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Calibration of the CMS Electromagnetic Calorimeter

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Abstract

Calibration is one of the factors that set limits on the ultimate performance of the CMS electromagnetic calorimeter (ECAL) at LHC. In situ calibration with physics events will be the main tool to reduce the constant term in the energy dependent resolution function to the design goal of 0.5%. At the start of detector operation, a fast intercalibration method, based on phi symmetry in minimum bias events, will be used, exploiting the uniformity of energy deposition as a function of ϕ at a given η . Energetic electrons from $Z \rightarrow e^+e^-$ decays will be recorded at a sufficiently high rate, even at the initial low luminosity, to provide an intercalibration of calorimeter regions and to set the absolute energy scale. Once the Tracker has been commissioned, intercalibration of different crystals within a single module may be achieved using E/p measurement of isolated electrons. This calibration strategy will be described in detail and illustrated with simulated results.

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1 Introduction

The performance of the CMS crystal calorimeter [1], which may be quantified by taking as a benchmark the power to discover an intermediate mass Higgs boson via the two photon decay channel, depends on its excellent energy resolution; an accurate measurement of its mass requires a precise energy scale.

The design goal of the energy resolution function is expressed by the following parametrization (with E in GeV):

$$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.15 \text{ GeV}}{E} \quad (1)$$

where the stochastic term is the first one, the second one is the constant term and the last term represents the noise. Intercalibration precision goes directly into the constant term with a very little scaling, due to the fact that most of the energy of an electromagnetic cluster is contained in a single crystal.

2 Tracker Material

The big amount of material between the interaction point and the electromagnetic calorimeter represents the main difficulty in performing in situ calibration. In terms of radiation lengths, the tracker material thickness rises from about 30% X_0 at $\eta=0$ to a peak of more than 1 X_0 at an eta corresponding to the ECAL endcap region.

Such quantity of material gives rise to electron bremsstrahlung and photon conversion, degrading the energy resolution of electromagnetic particles; physical distributions relevant for the calibration, such as the electron pair invariant mass peak in the Z channel or E/p resolution in the W channel, are strongly bremsstrahlung dependent.

The spread of measured energy with respect to the true MC energy for $p_T = 35$ GeV electrons is shown for the barrel part of ECAL in Fig. 1. The large asymmetric tail on the left is precisely due to bremsstrahlung.

Figure 1: Distribution of measured energy over true MC energy for $p_T = 35$ GeV electrons in the Barrel.

3 Phi Symmetry

Raw intercalibration from laboratory measurements of crystal Light Yield performed during assembly together with CERN SPS test-beam results of supermodules will represent the precalibration of the electromagnetic calorimeter. Following the present construction schedule, less than half of the ECAL will be precalibrated in the test beam. The raw intercalibration expected for channels that have not been precalibrated in the test beam is $\sim 5\%$ [2]. The optimal functioning of the complete CMS detector required to reach the design calibration, will take some time. However it will be possible to improve the calibration precision just at the start-up by using the ϕ -symmetry of transverse deposited energy; this method, so called also energy flow, leads to a reduction of the number of intercalibration constants. Within a few days, it should be possible to determine the remaining constants using $Z \rightarrow e^+e^-$ decays.

The proposed method has been tested with a sample of 18 million fully simulated minimum-bias events [3] corresponding to few hours at the start-up luminosity $2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$ assuming 1 kHz Level 1 Trigger bandwidth dedicated to the calibration; the total transverse energy deposited from a large number of events should be the same for all crystals in a ring at fixed η , so the intercalibration of crystals in the ring can be performed by comparing the total transverse energy deposited in a single crystal with the mean of the distribution of total transverse energies for all crystals at the same pseudorapidity.

After a lower threshold cut, due to the fact that at low energy the noise is dominant, and an upper threshold cut, applied to avoid the effect of few events with very high energy deposits, the crystal energy deposited sums of each ϕ ring are plotted. In Fig. 2 the truncated (after energy cuts) $\sum E_T$ distribution is shown for all crystals at $|\eta| = 1.0$ with a fitted gaussian superimposed.

