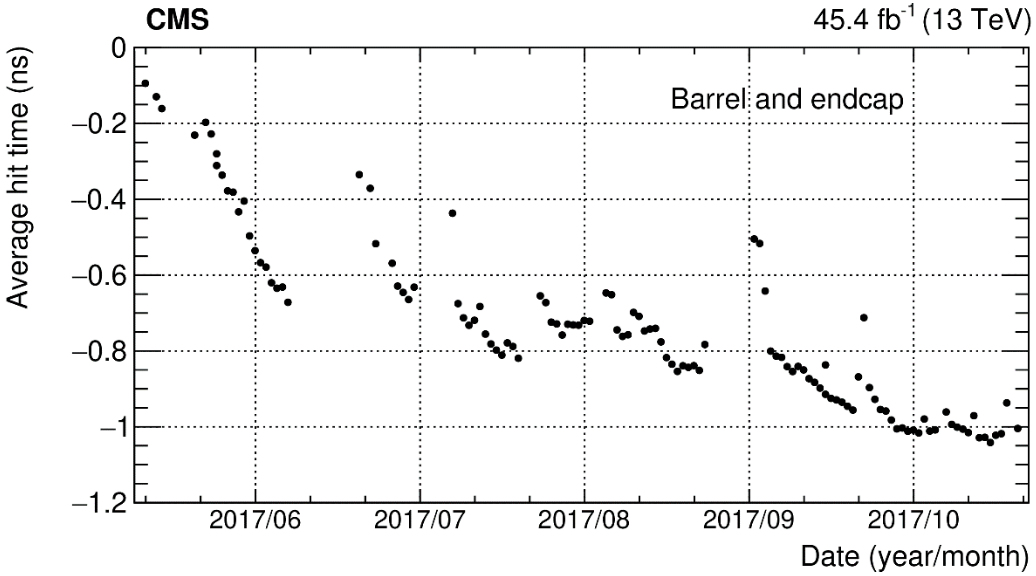
Pedestal & timing measurements

Pedestals drift in Run 2:
red – long term aging effects, **green** – short term effects that depend on instantaneous luminosity.

Time shift due to irradiation is corrected multiple times every year





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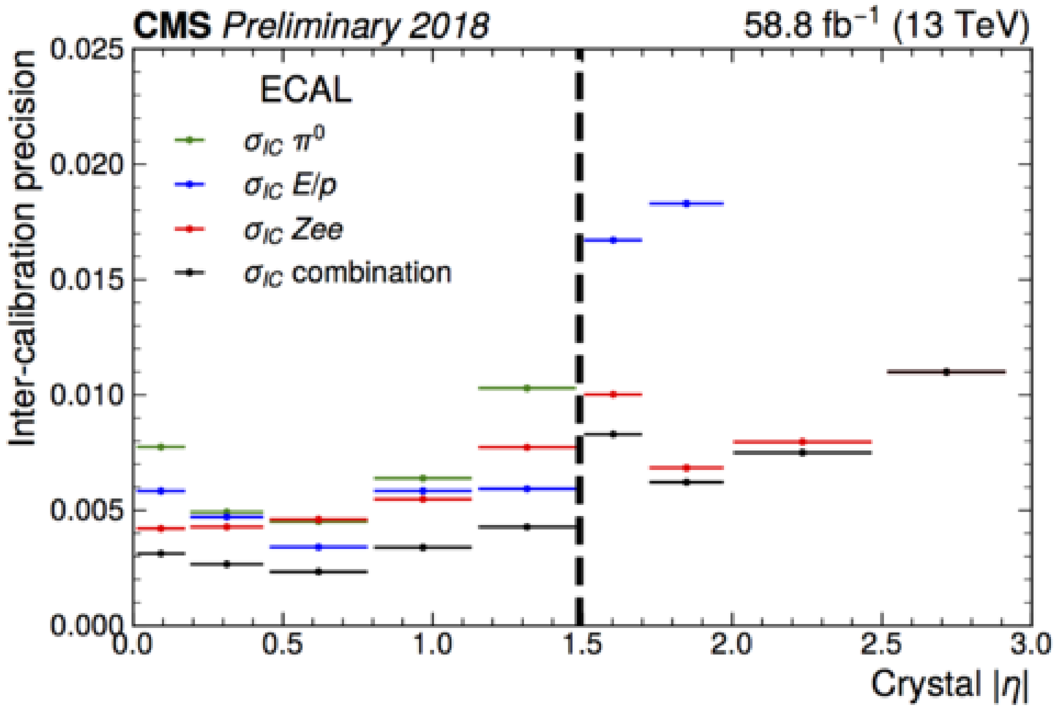
Pedestal & pulse shape measurements for each channel are directly used in the multi-fit reconstruction.

ECAL intercalibration

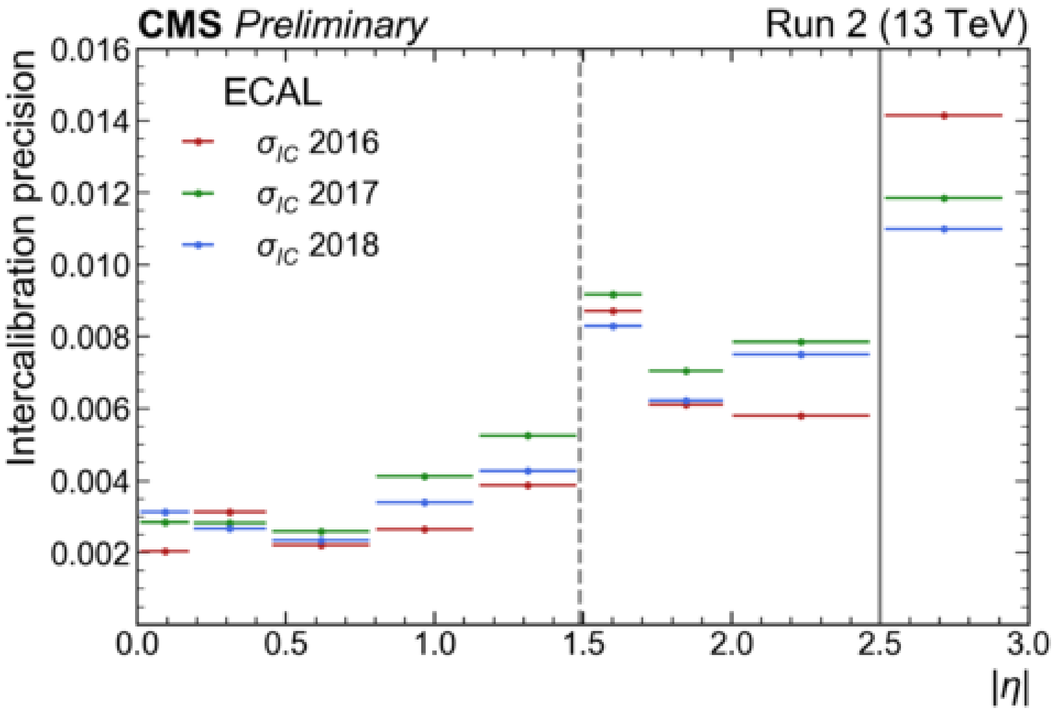
Equalize response of different crystals at the same η combining different methods:

- $\pi^0 \rightarrow \gamma\gamma$, $Z \rightarrow e^+e^-$, E/p (using isolated electrons from W/Z decays)

The achieved precision is better than 0.5% in Barrel and 1% in Endcaps ($|\eta| < 2.5$) and enters in the constant term of the energy resolution



CMS-DP-2019/038



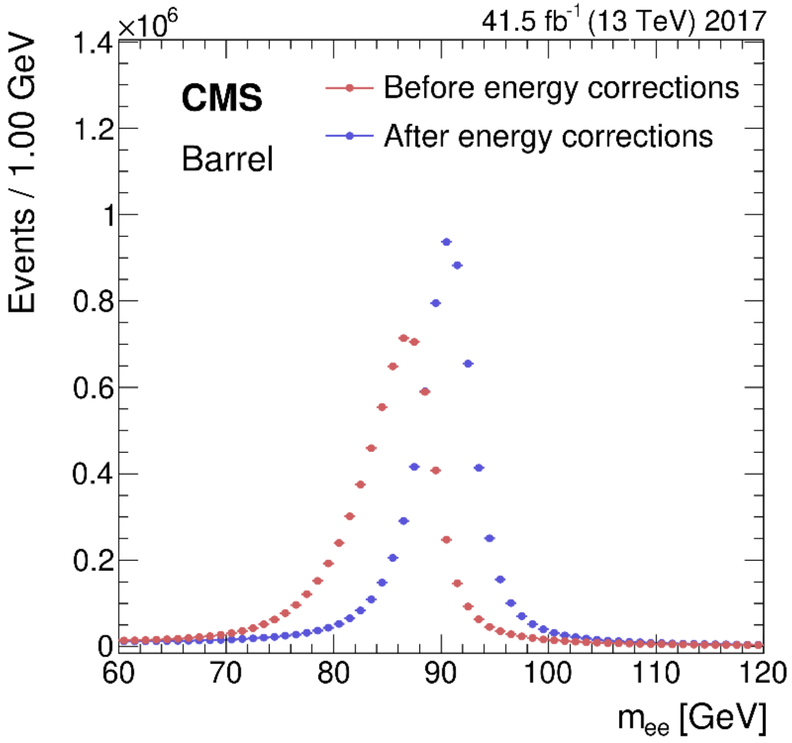
CMS DP-2020/021

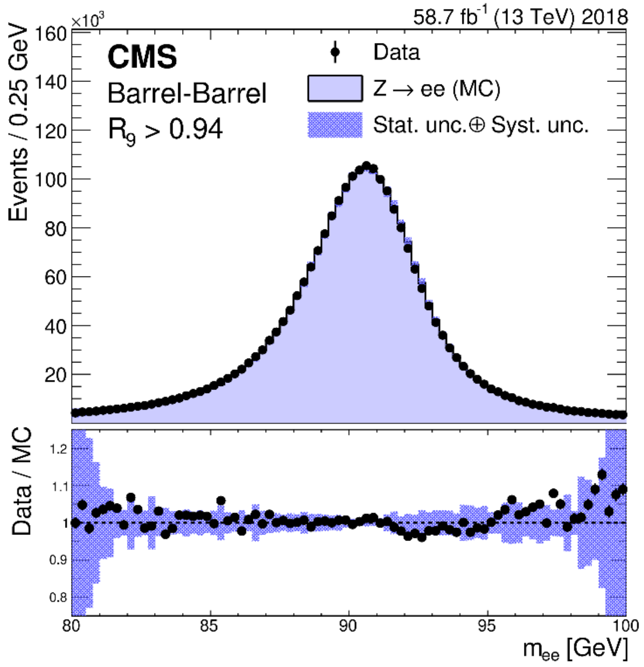
Cluster & scale energy corrections

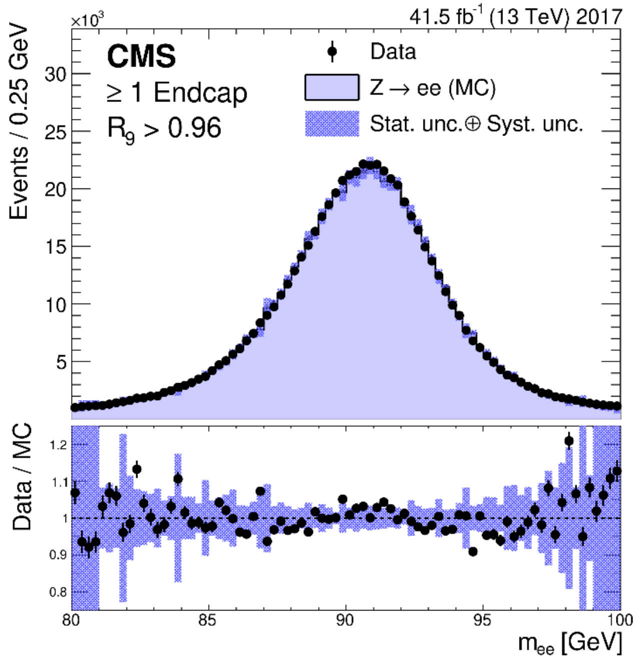
The material in front of ECAL (~ $2X_0$) and dead material in ECAL effect the deposited energy. So the following corrections are applied:

- multivariate corrections applied to reconstruct the original deposited energy of the particle
- energy scale VS η corrections in data to match simulation using $Z \rightarrow e^+e^-$ mass peak

