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In-Situ Calibration of the CMS Electromagnetic Calorimeter

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Abstract

The *in-situ* intercalibration of the PbWO_4 crystals of the CMS electromagnetic calorimeter will be performed using three techniques: An energy-flow method will be used at startup to intercalibrate to a precision of around 2% within about three hours. The energy/momentum measurement of isolated electrons from $W \rightarrow e\nu$ events will then be used to obtain the design goal precision of 0.5% within about two months. Global intercalibration of different regions of the calorimeter and the determination of the absolute energy scale will be performed using energetic electrons from $Z \rightarrow e^+e^-$ events.

1 Introduction

The CMS Electromagnetic Calorimeter consists of 75848 lead tungstate crystals. To achieve the target energy resolution, precise *in-situ* intercalibration of the individual crystals using physics events is required. The importance of this can be seen by considering, for example, the potential discovery and mass measurement of an intermediate mass Higgs boson in the $H \rightarrow \gamma\gamma$ channel, which would greatly benefit from an energy resolution with a constant term of less than about 0.5%. The intercalibration error goes directly into this constant term with very little scaling, because most of the energy goes into a single crystal.

2 The CMS Electromagnetic Calorimeter

A detailed description of the CMS ECAL can be found in [1]. Figure 1 shows a transverse section of the ECAL.

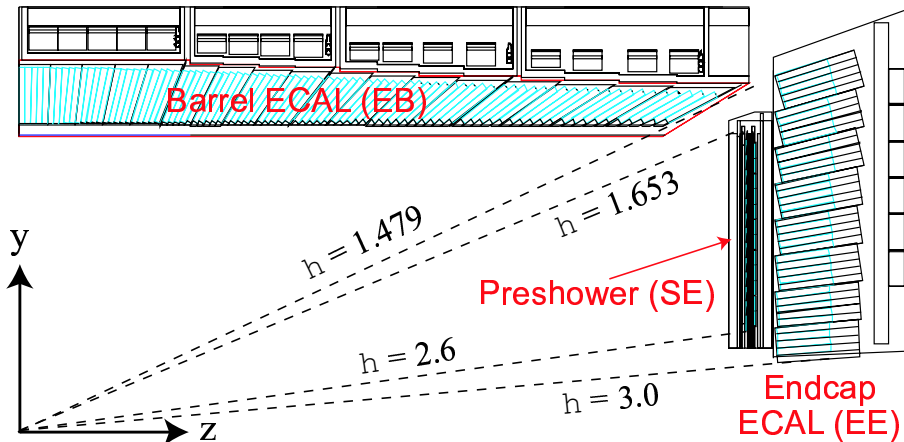


Figure 1: Transverse section of the ECAL, as described in GEANT3/CMSIM.

Each half-barrel consists of 18 super-modules each containing 20×85 PbWO_4 crystals. The crystals are tilted so that their axes make an angle of 3° with a line from the nominal vertex point, and each covers approximately 0.0174×0.0174 in $\eta\phi$. The crystals are 230 mm in length, which corresponds to $25.8 X_0$.

The endcap consists of identically shaped crystals, slightly shorter (220 mm, $24.7 X_0$) and a little larger in cross-section than the barrel crystals, grouped in mechanical units of 5×5 crystals arranged in a rectangular xy grid, with the crystal axes off-pointing from the nominal vertex by angles between 2° and 5° . A $3X_0$ silicon strip preshower detector is situated in front of most of the endcap ($|\eta| > 1.653$).

3 The Electron/Photon High Level Trigger

The online reconstruction and selection of physics objects will be performed using the CMS High Level Trigger (HLT), described in detail in [2]. This will be done flexibly using a single online CPU farm, made up of approximately 2000 processors, using the same object-oriented environment and code as the offline software. The CPU time targets are already being met.

The Electron/Photon HLT selection is performed in three stages:

1. “*Level-2*”: Clusters of crystals are constructed using a bump-finding algorithm. The spray of bremsstrahlung energy radiated in the tracker material is collected in “super-clusters”. At low luminosity, the transverse energy of the super-cluster is required to be greater than 26.0 (14.5) GeV for single (double) triggers.
2. “*Level-2.5*”: The energy-weighted average impact point of the super-cluster is propagated back to the nominal vertex point and hits in the pixel detector are sought. If at least two pixel hits are found, the candidate is classified as an electron, otherwise it is classified as a photon. For the photon stream at low luminosity, the transverse energy of the super-cluster is required to be greater than 80 (20) GeV for single (double) triggers.
3. “*Level-3*”: For electrons, tracks are reconstructed and cuts are applied on the ratio of the super-cluster energy to the track momentum and on the difference in pseudorapidity, η , between the extrapolated track and the super-cluster position. Isolation requirements are made for both electrons and photons.

