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Inter-calibration of the CMS electromagnetic calorimeter with cosmic rays before installation

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Abstract

The possibility of using cosmic rays to pre-calibrate the ECAL barrel electromagnetic calorimeter of the CMS experiment was investigated using real data collected with a cosmic telescope and simulated data based on the GEANT4 toolkit. The data collected are well described by simulation and confirm that an inter-calibration of the calorimeter channels after assembly in super-modules can be performed with sufficiently good precision even without an external tracking device, following a schedule compatible with the CMS construction plans. A possible selective trigger setup based on scintillator planes is also proposed.

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1 Introduction

The CMS (Compact Muon Solenoid) experiment is one of the two general purpose detectors to be installed on the LHC ring. It basically consists of a silicon central tracker, surrounded by (electromagnetic and hadronic) calorimetry and by a muon detector. The tracker and the calorimeters are immersed in a 4 T solenoidal magnetic field. A detailed description of the CMS experiments and of its finalities can be found elsewhere [1].

The electromagnetic calorimeter (ECAL) of CMS is described in [2] and consists of $PbWO_4$ scintillating crystals equipped with with avalanche photo-diodes (APDs) in the barrel and photo-triodes in the endcaps for the light yield measurement. ECAL is organized in 36 super-modules (each containing 1700 crystals) in the barrel and in four *dees* (each consisting of 3662 crystals) in the endcaps. In turn, barrel super-modules are divided into four modules along the direction corresponding to increasing η in CMS (simply "η" hereafter), and labelled 1 (at small η) to 4 (at large η). The calorimeter has been designed to achieve excellent energy resolution and granularity to permit the discovery of the Higgs boson through its electromagnetic decay ($H \rightarrow \gamma\gamma$). $PbWO_4$ crystals also present sufficient radiation hardness to survive the hostile LHC environment for the CMS lifetime.

One necessary condition for optimal performance is an adequate inter-calibration of the response to deposited energy of all channels. To fully exploit the physics potential of CMS the ultimate inter-calibration precision should be kept well below 0.5%, which can only be obtained with in-situ physics data analysis, such as E/p measurements in $W \rightarrow e\nu$ (or invariant mass reconstruction in $Z \rightarrow ee$). However, the low cross sections of high-p_T processes require long data-taking periods in stable conditions or high luminosities to collect sufficient statistics. Some kind of pre-equalization of the channels's response can thus be crucial to guarantee an acceptable performance already at the startup.

The overall initial spread of the channel response after assembly is expected to be around 8% (rms). To improve the pre-calibration precision, all super-modules were initially foreseen to be tested on dedicated electron beams at two energies. However it is now clear that the extremely tight construction schedule of CMS makes this option impractical and only a fraction of the barrel super-modules will be calibrated on test beam before insertion in CMS.

To cope with this difficulty, alternative methods of pre-calibration were developed, based on a series of laboratory measurements of the separate detector components before assembly. These measurements aim at determining with the highest possible precision the optical properties of the crystals [3] and the gain of the electronics for each channel. However, laboratory tests cannot provide an equalization precision better than about 4% (one standard deviation). In addition, being performed on individual components before assembly, these tests present a much lower degree of reliability than a final check on test beam.

One possible solution was suggested in [4], where it is argued the crystals of complete ECAL barrel super-modules might be equalized in gain with cosmic rays before insertion in CMS. The idea consists in preparing a cosmic telescope, possibly including a tracking device capable of selecting cosmic muons traversing the crystals along the direction parallel to their axes, hosting a full super-module. Indeed, some kind of tracking information is essential, as the energy deposited in each crystal by minimum ionizing particles, which in turn determines the amount of scintillation light, depends linearly on the total path length inside the crystal. In addition, because of the large multiple scattering, tracking information should be required at both the entrance and the exit of crystals.

