Attaining the Optimal Performance of the CMS Electromagnetic Calorimeter in the Run 3 of LHC

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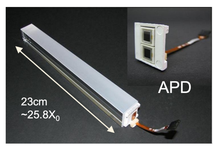
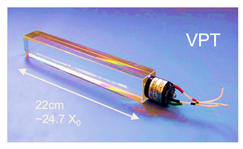
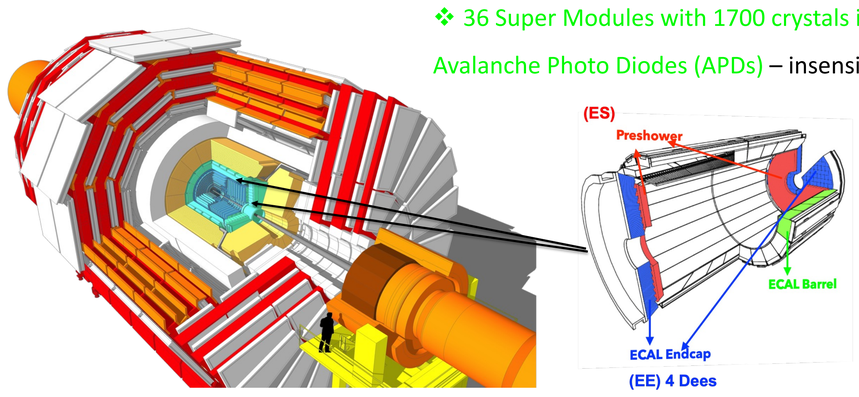
CMS Electromagnetic Calorimeter (ECAL)

CMS general-purpose detector for Standard Model test and search for New Physics







❖ 36 Super Modules with 1700 crystals in EB, $|\eta| < 1.48$

Avalanche Photo Diodes (APDs) – insensitive to magnetic field

❖ 7324 crystals in each of the two EE, $1.48 < |\eta| < 3.0$

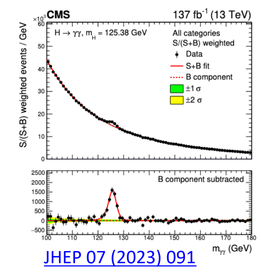
Vacuum Photo Triodes (VPTs) – high radiation tolerance

❖ Preshower: $1.65 < |\eta| < 2.6$; $3X_0$ thickness of Pb plates; sampling Si strips with Pb absorber to discriminate between high-energy isolated photons and from π^0 decay (close photons)

ECAL is designed to provide highly efficient and accurate energy reconstruction of e/γ

$$E_{e,\gamma} = F_{e,\gamma} \cdot [G(\eta) \cdot \sum_{i=crystals} LC_i(t) \cdot IC_i(t) \cdot A_i(t) + E_{ES}]$$

The ECAL plays a crucial role in the CMS physics analyses that involve e/γ and jets.



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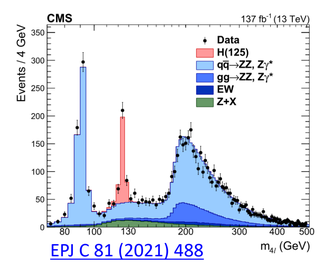

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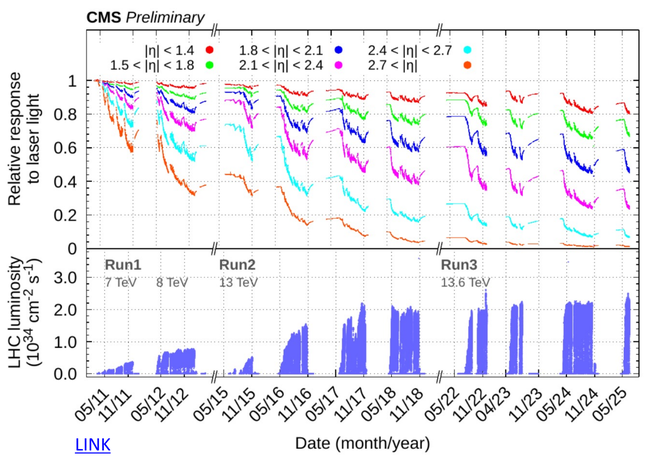
Laser transparency loss and recovery $LC_i(t)$