3.1 Performance

Table 1 shows the electron and photon rates output by the HLT at both low and high luminosity. The single electron background comes from π^\pm/π^0 overlap, π^0 conversions and genuine electrons from $b/c \rightarrow e$. The efficiency for $H \rightarrow \gamma\gamma$ for $m_H=115$ GeV at low luminosity after the complete selection chain is 77% for events with both photons in the fiducial region, and 84% for events for which the photons also pass the offline p_T cuts to be used for Higgs searches.

Table 1: Electron and photon rates output by the HLT

	$2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$			$10^{34} \text{cm}^{-2} \text{s}^{-1}$		
	Signal	Background	Total	Signal	Background	Total
Single electron	$W \rightarrow e\nu$: 10Hz	23Hz	33Hz	$W \rightarrow e\nu$: 35Hz	40Hz	75Hz
Double electron	$Z \rightarrow ee$: 1Hz	~ 0	1Hz	$Z \rightarrow ee$: 4Hz	~ 0	4Hz
Single photon	2Hz	2Hz	4Hz	4Hz	3Hz	7Hz
Double photon	~ 0	5Hz	5Hz	~ 0	8Hz	8Hz
TOTAL:			43Hz			94Hz

4 Intercalibration Strategy

4.1 Precalibration

The raw intercalibration precision obtained from laboratory measurements of the APD gains and crystal light yields is $\sim 4.5\%$. The precision obtained from the transfer of the test beam precalibration to the assembled detector is predicted to be $\sim 2\%$. However, the present construction schedule implies that less than one quarter of the calorimeter elements can be precalibrated.

4.2 In-Situ Intercalibration Using Electrons From $W \rightarrow e\nu$ Events

The standard technique which will be used to obtain high-precision local intercalibration of the CMS ECAL is to use the E/p of electrons from $W \rightarrow e\nu$ decays, where E is the energy measured in the calorimeter and p is the measured momentum of the reconstructed track.

There are two dominating issues. The first is that the inclusion of electrons with large losses due to bremsstrahlung in the tracker material results in a large tail in the E/p distribution, leading to a tradeoff between electron efficiency and the width of the distribution. Electrons which radiate significantly can be removed by applying very hard cuts on ECAL shower shape variables. Since the amount of bremsstrahlung depends on the amount of material, which varies with η , the strategy is to intercalibrate crystals within small η regions first with loose bremsstrahlung cuts, and then to intercalibrate between the regions with much tighter cuts.

The second issue is that each electron shower involves up to 25 crystals ¹⁾, so there is a need to deconvolute the 25 individual calibration constants used to reconstruct the energy of each electron. The deconvolution is performed using an iterative algorithm which was used to solve the same problem in the L3 experiment at LEP. The algorithm was tested for electrons simulated in a 10×10 crystal matrix. Figure 2 shows the calibration errors as a function of the number of $W \rightarrow e\nu$ events per channel. A few tens of events per channel are sufficient to obtain an intercalibration precision better than the target of 0.5%. The time required depends on the cuts applied to remove electrons with large bremsstrahlung losses. Conservative calculations indicate a time scale of around two months at low luminosity.

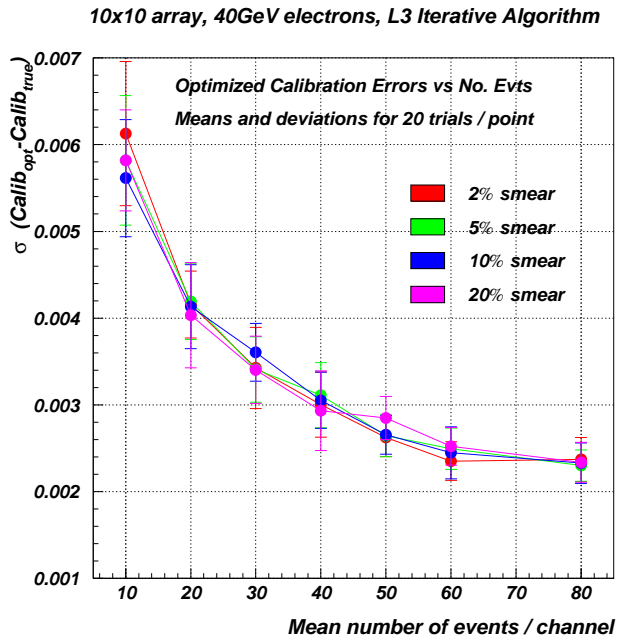


Figure 2: Calibration errors as a function of the number of $W \rightarrow e\nu$ events per channel, obtained using the L3 iterative algorithm to unscramble the calibration constants.