A modified approach was suggested in [5], according to which barrel crystals may be inter-calibrated even without any external tracking device. The method consists in using only those cosmic events releasing energy in a single crystal by vetoing on the neighboring channels, thus guaranteeing that the cosmic muon has traversed one and only one crystal along its path. This method is simple and economic, but it presents two difficulties. The first is that the signal induced by minimum ionizing particles, equivalent to about 11 MeV/cm in $PbWO_4$, is comparable with the typical rms level of electronic noise (40 MeV equivalent) when only a small part of the crystal is traversed, which makes the veto inefficient. The second difficulty concerns all crystals at the borders of the modules, for which the efficiency of the surrounding veto would be reduced.

The first difficulty is easily overcome by increasing the multiplication voltage of the readout APDs, which can provide an increase of a factor four in gain. The consequences of the increase in APD gain are discussed in [5], but are not expected to significantly affect the measurements with cosmic rays. With this simple modification the rms noise in each channel becomes equivalent to the signal induced by minimum ionizing particles in 1 cm.

The second difficulty is more tricky but could also be overcome, even without a tracking device, by using a more selective trigger, based for example on a set of accurately positioned scintillators, as will be discussed in the following sections.

The study presented in this note represents an attempt to estimate the inter-calibration precision achievable by exposing ECAL barrel super-modules to cosmic rays for time intervals compatible with the CMS construction schedule and to assess whether the cosmic telescope would require an independent tracking device to define the incoming muon direction. To answer the above questions both simulated and real data were used: the detailed simulation of the ECAL response to cosmic rays provided the basic framework to develop possible calibration strategies; real cosmic data, collected with a scintillator telescope for a few days in November 2004, were used to validate the simulation for what concerns the general data quality, the noise level and the data rate. The analysis of simulated and real data are described, respectively, in sections 2 and 3. The perspectives for the detector calibration will be discussed in section 4, followed by final conclusions.

2 Simulated cosmic ray data

2.1 Simulation of cosmic rays

The collection of cosmic ray data in a ECAL barrel super-module was simulated assuming that the detector was exposed to muons. The energy deposition and the detector response were simulated by means of the GEANT4 package [6]. The detailed geometry of the super-module and the framework necessary to propagate the particles inside it were taken from the H4SIM package, which had been originally designed to reproduce the test beam setup and which was modified in such a way that beam particles were replaced by a flux of muons reproducing the typical energy and angular distributions of cosmic ray data at sea level. Figure 1 shows the assumed muon spectra and directions, which are based on the experimental data of reference [7].

To simulate the cosmic test, the super-module was assumed to lie horizontally, with the front of the crystals facing the ground. This orientation can be obtained by a 90° rotation with respect to the test beam position

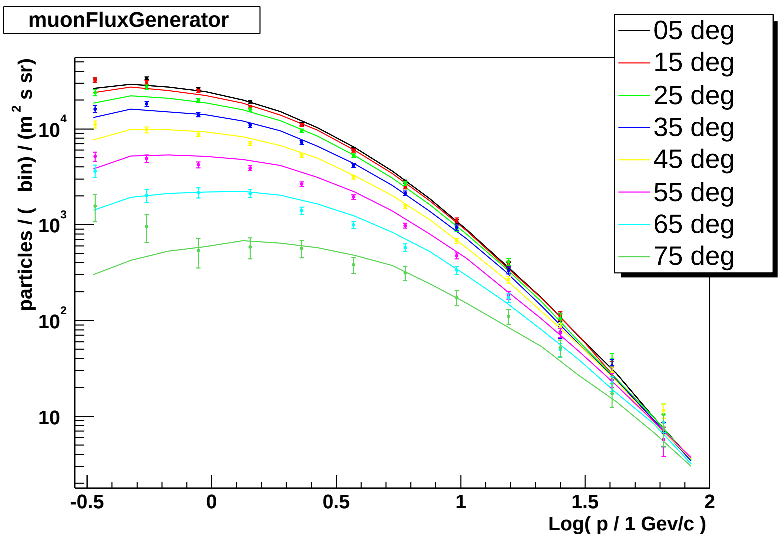

Figure 1: Distribution of the muon flux used in the simulation of the cosmic rays test (continuous lines) compared to the experimental data of reference [7] (dots). The flux decreases monotonically from 5 degrees (top line) to 75 degrees (bottom line).

