PROCEEDINGS OF SCIENCE

Precision Alignment of the CMS Electromagnetic Calorimeter

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The electromagnetic calorimeter (ECAL) of the CMS detector is a homogenous, fine-grained detector made of scintillating lead-tungstate crystals. It was designed to provide excellent energy resolution for electrons and photons and was crucial in the discovery of the Higgs boson. The performance of ECAL is essential for CMS physics analyses. The precise alignment of ECAL is necessary to achieve the high-level position resolution required for photon and electron reconstruction in CMS and their identification. The position of each ECAL module is determined to an accuracy of 1 mm using photogrammetry measurements in CMS; however, the calorimeter is placed within a 4 Tesla superconducting solenoid and to the effect of its strong magnetic field can slightly displace it. Further alignment of ECAL with respect to the CMS Tracker is performed using a dedicated data analysis. This poster will describe the CMS ECAL alignment procedure, present the alignment accuracy reached at the LHC Run 3, and introduce the alignment process automation put in place.

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1. Introduction

The CMS electromagnetic calorimeter (ECAL) plays a critical role in particle identification and energy measurement for electrons and photons. ECAL is comprised of two sections, the barrel (EB) and the endcaps (EE). The EB is comprised of 36 substructures called supermodules (SM), and is made up of 61,200 lead tungstate crystals. Each EE is made of two substructures called Dees, each containing 7,324 lead tungstate crystals. Attached to each crystal is either an avalanche photodiode (APD) in the EB or a vacuum phototriode (VPT) in the EE which convert the scintillation from the crystal into an electronic pulse. In addition, the preshower (ES) detector in front of the endcaps contains silicon strips which assists in the distinction between single high-energy photons and low-energy diphotons [Figure 1]. The position of each ECAL substructure is positioned with an accuracy of 1 mm using photogrammetry. However, the calorimeter is placed within a 4T superconducting solenoid which displaces each component of ECAL. Each substructure can displace for various other reasons, such as magnet cycles, earthquakes, or opening the detector for maintenance and upgrades. Therefore, alignment of ECAL with respect to the tracker is performed using dedicated analysis techniques. Misalignment between the ECAL and Tracker can lead to mismatches between the reconstructed particle positions and energy deposits, which would degrade the resolution for electrons and photons. Ensuring precise alignment is thus crucial for accurate measurements of energy and direction, particularly for events like $H \to \gamma\gamma$ decays, where precise vertex identification is required.

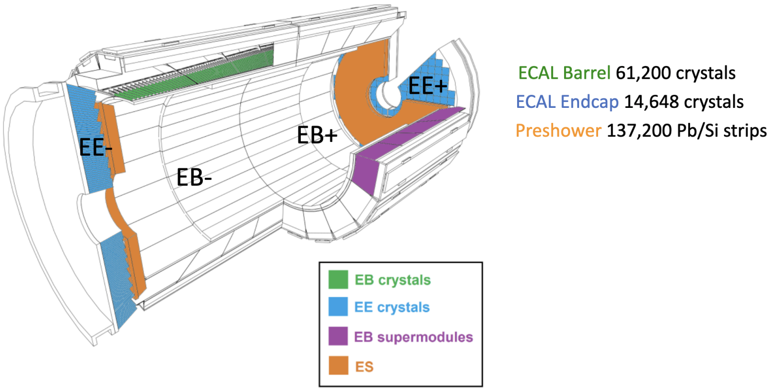

Figure 1: Architecture of the ECAL and the ES

2. Alignment Procedure

The alignment of ECAL with respect to the CMS Tracker is performed using low bremsstrahlung electrons from Z boson decays ($Z \to e^+e^-$). The angular distance between the position extrapolated track from the Tracker and the mean cluster position in ECAL is minimized with respect to Monte Carlo (MC) simulations [Figure 2]. This process is performed for each substructure by minimizing a χ^2 function given in equation 1.

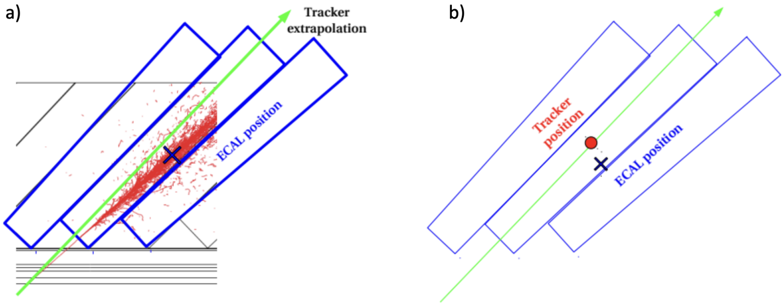

Figure 2: Figure (a) is the position reconstructed by ECAL (blue cross) and Figure (b) is the position extrapolated from the tracker (red dot)

$$\chi^2 = \Sigma_{lepton}(\Delta\phi - < \Delta\phi_{\pm}^{MC} >)^2/\epsilon_{\phi}^2 + (\Delta\eta - < \Delta\eta_{\pm}^{MC} >)^2/\epsilon_{\eta}^2 \tag{1}$$