Uncertainty on energy scale is 0.05-0.1% in the EB and 0.1-0.3% in the EE



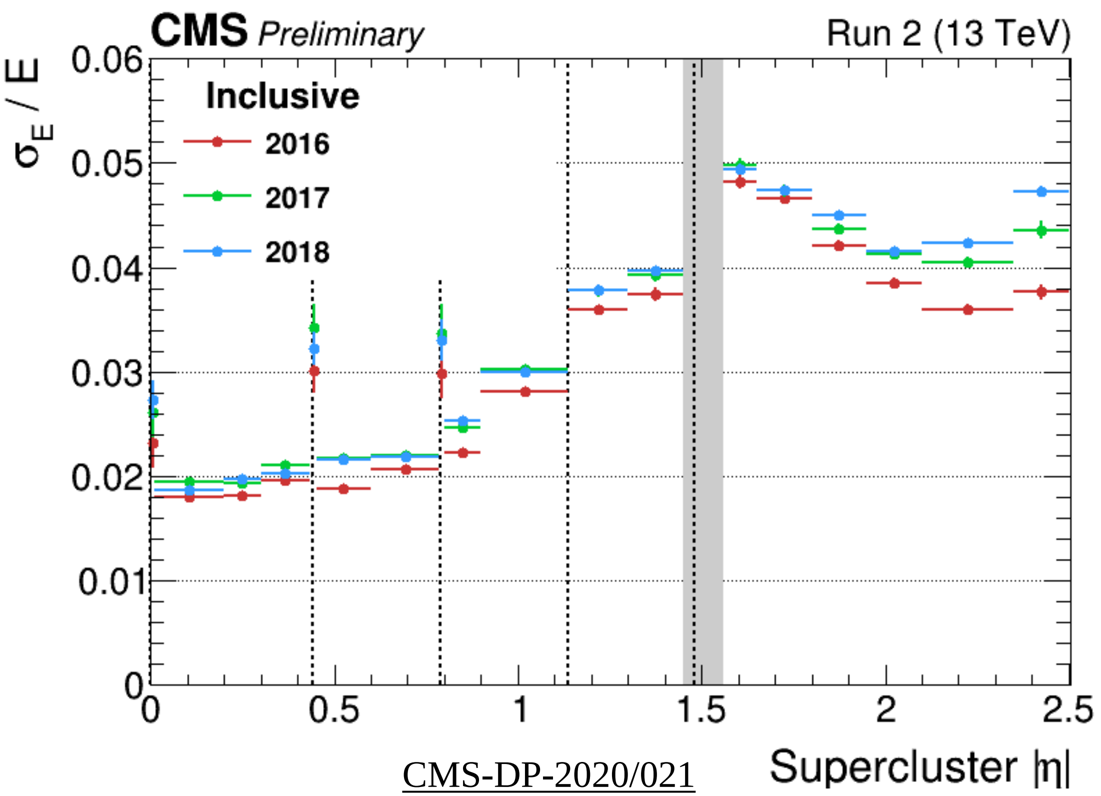




JINST 16 (2021) P05014

ECAL performance in Run 2

Time stability, invariant mass distribution and energy resolution of the di-electron invariant mass obtained using $Z \rightarrow e^+e^-$ illustrate high performance of ECAL during Run 2.



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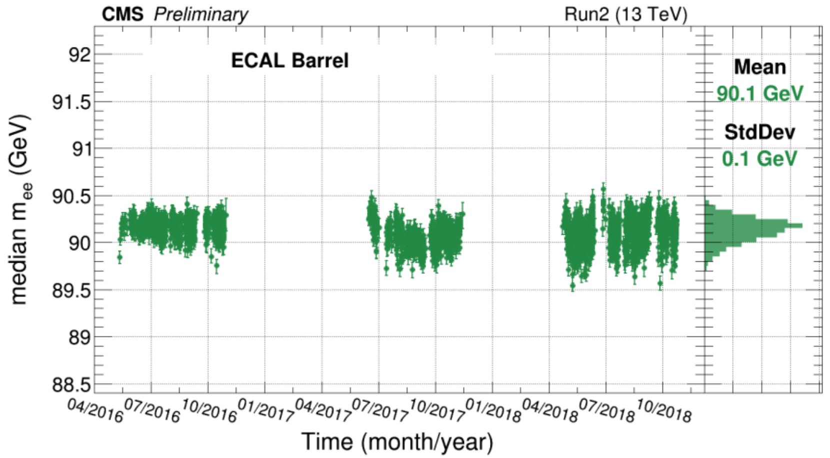
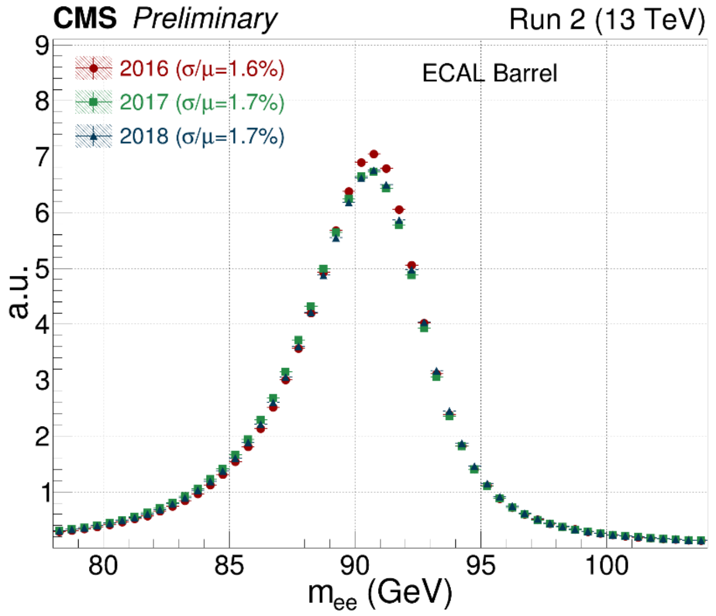
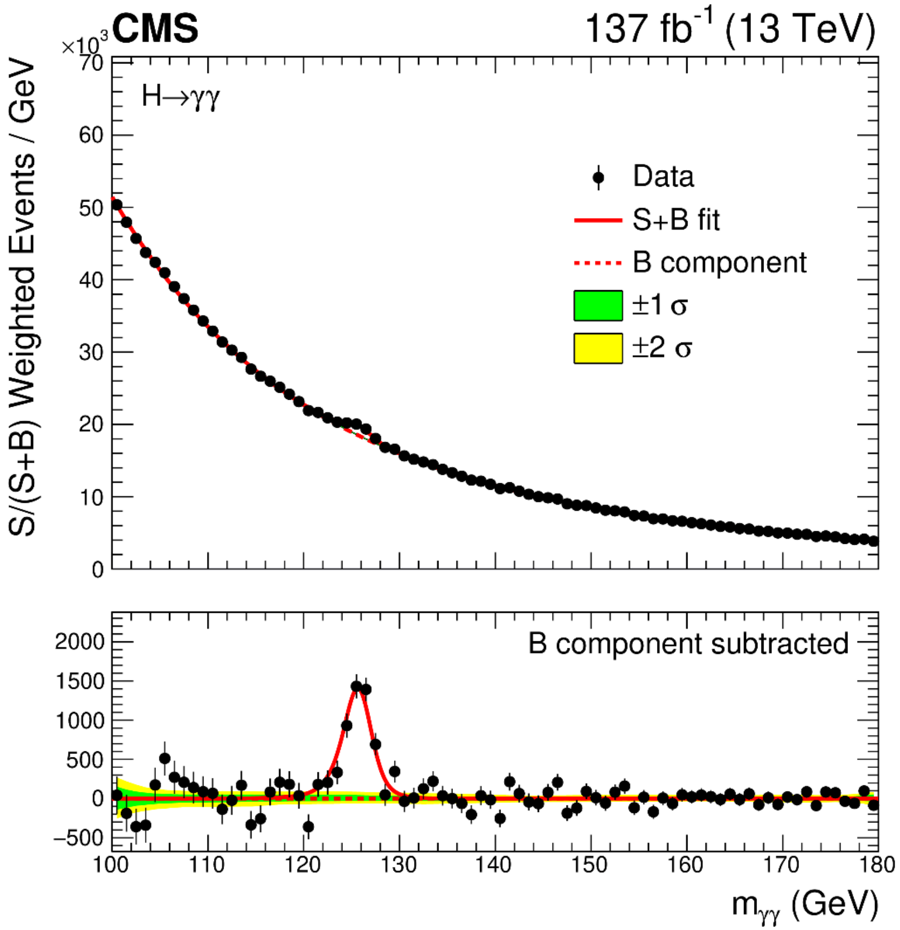