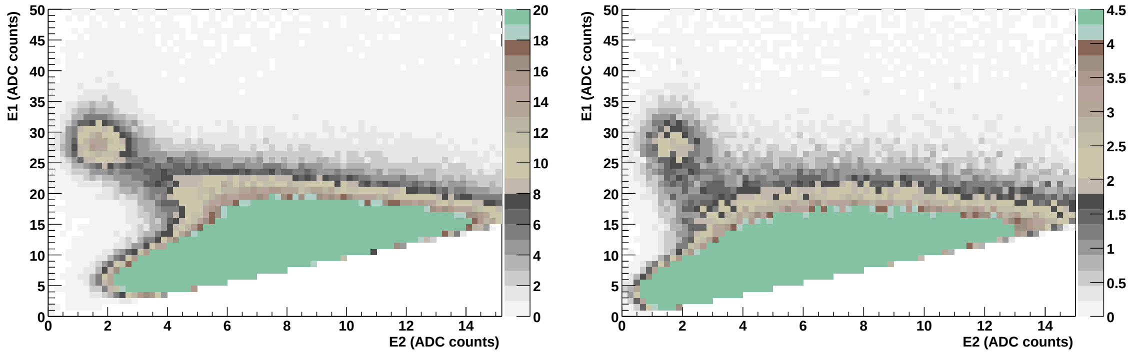

Figure 2: Simulation: scatter plot of E_1 vs E_2 in simulated cosmic events corresponding to one week of data taking. E_1 is the energy deposited in the crystal with the highest signal, while E_2 is the highest energy deposition in the immediately surrounding crystals. Edge crystals have been removed. Left: crystals in module 1. Right: crystals in module 4.

around an axis parallel to its longest side (η direction). Due to the increasing inclination of crystals along η (which has been designed to obtain a quasi-pointing geometry for particles generated in LHC collisions), this position corresponds to essentially vertical crystals in module 1, while crystals in module 4 inevitably present an inclination up to about 61° with respect to the azimuth. Since the mechanical structure does not allow the super-module to be inclined by large angles along η, the crystals in module 4 are the most difficult to calibrate because of the low cosmic rate at large angles.

The simulation also assumed that the cosmic muons were triggered by an independent device, such as a telescope of plastic scintillators. The trigger efficiency was taken to be 100%. No external tracking device was assumed, so the direction and energy of individual cosmic particles, whenever needed in the analysis, were taken directly from the generated data.

The digitization of the detector response was performed according to a simplified scheme. In more detail, the signal from each crystal was calculated as:

$$E_j = \frac{E_{j,original} \times G}{35.6 \text{ MeV/ch}} , \quad (1)$$

where $E_{j,original}$ is the signal size (in MeV) provided by the H4SIM simulation and G is the increase (roughly a factor 4) in the APD gain obtained by modifying the APD biasing voltage. Tests performed independently [8] showed that such a change in the APDs setting for limited time periods is safe and does not reduce significantly their lifetime. The assumed energy/(ADC counts) conversion factor is 35.6 MeV/ch.

The effect of the noise was also simulated by adding a gaussian smearing with a standard deviation of 40 MeV. The data acquisition system was assumed to be identical to that prepared for the electron test beam.

2.2 Analysis of simulated data

The analysis is based on purely calorimetric data, i.e. assumes no external tracking information, and relies on a series of simple cuts, applied in sequence. The muon candidate selection is essentially based on the two variables E_1 and E_2, defined as follows. In each event, the crystal with the highest deposited energy is selected and the 8 surrounding crystals (i.e. the full 3×3 matrix centered around the candidate muon) are considered. The signal in the highest energy crystal (in ADC counts) is described by E_1, while the variable E_2 describes the highest signal in the 8 surrounding channels.

