PROCEEDINGS OF SCIENCE

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

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The CMS Electromagnetic Calorimeter (ECAL) plays a central role in precision measurements involving electrons and photons. During Run 3 of the LHC, increased luminosity and detector ageing posed significant challenges for maintaining optimal energy resolution and stability. Since 2024, ECAL calibration workflows have been fully automated, resulting in a 10-fold reduction in calibration latency. This paper presents the methods and automation framework. It shows results demonstrating stable ECAL energy resolution of about 2% in the central barrel and better than 5% in the endcaps, with a stable energy scale across years of data taking.

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1. Introduction

The CMS ECAL is designed for precise energy measurement of electrons and photons, which are critical for Standard Model precision tests and searches for new physics. Run 3 brought higher luminosity and radiation doses, requiring robust calibration strategies to preserve energy resolution. The Detector Performance Group (DPG) has implemented real-time calibration and automation workflows to ensure stability of the ECAL performance.

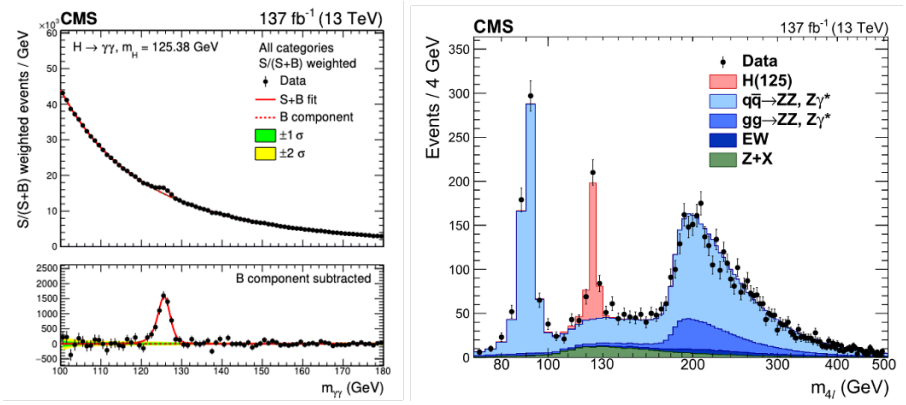

Figure 1: The ECAL plays a crucial role in the CMS physics analyses that involve electrons, photons and jets.

2. Detector and Calibration Strategy

The ECAL consists of 61,200 $PbWO_4$ crystals in the barrel (EB, $|\eta| < 1.48$) read out by avalanche photodiodes (APD), and 7,324 crystals in each of the two endcaps (EE, $1.48 < |\eta| < 3.0$) read out by vacuum phototriodes (VPT). A preshower (ES) detector covers $1.65 < |\eta| < 2.6$ for photon/π^0 discrimination.

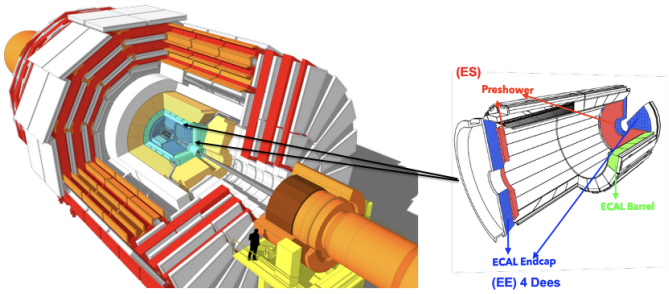

Figure 2: Schematic view of the CMS and the ECAL.

The calibration of the CMS ECAL relies on several components:

- **Laser transparency monitoring:** 447 nm laser light injected every 40 minutes to monitor radiation-induced transparency loss (up to 15% in EB, 70–99% in EE).

- **Intercalibration:** Combining methods ($\pi^0 \to \gamma\gamma$, ϕ-symmetry, E/p from W/Z electrons, $Z \to ee$ mass) to equalize crystal response.
- **Alignment:** ECAL and preshower aligned with the tracker using low-bremsstrahlung $Z \to ee$ electrons.
- **Timing:** Ratio timing and cross-correlation (CC) algorithms optimize time resolution and mitigate out-of-time pileup.

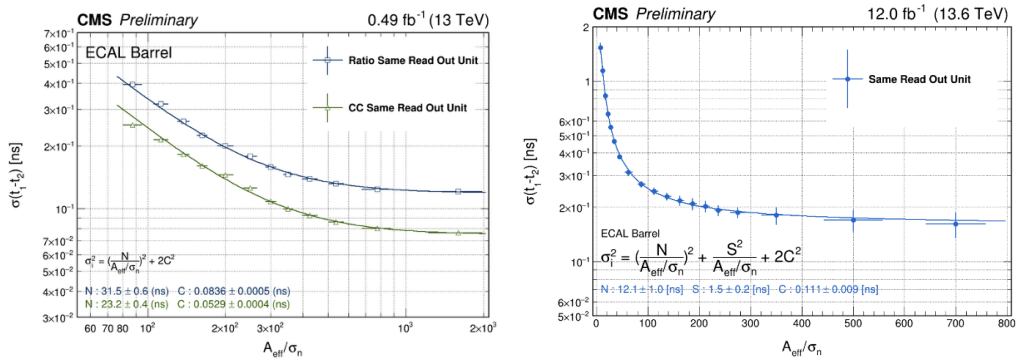

Figure 3: Left: Cross-Correlation (CC) vs Ratio Timing resolution comparison in Run 2. Right: The CC algorithm in Run 3 collision data. The CC algorithm improves time reconstruction by subtracting out-of-time signals, then fitting the cleaned signal to the expected pulse shape to extract the in-time pulse timing.