Information about ingredients to energy resolution can be found in Backup (slide 22)

ECAL performance for Higgs physics

Di-photon invariant mass distribution for H→ γγ



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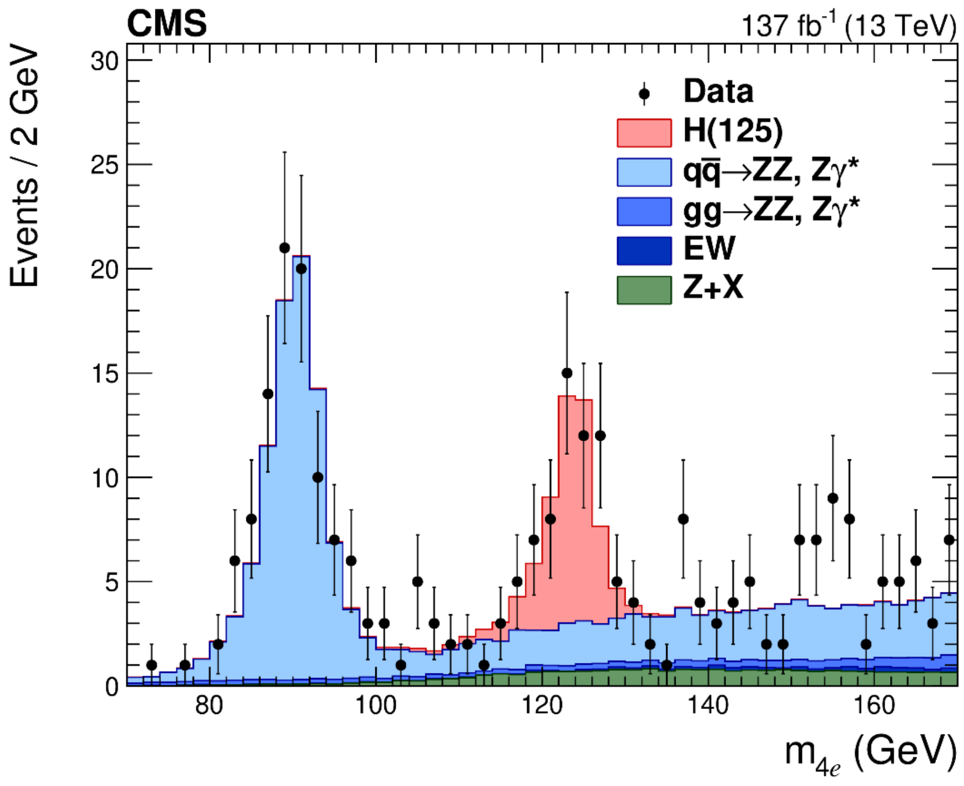
Four lepton mass distribution in 4e final state
(H→ ZZ → 4*l* process)



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ECAL improvements during Run 3

Main goals of improvements:

- Improve HLT electron rates and resolution
- Get calibration from data as soon as they are available
- Improve the quality of prompt reconstruction data
- Reach performance at the level of legacy at the end of Run 2 or better