Figure 2 contains the scatter plots E_1 vs E_2 for module 1 and module 4 obtained after removing edge crystals (crystals at the borders of the module or adjacent to dead channels), for simulated statistics equivalent to a 7-day data taking period: the signal of well aligned muons is clearly visible as the blob at the top left corner, however, as expected, the situation is significantly worse in module 4 than in module 1, due to the smaller rate of properly aligned cosmics. To select through-going muons parallel to the crystal axes, the cuts $E_1 > 10$ ADC counts and $E_2 < 3$ ADC counts were imposed.

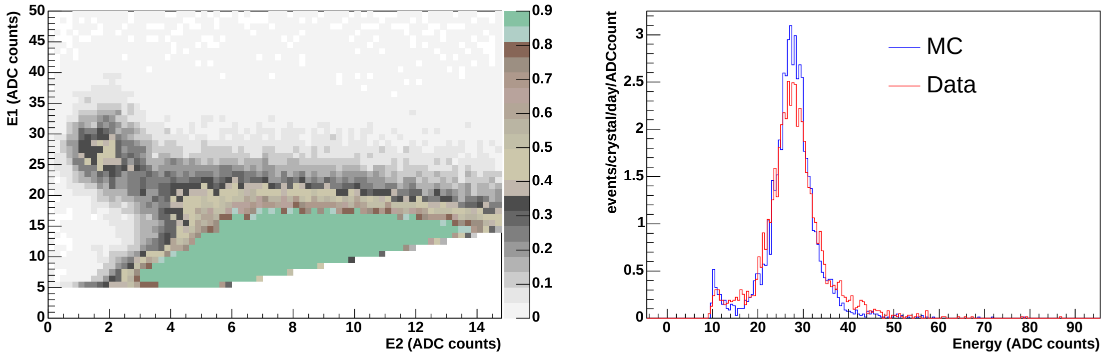

Figure 3: Left: Scatter plot of E_1 vs E_2 in real events (after removing edge crystals). Right: energy peak deposited by cosmic muons in real and simulated data after the final selection. The histograms contains the data from all channels (after equalization)

3 Real cosmic-ray data

3.1 Collection of real cosmic data

A data-taking campaign dedicated to cosmic rays was launched on the ECAL super-module SM10 from November 18 to November 21, 2004, at the CERN north area. The total live time of the collected data corresponds to about 41 hours.

Super-module SM10 had been previously exposed to an electron test beam in order to determine its calibration constants with high accuracy. The super-module was then rotated by 90° along η in order to bring the largest possible number of crystals close to the vertical position. As for the simulation, the gain of the APDs was increased by a factor four with respect to normal running conditions. To provide the trigger information, two plastic scintillators were positioned, respectively, above and below the super-module, in such a way that most of module 1 was efficiently covered. No data could be taken in the other modules. The data were collected using the H4 test beam acquisition system. Due to technical reasons, one full trigger tower (composed by 5×5 crystals) of module 1 could not be properly readout and was completely disconnected.

3.2 Analysis of real data

The real data were analyzed following the same procedure as the simulated data. Events corresponding to muons passing through inactive regions of the detector (such as the disconnected tower) were immediately discarded by a preselection requiring a minimum energy deposition $E_1 \geq 5$ ADC counts in at least one crystal.

The plot equivalent to Figure 2, but obtained with real events, is shown in Figure 3 (left). As for the simulated case, this plot does not contain particles detected at the edges of the super-module or at the border of inactive regions, where the veto based on the calorimetric information alone is known to be inefficient. The plot also refers only to the region covered by the trigger scintillators.

The map of the preselected events, in the form of an occupancy plot as a function of crystal position in η and ϕ, where ϕ indicates the coordinate of the azimuthal angle in CMS, is shown in Figure 4 (left). As expected, the occupancy distribution is hill-shaped due to the varying angular acceptance defined by trigger scintillators as a function of the muon impact point. The squared dead region corresponds to the inactive trigger tower.