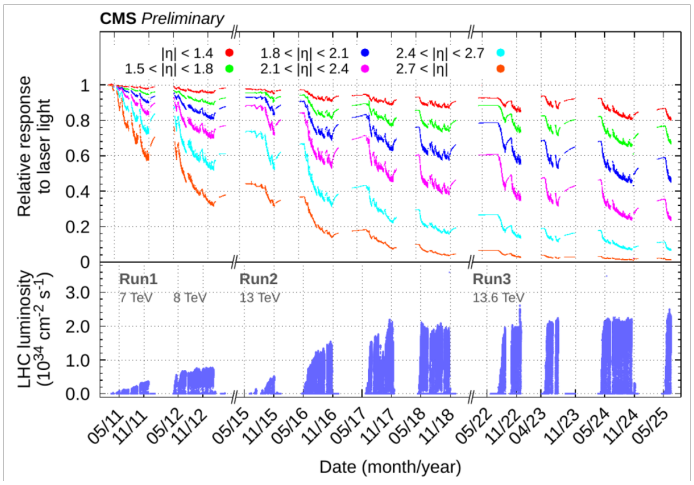

Figure 4: Laser transparency monitoring showing radiation-induced transparency loss and partial recovery during non-collision periods.

3. Automation Framework

Since 2024, calibration workflows are fully automated using CERN IT services such as Openshift, InfluxDB, Jenkins, and HTCondor. The framework handles job submission, monitoring,

resubmission of failed tasks, and database uploads. Calibration latency has been reduced by an order of magnitude. In 2024–2025, for example, 243 laser transparency updates were automatically applied to HLT and L1 reconstruction.

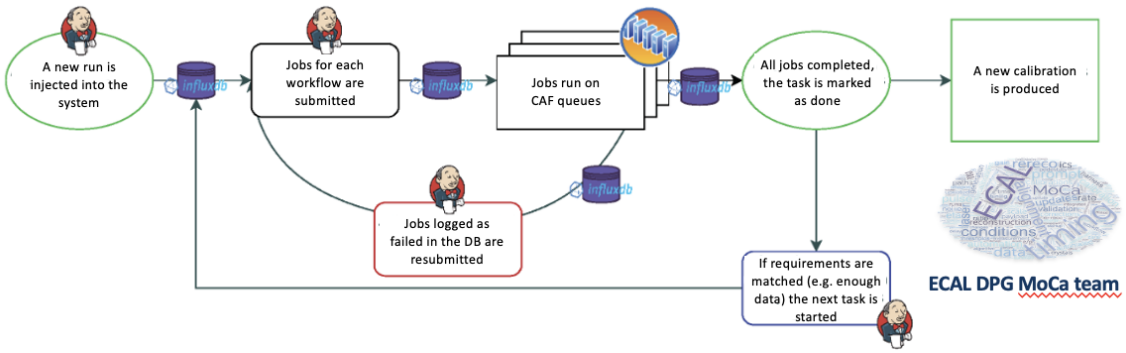

Figure 5: Automated calibration workflow of the CMS ECAL, integrating alignment, timing, intercalibration, and transparency corrections.

4. Performance Results

Despite harsher conditions in Run 3, the ECAL has maintained excellent stability:

- Energy resolution of about 2% in the central barrel and $< 5\%$ in the endcaps.
- Energy scale stability within 0.2% over time.
- Shower-shape variable $R9$ measured with StdDev $\approx 0.13\%$.
- Invariant mass distributions of $Z \to ee$ remain stable between 2022 and 2024.
- Timing resolution improved using cross-correlation to subtract out-of-time signals.

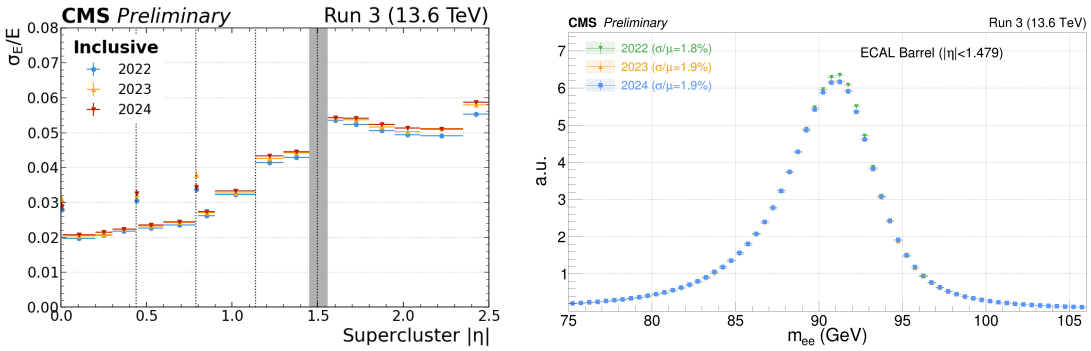

Figure 6: A stable ECAL energy resolution is observed between 2022, 2023, and 2024 despite the increased LHC luminosity and the ageing of the detector. The invariant mass distribution of electrons from $Z \to ee$ decays measured with the ECAL demonstrates the outstanding stability of the energy scale.

5. Conclusions

The CMS ECAL has achieved optimal performance during Run 3, with stable energy resolution and scale despite detector ageing and increasing luminosity. The introduction of automation has streamlined calibration workflows, reducing human intervention and enabling prompt updates. These developments ensure ECAL readiness for the High-Luminosity LHC.

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