Figure 2: Distribution of $\sum E_T$ obtained with 18 million minimum-bias events, for the pair of rings of crystals at $|\eta| = 1.0$.

To test the method, an artificial miscalibration of 6% is applied to the crystals in each ring. After this miscalibration, for each crystal i a calibration constant c_i is extracted using this ratio:

$$c_i = \frac{\langle \sum_{all\ events} E_T \rangle_{ring}}{(\sum_{all\ events} E_T)_{crystal\ i}} \quad (2)$$

This procedure can be iterated but already after the first iteration the spread of residual miscalibration is compatible with the expected calibration precision due to the variation of $\sum E_T$ seen in perfectly calibrated crystals (Fig. 2). This spread is due to the fact that the ϕ symmetry of the detector is not exact; the main source of asymmetry is the inhomogeneity of tracker material that results in a spread in the $\sum E_T$ values which cannot be reduced by increasing the statistics of the event sample. The limit on the precision achievable without using explicit knowledge of tracker inhomogeneity is represented as a function of η in the barrel range in Fig. 3 by square points. In the same figure the round points represent the precision which can be obtained using 18 million of minimum-bias events. With increasing knowledge of tracker material distribution effects, from Montecarlo studies, this precision could decrease down to 1% in the whole barrel region.

4 Intercalibration with Z events

At the LHC center of mass energy, $\sqrt{s} = 14$ TeV, the $Z \rightarrow e^+e^-$ cross section is ~ 1.4 nb; the clear signature of these decays will assure enough data to set the ECAL absolute energy scale and to intercalibrate different regions of the calorimeter.

The calorimeter rings can rapidly be intercalibrated using Z events by the electron pair invariant mass reconstruction; it will be possible, together with the phi symmetry method, to calibrate in this way the whole ECAL at $\sim 2\%$ just at the start-up and without using tracker momentum measurements. In fact, in order to reach such a precision, around 100 electrons per ϕ ring at fixed η are needed, and this amount of data can be collected in less than one day

Figure 3: Intercalibration precision which can be obtained with 18 million minimum-bias events and systematic limit of the precision due to the ϕ asymmetry of the detector.

at $L = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

The Z channel gives energetic correlated electrons in different regions of the calorimeter, hence a large fraction of events allows to intercalibrate the endcaps with respect to the barrel. Typically the transverse momentum of the Z is low, giving essentially back-to-back electrons in the azimuthal plane. Furthermore the $Z \rightarrow e^+e^-$ rate versus η is flat over most of the ECAL range.

Exploiting the invariant Z mass relation, each selected event gives one equation in the calibration linear system:

$$\sum_{\phi_1, \eta_1} \sum_{\phi_2, \eta_2} C(\eta_1) \cdot E(\phi_1, \eta_1) \cdot C(\eta_2) \cdot E(\phi_2, \eta_2) = \frac{M_Z^2}{4 \cdot \sin^2\left(\frac{\theta_{12}}{2}\right)} \cdot (1 - \epsilon_{out}^{\phi_1, \eta_1}) \cdot (1 - \epsilon_{out}^{\phi_2, \eta_2}) \quad (3)$$

where the sums are over the crystals of both electromagnetic clusters, θ_{12} is the measured angle between electrons and ϵ_{out} is the average crystal energy fraction loss, determined by Montecarlo studies, because of not fully longitudinal shower containment, boundary effects and clustering inefficiencies. There are 170 unknown parameters $C(\eta_i)$ for the barrel and 80 for the endcaps.