- 447 nm laser light injected into each crystal to monitor the transparency change induced by the irradiation: one measurement point every 40 min.
- Derived corrections applied within 48 hours to the prompt reconstruction.
- Response change:
  - Up to 15% in the barrel.
  - Up to 70% at |η|≈2.5, near tracker edge.
  - Up to 99% closest to beam pipe.
- Partial recovery during non-collision period



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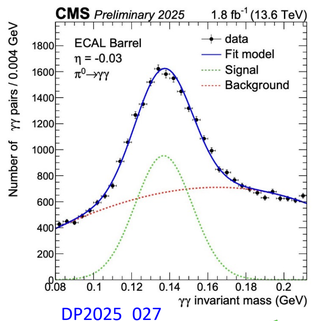
Intercalibration $IC_i(t)$

- Equalizes ECAL response for crystals at the same η
- Combine different methods weighted by their precision:
  - π^0 mass (from $\pi^0 \to \gamma\gamma$ decays)
  - ϕ – symmetry
  - E/p (ECAL energy vs tracker momentum from W/Z electrons – sensitive to alignment)
  - $Z \to e^+e^-$ (invariant mass of ECAL electrons)



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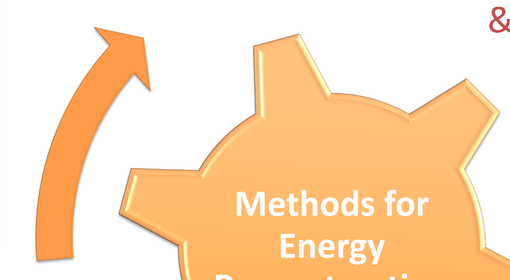
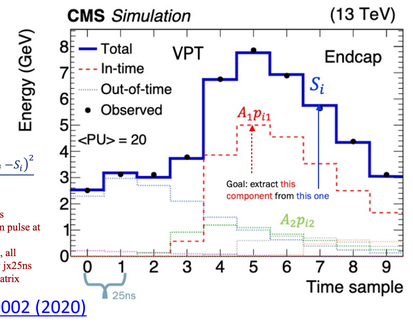


Amplitude reconstruction $A_i(t)$

- Each pulse from APD/VPT is digitized in 10 samples: 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. The **'multifit' reconstruction method** is robust against pile-up increase.

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

- 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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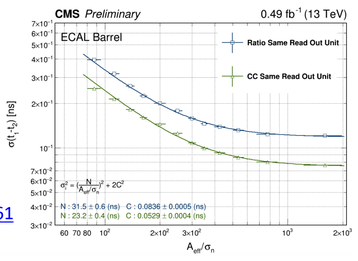
Timing (ratio timing & cross correlation)

- Optimized time resolution for signals reconstructed in the ECAL barrel.



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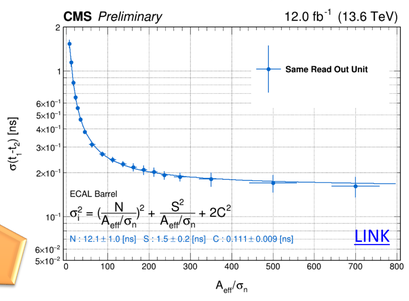

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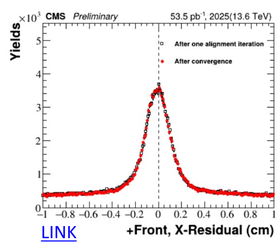
- The Cross Correlation algorithm improves time reconstruction by subtracting out-of-time signals, then fitting the cleaned signal to the expected pulse shape to extract the in-time pulse timing.