The development was performed at

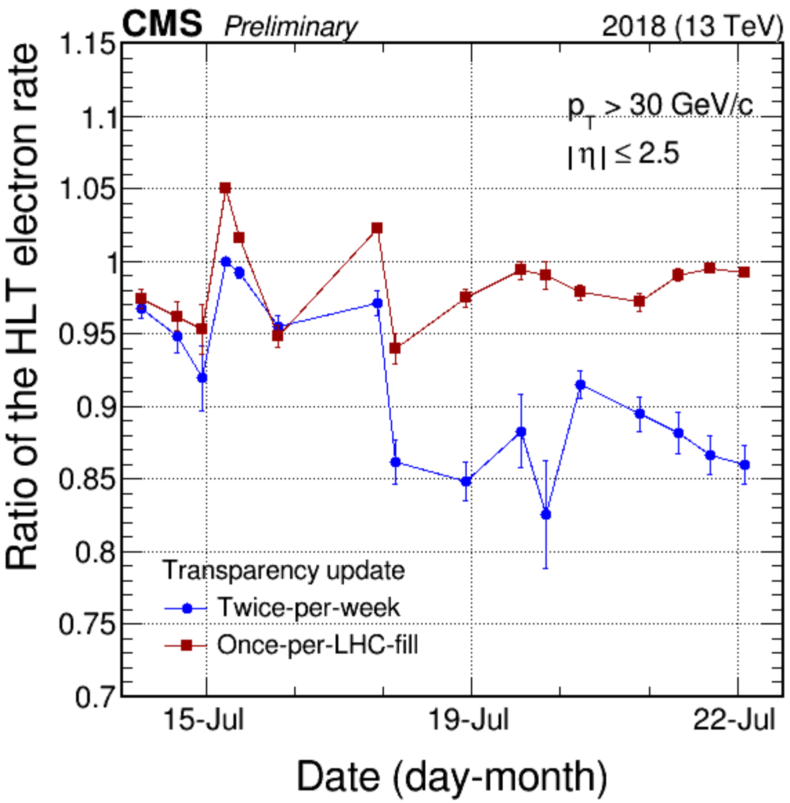
- Online level
- Offline level

New super-clustering approach based on Machine learning (GNN) was developed and is testing now. Details can be found in dedicated talk of Polina Simkina

ECAL improvements during Run 3: online level

For Run 3, at L1/HLT **frequency of laser updates has been increased** from twice-per-week (Run 2) to once per-fill (Run 3)

- Checked on Run 2 data with **Run 2** and **Run 3** conditions applied and compared with the refined calibration
- New laser workflow with faster processing of laser data enabled frequent updates



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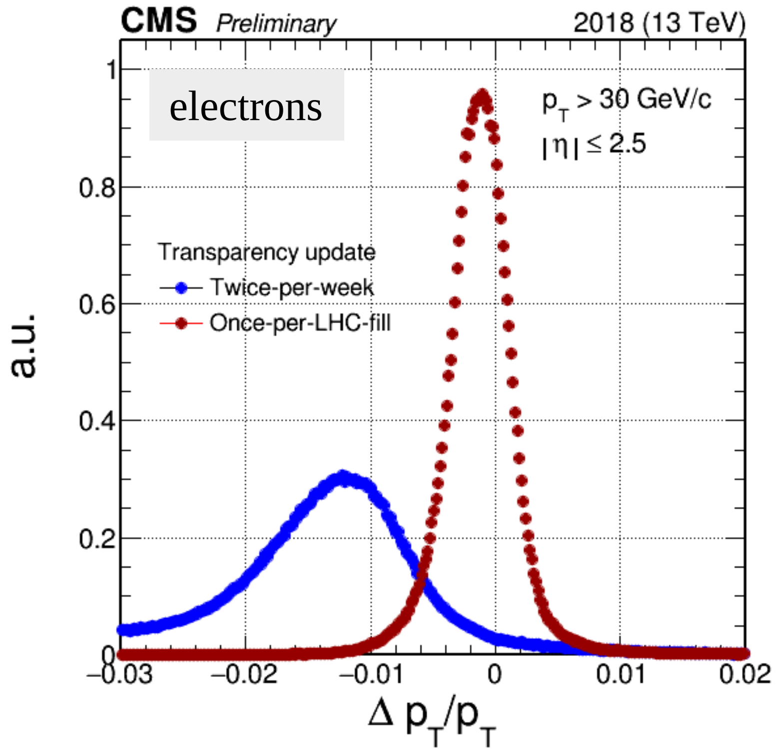
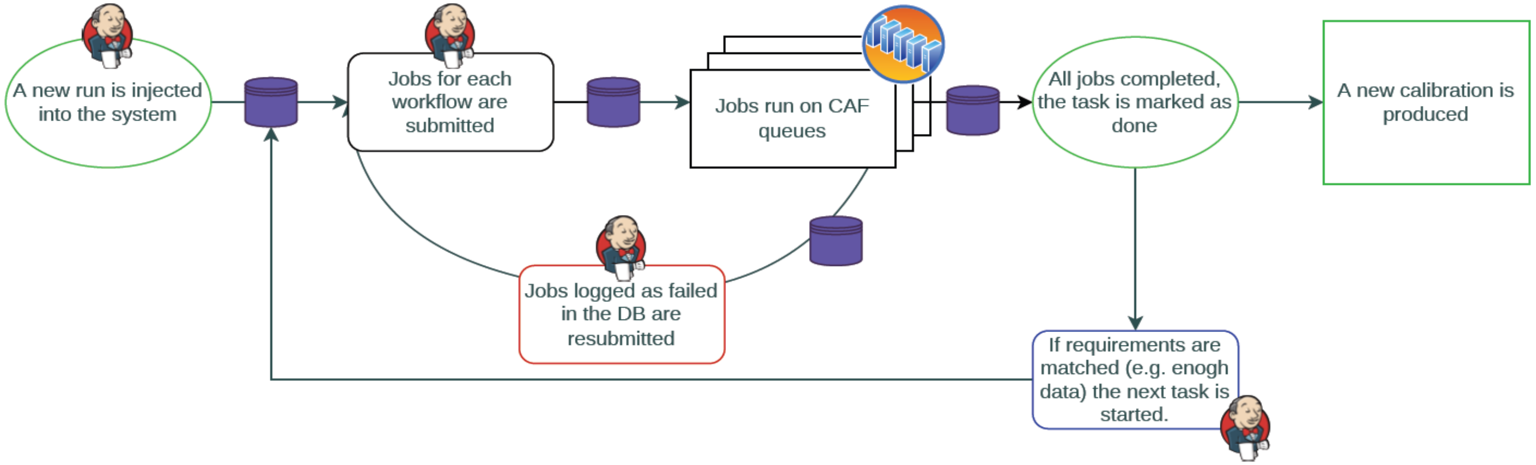