When performing alignment, each SM has three transitional degrees of freedom $(\Delta x, \Delta y, \Delta z)$ and each Dee has three translation and three rotational degrees of freedom $(\Delta x, \Delta y, \Delta z, \Delta\theta, \Delta\phi, \Delta\psi)$ in which the substructures can be shifted. We then extrapolate from these shifts, the two coordinates $(\Delta\eta, \Delta\phi)$ of correction for each substructure, the uncertainty correlated to each coordinate $(\epsilon_{\eta,\phi})$ and correct with respect to the MC expectation values. The MC expectation values are non-zero due to the tilt of the crystal and the interplay with charged particles and the magnetic field. This procedure is performed for both electrons and positrons, and adjustments are made for each SM in the EB and for each Dee in the EE [Figure 1].

2.1 Automation of the Alignment Process

The CMS collaboration has introduced an automated process to improve the efficiency of the alignment procedure. By automating the data analysis, the alignment can be updated more frequently, ensuring optimal detector performance throughout LHC Run 3 and future runs. The automation relies on real-time monitoring of the detector conditions and uses open-source softwares to automatically execute the calibration workflows. The process will be fully automated by the start of data taking in 2025, with only manual checks needed if new conditions are introduced to the MC by the tracker.

3. Run 3 Achievements

During LHC Run 3, the alignment precision reached in the ECAL relative to the Tracker has met the stringent requirements for high-quality physics analyses. Using Monte Carlo (MC) simulations as a reference, the relative alignment is optimized by minimizing the residuals between the reconstructed position in ECAL and the extrapolated track from the Tracker. In LHC Run 3, this method achieved an alignment precision of 3×10^{-3} in pseudorapidity (η) units and 7.1×10^{-3} milliradians in azimuthal angle (ϕ). These results surpass the requirements for electron identification in CMS, where the thresholds are 4×10^{-3} in η and 20 milliradians in ϕ [Figure 3]. The automation of the alignment process has allowed for faster corrections and has significantly reduced the time required for recalibrations. The alignment accuracy achieved during Run 3 ensures optimal performance for ongoing and future physics analyses, including precision measurements of electroweak processes and searches for new physics beyond the Standard Model.

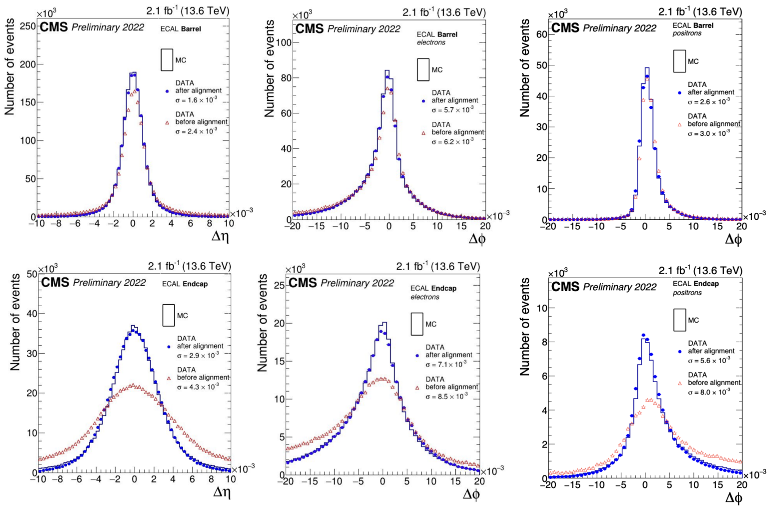

Figure 3: $\Delta\eta$ and $\Delta\phi$ distributions in the EB and EE, before (red) and after (blue) alignment and in the nominally aligned MC (black) and the beginning of Run3 of LHC. The data after the alignment is in good agreement with the MC

4. Conclusion

The alignment of the CMS ECAL is essential for maintaining the detector's ability to precisely measure the energy and position of electrons and photons. Through dedicated analysis of $Z \to e^+e^-$ events and automation of the alignment process, the CMS collaboration has achieved sub-millimeter accuracy in the relative positioning of ECAL and the Tracker during LHC Run 3. These improvements ensure the ECAL continues to provide critical data for the most precise physics measurements at CMS.

References

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