ECAL Alignment

- Critical for accurate position and energy measurements of electromagnetic objects.
- ECAL and PreShower are aligned relative to tracker



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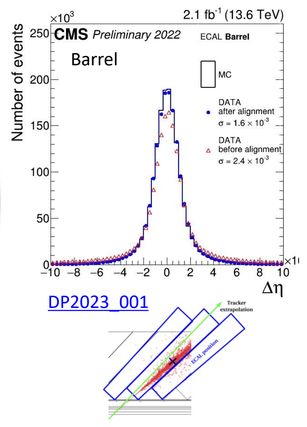
- Performed using low bremsstrahlung electrons from Z boson decays



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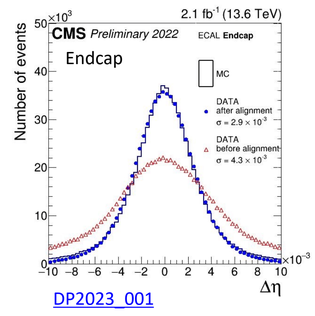

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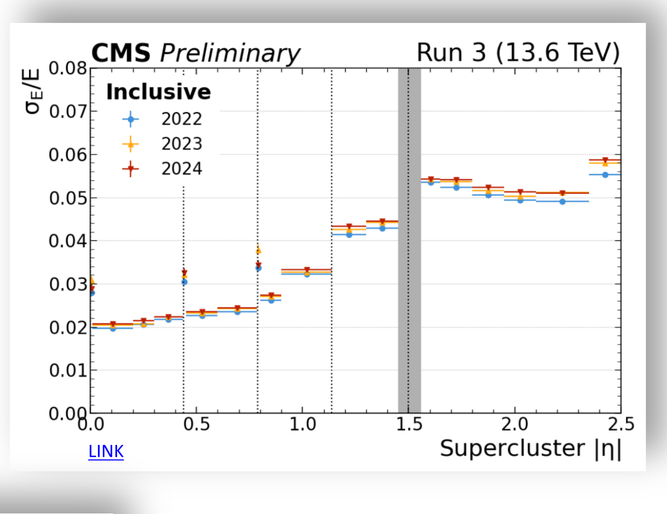
Stability with time, invariant mass distribution and energy resolution using electrons from $Z \to e^+e^-$ demonstrate the optimal performance of ECAL during Run 3.

- A stable ECAL energy resolution is observed between 2022, 2023 and 2024 despite the increased LHC luminosity and the ageing of the detector.
- Resolution at ~2% in the central part of the barrel, < 5% elsewhere.
- Stability with time: energy scale stable with StdDev: < 0.2%



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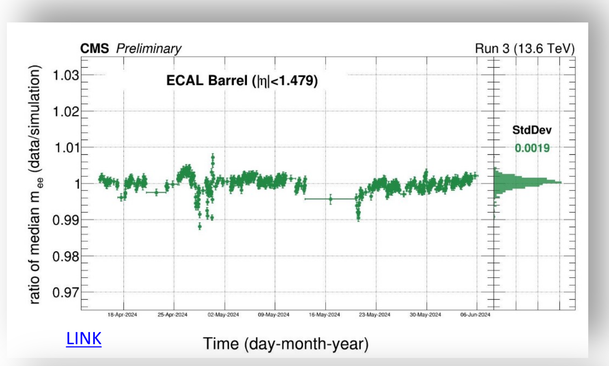
- The shower shape is measured by the variable R9 (ratio of the energy deposit in the 3x3 crystal matrix around the seed crystal to that in the supercluster).
  - Important variable for the electron and photon identification
  - StdDev = 0.13%