ECAL improvements during Run 3: offline level

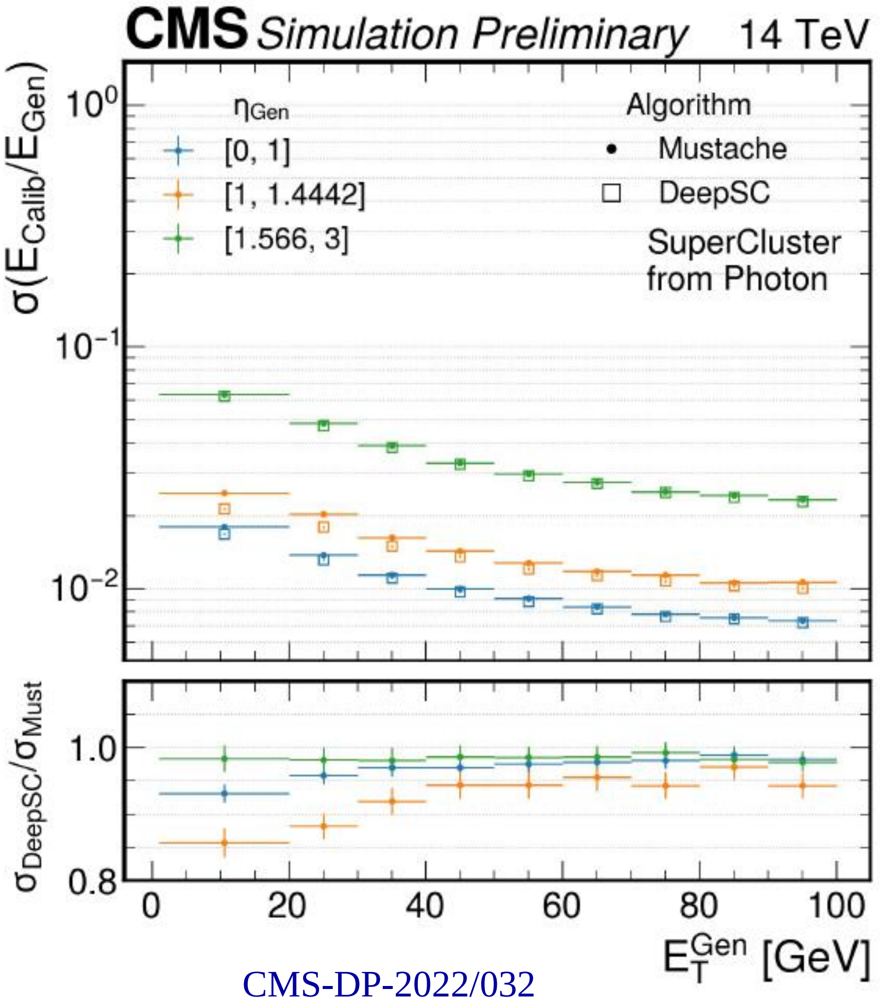


- ECAL calibration automation framework was developed that integrates many ECAL calibration and monitoring methods. Implement each calibration workflow as a **finite state machine**.
  - including pulse shape updates, timing calibration, alignments, various steps in energy calibrations, performance monitoring …
  - optimized workflow for prompt ECAL calibration deployment
  - improves the quality of prompt reconstruction data
- Execute jobs regularly updating conditions when predefined conditions are met.
- Exploit tools from industry deployed by CERN IT: **Openshift, influxdb, Jenkins, HTCondor**.

The system operated smoothly without interruption through the 2022-2023 years of data taking, executing an average of 500 jobs per day.

ECAL improvements during Run 3: super-clustering

- New development based on **Graph Neural Network**
  - Input features include information from clusters and its crystals (rechits)
  - Multiple outputs: Cluster classification (whether in/out of SC) object identification (electron/photon/jet), and energy regression
- Resolution better in most of the cases compared to the current algorithm developed during Run 2



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Summary

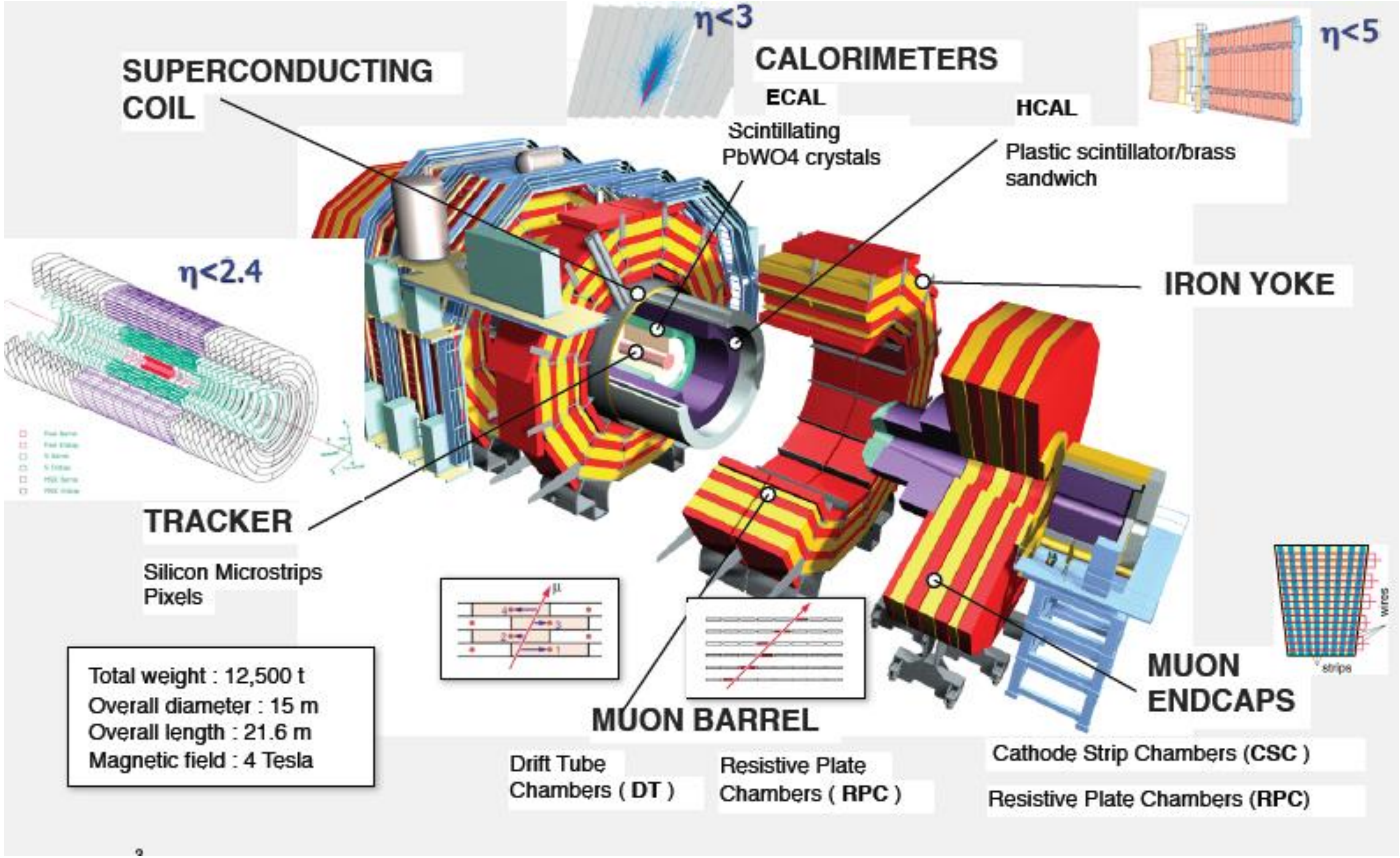
- ✓ **ECAL has operated smoothly and with excellent performance during Run 2 thanks to**
  - ECAL online and offline reconstruction adaptation to meet the challenges of higher LHC luminosity and detector aging
  - Regular monitoring and updates of crystal response, pedestals, pulse shape during data taking to maintain energy resolution
  - Effective suppression of out-of-time PU using the multi-fit algorithm