¹⁾ A 5×5 crystal array is used to reconstruct the energy in the calorimeter.

4.3 ϕ -Symmetry Intercalibration

The standard $W \rightarrow e\nu$ intercalibration requires approximately two months of stable running at $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ luminosity and requires the entire detector to be functioning optimally (e.g. perfect tracker alignment), conditions which may take some time to achieve. ϕ -symmetry intercalibration [3] is proposed as a method to rapidly achieve a target intercalibration precision of 2% at startup, by exploiting the uniformity of energy deposition in minimum-bias events to intercalibrate pairs of rings of crystals at fixed $|\eta|$. Minimum-bias crossings are used to avoid trigger bias, but the use of jet-triggers, which have the advantage of much larger energy deposits, is also being investigated. The number of intercalibration constants can thus be reduced from 75848 (no. of crystals) to 125 (no. of fixed $|\eta|$ ring pairs). Ring-to-ring intercalibration will then be performed using $Z \rightarrow e^+e^-$ events (Section 4.4).

Distributions of the total transverse energy deposited in each crystal from 18 million fully simulated minimum-bias events are formed for 85 (40) pairs of rings in the barrel (endcaps). The summations do not include energy deposits below 150 MeV in the barrel and below 750 MeV in the endcaps in order to exclude noise. The intercalibration precision attainable for each pair of rings is determined from the Gaussian width of the distribution via an empirically determined constant of proportionality.

The technique has been directly tested by performing a complete simulation of the method to a pair of rings with miscalibrations assigned randomly from a Gaussian of width 6%. Figure 3(a) shows the residual miscalibration after a single iteration of the method.

If the symmetry were exact the attainable precision would be proportional to $1/\sqrt{N}$, where N is the number of events. In reality, a limiting precision is reached when the inhomogeneity of tracker material breaks the ϕ -symmetry of the energy deposition. This limit can be calculated for each pair of rings by fitting the precision as a function of $1/\sqrt{N}$ to a function of the form $f(1/\sqrt{N}) = \sqrt{s^2 + (m/\sqrt{N})^2}$, where m is a constant and s is the limiting precision. This procedure is illustrated in Figure 3(b).

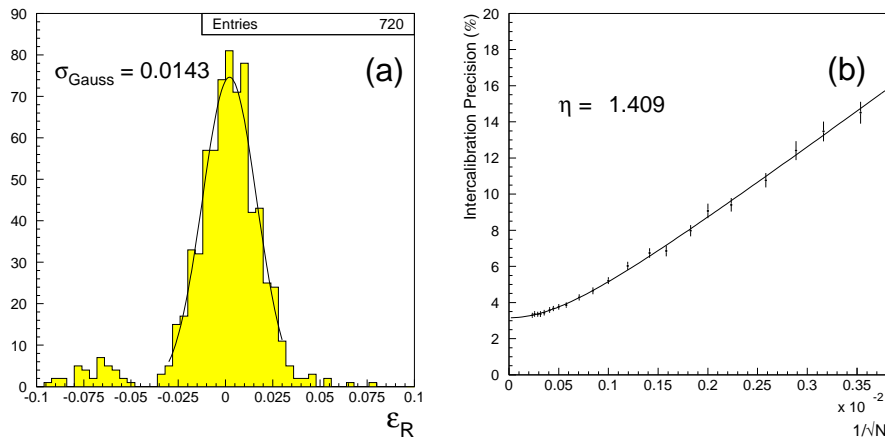


Figure 3: (a) Distribution of residual miscalibrations, for the 720 crystals in the pair of rings at $|\eta| = 0.23$, after a single iteration of ϕ -symmetry intercalibration. (b) Variation of the intercalibration precision with $1/\sqrt{N}$, for crystals at $|\eta| = 1.41$. The limit corresponds to the y -intercept of the fit.