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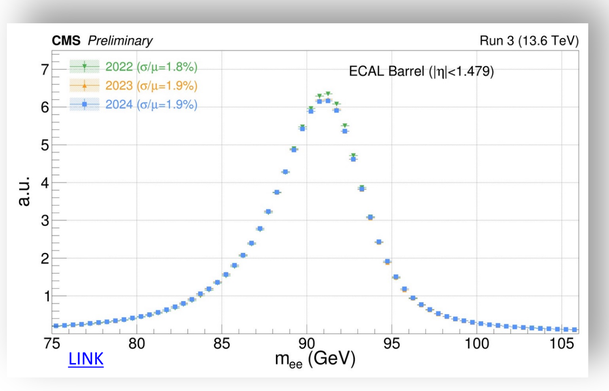

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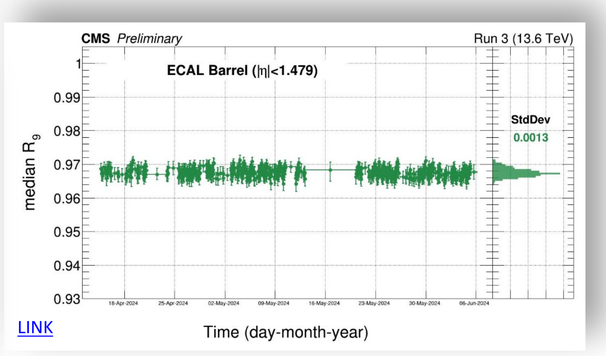

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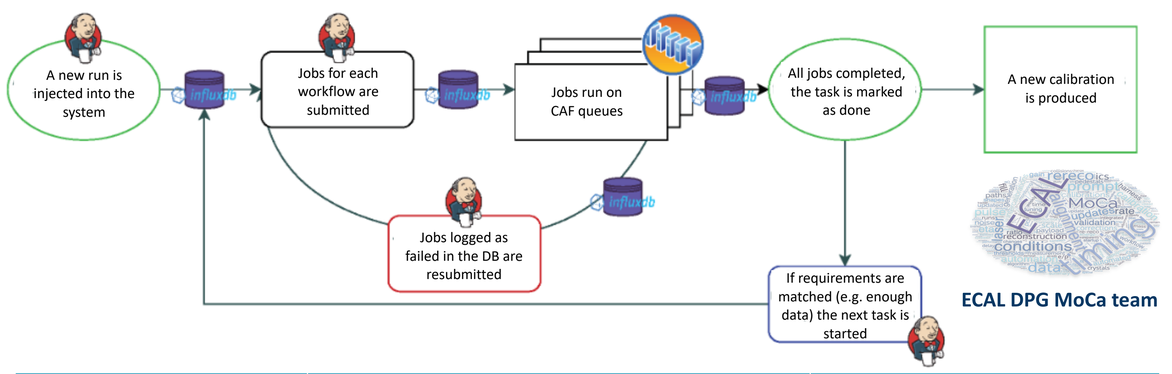
- Invariant mass distribution for electron pairs from Z boson decays (inclusive – all electrons)

- Since 2024, ECAL calibration workflows run automatically during data taking using CERN IT tools like Openshift, InfluxDB, Jenkins, and HTCondor. This framework reduces calibration time by a factor of 10 and integrates multiple methods including pulse shape updates, timing calibration, alignment, intercalibration, and performance monitoring.



Task	pp + pp_{ref} + PbPb (2024)	Automation (2025)
ECAL/ES Alignment	At the beginning of each run	ok + manual upload to the DB
Pulse Shapes	24 updates	ok + manual upload to the DB
Timing calibrations	30 Ratio Timing + 9 Cross Correlation	ok + manual upload to the DB
η scale & crystal ICs	35 new IC tags validated with 22 deployed in Prompt, Express and High Level Trigger (HLT)	ok + manual upload to the DB
Channel status	37 new IOVs (due to APD issues ~15 updates)	ok + manual upload to the DB
Online Laser/Transparency	243 updates @HLT+L1	100%
Pedestals/Timing @L1	5 / 3 uploads	ok + manual upload to the DB
Electron Ntuple Production	…	100%
m_{ee} & π^0 (monitoring)	…	100%