  With these updates, the excellent energy resolution and stability achieved during Run 1 has been maintained in Run 2

- ✓ **For Run 3 (2022-2025) more frequent recalibrations and optimized clustering methods will be used to mitigate high pile-up and ageing effects:**
  - Increased laser correction update for L1 and HLT
  - Automated calibration workflow - fast and continuous tracking of the detector calibration with time
  - GNN based super-clustering methods show improvement and more resistance towards pile-up and noise

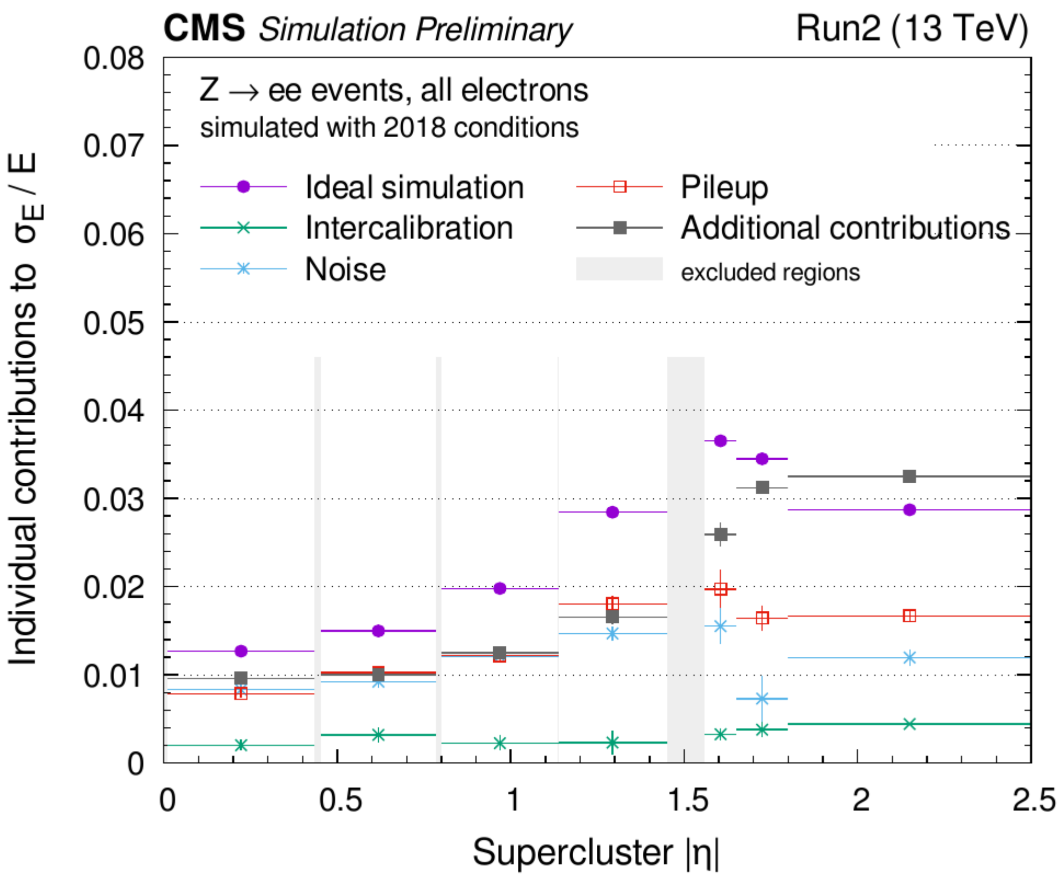
Backup slides

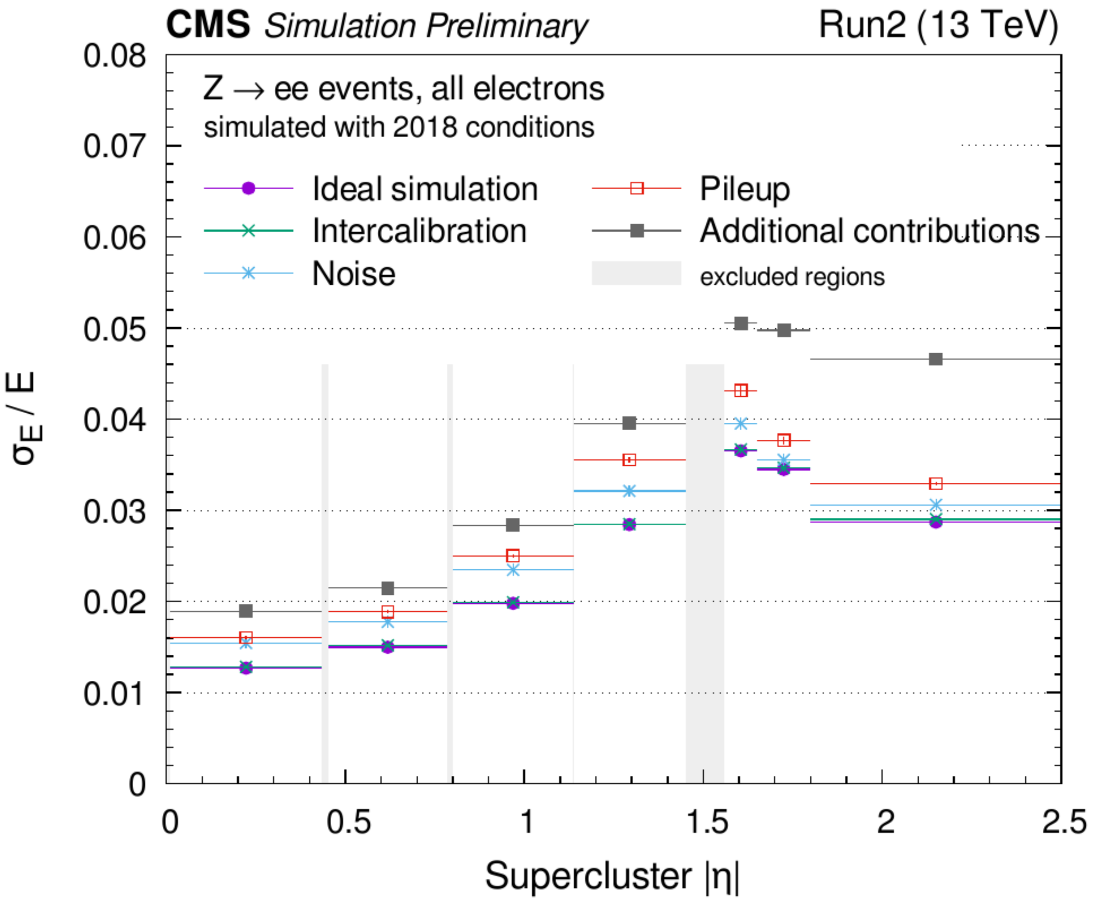