The intercalibration precision which can be obtained with 18 million minimum-bias events, and the limit on the precision are shown as a function of η in Figure 4. The precision with 18 million events is between 1.2% and 3.5% throughout the fiducial region. Allocating 1kHz of Level-1 bandwidth for minimum-bias, 18 million events could be taken in less than three hours. Complete ignorance of the tracker material distribution is assumed. With knowledge of the distribution after precise independent $W \rightarrow e\nu$ intercalibration, there is the potential for rapid and repeated high-precision intercalibration (<1% every few hours).

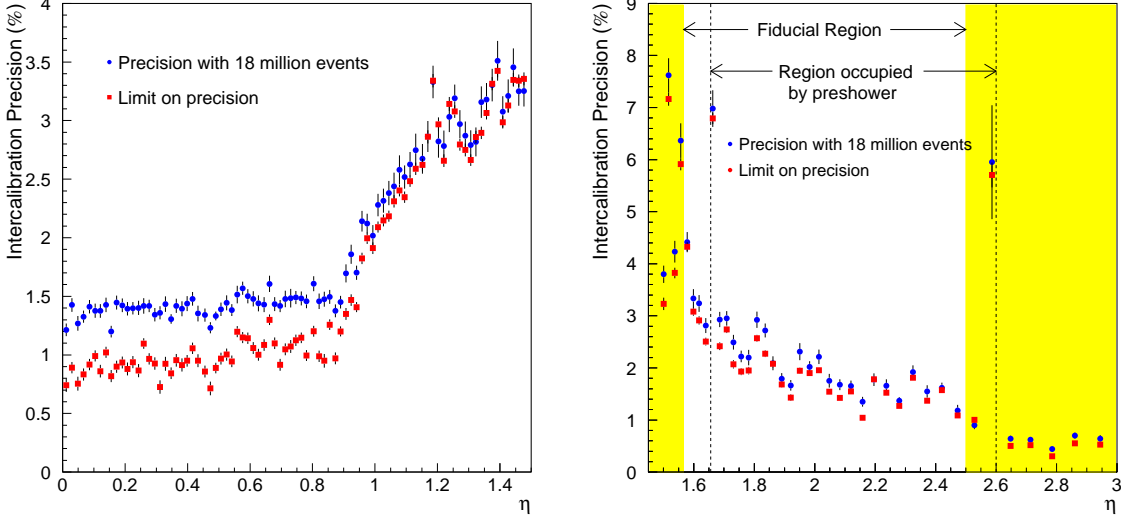


Figure 4: Intercalibration precision which can be obtained with 18 million minimum-bias events and the limit on the intercalibration precision as a function of η .

4.4 Intercalibration Using Electrons From $Z \rightarrow e^+e^-$ Events

High energy electrons from $Z \rightarrow e^+e^-$ events are used

1. to perform ring-to-ring intercalibration after performing ϕ -symmetry intercalibration of the crystals within the rings,
2. to perform global intercalibration between different regions of the calorimeter,
3. to set the absolute energy scale.

The principle of the technique is to reconstruct the Z mass, M_Z :

$$E_1 E_2 = \frac{M_Z^2}{4 \sin^2(\theta_{12}/2)},$$

where E_1 and E_2 are the energies of the electrons reconstructed in the ECAL and θ_{12} is the 3D angle between them. The same problems described in Section 4.2 are encountered and are solved in a similar manner. The problem of deconvoluting the calibration constants is more acute since the Z mass reconstruction provides information only about the product of the shower energies. Around 100 electrons per ring are sufficient to perform ring-to-ring intercalibration to a precision of 0.5%. This yield can be achieved within a few days.

5 Summary

The *in-situ* intercalibration of the CMS electromagnetic calorimeter crystals will be performed using three techniques. At startup, ϕ -symmetry intercalibration will provide a means of attaining a precision of around 2% within about three hours. The design goal precision of 0.5% will subsequently be achieved using the E/p of electrons from $W \rightarrow e\nu$ events in about two months. Global intercalibration of different regions of the calorimeter and the determination of the absolute energy scale will be performed using electrons from $Z \rightarrow e^+e^-$ events on a time scale of a few days.

References

- [1] CERN/LHCC 97-33, CMS TDR 4, *The Electromagnetic Calorimeter Project*.
- [2] CERN/LHCC 2002-26, CMS TDR 6.2, *Data Acquisition and High Level Trigger*.
- [3] D. Futyan and C. Seez, *Intercalibration of ECAL Crystals in Phi Using Symmetry of Energy Deposition*. **CMS Note-2002/031**. To be published in J. Phys. A: Nucl. Part. Phys.