To solve such a big overdetermined linear system, two methods are under study. In the first one, the L3 iterative method [4], the calibration constants are unscrambled by some weight factors w_i proportional to the deposited energies:

$$C_N(\eta_i) = C_{N-1}(\eta_i) \cdot \frac{\sum_n \left(\frac{M_Z}{M_{inv}^n} \right)^\alpha \cdot w_{i,n}}{\sum_n w_{i,n}} \quad (4)$$

where N is the iteration index and n is the event index; the sum affects only the events with one energy cluster in the ring i . The correction factors are applied in each step and the iteration stops when the calibration coefficients converge.

The other method is the Householder algorithm [5]; it requests a least square application after a linear transformation of the calibration system and seems to be well suited to handle systems with a big number of unknowns.

The L3 method application result, in preliminary studies [6], is shown in Fig. 4; starting from an artificial crystal energy miscalibration of 20%, the algorithm converges after around 10 iterations. The residual miscalibrations is still higher than the expected one because of bremsstrahlung that spoils the calibration resolution. If a cut on electron bremsstrahlung is applied, the residual miscalibration becomes lower but the number of selected events is dramatically decreasing.

Variables such as the energy sum in the 9 crystals matrix around the most energetic deposit ($E_{3 \times 3}$), the 25 energy sum ($E_{5 \times 5}$) or the energy of the electromagnetic cluster, arranged by a variable number of crystals, allow to select good electrons, in term of bremsstrahlung, using only ECAL informations.

Figure 4: Electron pair invariant mass peak reconstructed with the L3 iterative method after an artificial crystal energy miscalibration of 20%.

5 Intercalibration with W events

$W \rightarrow e\nu_e$ is a very high statistics channel particularly important during the start-up low luminosity phase, when the rate will be ~ 10 Hz. The use of tracker measurements of isolated electron momentum will lead to the determination of the calibration coefficients for individual crystals. As in the Z channel, the electron shower involves many crystals, therefore the unscrambling of the calibration constants is required. Again the methods under study are the Householder and the L3 iterative algorithm, where the iterative formula now takes into account the tracker information E_{tr} :

$$C_N(\eta_i, \phi_i) = C_{N-1}(\eta_i, \phi_i) \cdot \frac{\sum_n \left(\frac{E_{tr}}{E_{5x5}} \right) \cdot w_{i,n}}{\sum_n w_{i,n}} \quad (5)$$

Preliminary investigations [7] give the results shown in Fig. 5 where the resolution of the calibration as a function of number of events per crystal is shown for the Householder algorithm; the L3 method produces a similar convergence. Furthermore, initial artificial miscalibration doesn't affect too much the convergence of calibration coefficients. Similar results are obtained in the Z studies. To reach the desired resolution 40-50 events per crystal

Figure 5: Calibration precision as a function of number of events per crystal obtained with the Householder method.

are needed; this amount of data corresponds to few weeks at $L = 2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. As already mentioned, electron bremsstrahlung gives a long tail in the E/p distribution, therefore some cuts should be applied to avoid using

electrons which belong to the tails. As in the Z channel, a compromise must be found between hard cuts and the necessity to select an adequate number of events per crystal; a strategy could be to use hard cuts to intercalibrate groups of crystals and then, by loose cuts application to get high statistics, to intercalibrate single crystals of the same group.

6 Conclusions

The goal of in-situ calibration is to achieve a level of 0.5% for the energy resolution constant term. As seen the amount of material in front of ECAL is a big hurdle in the calibration procedures.

At the start-up it should be possible to intercalibrate at 2% level in a couple of days using the phi symmetry method together with $Z \rightarrow e^+e^-$ events. In a couple of months at $L = 2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$, exploiting the full tracker information, the high statistics $W \rightarrow e\nu_e$ decays will allow to reach 0.5% resolution.

It is worthwhile to stress that when everything will be fully functioning, we should rapidly reach the desired intercalibration precision even if the starting miscalibration will be high; but at the start-up it is quite probable that something won't be optimally functioning and so in absence of test beam calibration, with a 5%-6% starting intercalibration expected, High Level Trigger and electron selection would be less efficient.

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