Detector layout



ECAL energy resolution in Run 2

Contributions of different ingredients to energy resolution of electrons using $Z \rightarrow e^+e^-$





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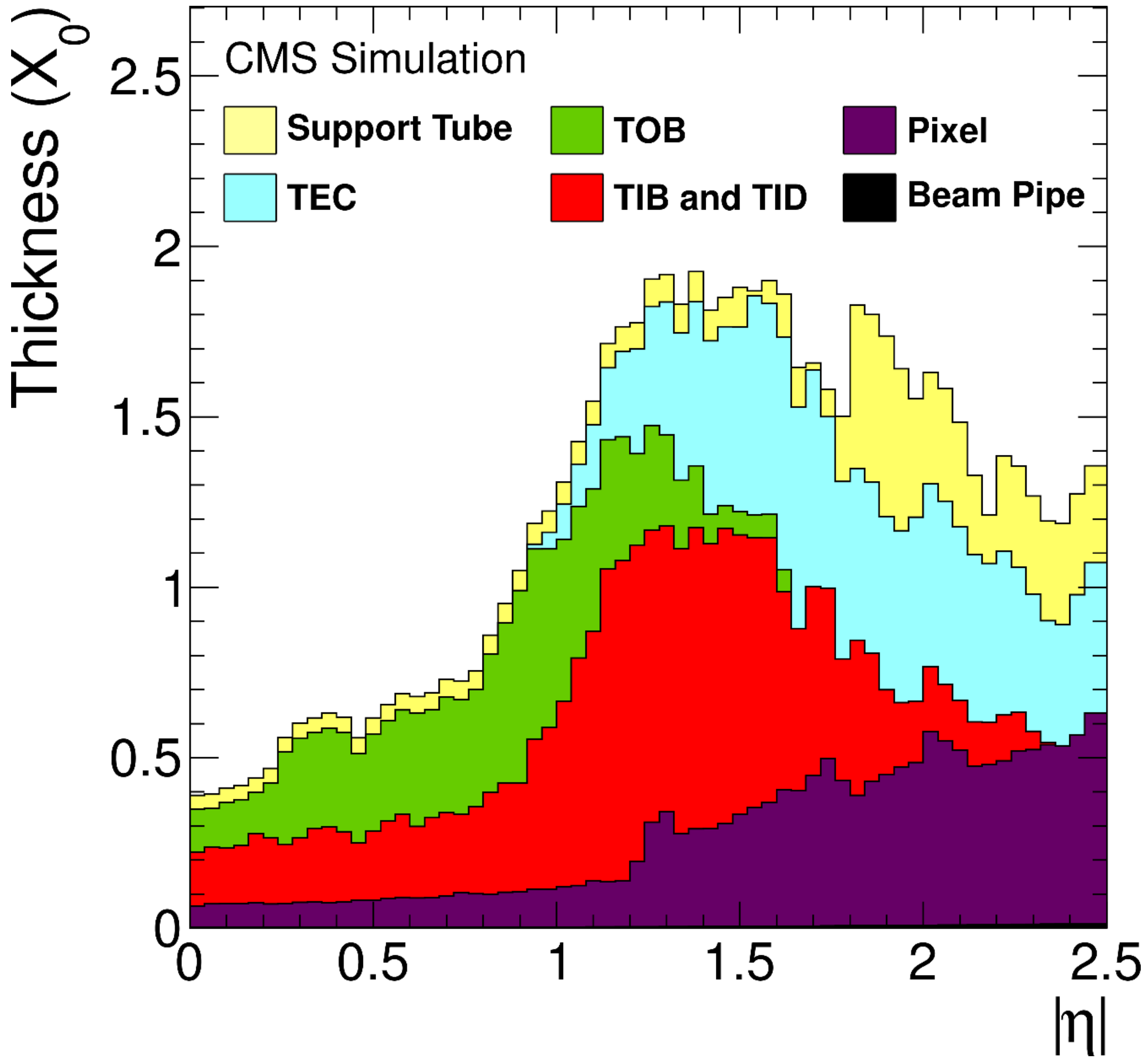
Material before ECAL



Tracker material, in radiation lengths, between interaction point and the ECAL as a function of η. The components are added to give the total tracker material budget. **TOB** is a tracker outer barrel, **TIB** – tracker inner barrel, **TID** – tracker inner discs, **TEC** – tracker endcaps.

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