As for the simulation, the final sample of cosmic muons useful for the calibration, i.e. well oriented with respect to the crystals, was selected by requiring $E_1 > 10$ ADC counts and $E_2 < 3$ ADC counts. The

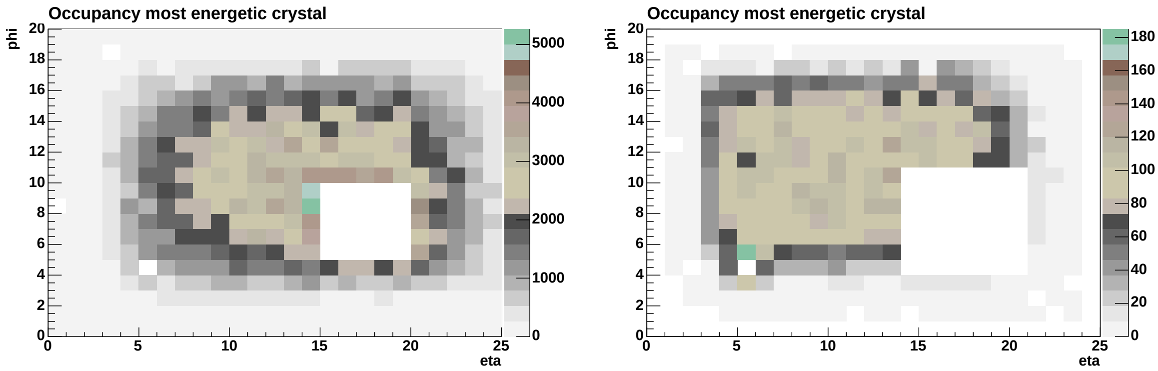

Figure 4: Distribution (occupancy) of the cosmic events versus the crystal position as obtained after the event preselection (left) and after final selection (right).

resulting occupancy plot as a function of crystal position in η and ϕ is shown in Figure 4 (right). Here the occupancy distribution is rather flat, apart from the region at the borders of the trigger scintillators due to acceptance inefficiency. The different shape with respect to Figure 4 (left) is an effect of the selection cuts, that, by keeping only those events parallel to the crystal axes, tend to equalize the geometrical acceptance of all channels.

Figure 3 (right) shows the E_1 distribution obtained in the final sample by superimposing the signal distribution in all channels after applying the calibration constants described below. A good agreement is observed between data and simulation.

The observed rate of selected cosmics in the data is 55 ± 2 per day per crystal on average, to be compared to an expectation of 61 ± 2, based on simulation. The disagreement may be explained by some trigger inefficiency in the data and by possible inaccuracies of the cosmic rate normalization in the simulation.

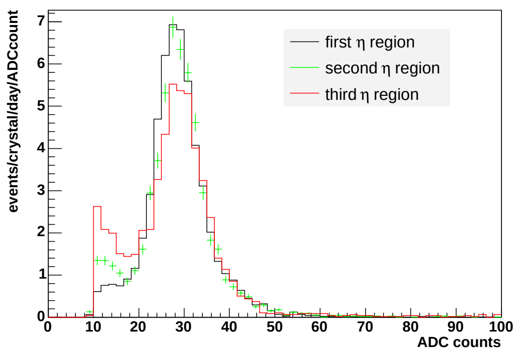

Figure 5: E_1 distributions observed in three η regions of module 1. The black histogram refers to rows 5 to 10 in η, the crosses to rows 11 to 16 and the red histogram to rows 17 to 22. Three functions were derived from the histograms by linearly interpolating the bin contents. The curves were then fitted to the spectrum in individual channels to determine their calibration constants.

The calibration constants were extracted from a fit to the E_1 spectrum in each channel. Since the shape of the E_1 distribution is not perfectly gaussian, the peak position was obtained by fitting the data with functions that better reproduce the observed histograms. The functions were derived from the data themselves, by averaging over the spectra of the crystals belonging to three separate η regions of module 1 (see the three histograms in Figure 5). Three functions were then obtained by linearly interpolating the contents of adjacent bins. The calibration constant for each channel was then extracted from a fit (through likelihood maximization) of the observed spectrum with all three functions, retaining the case with the best likelihood. The overall normalization and the energy scale factor (which defines the calibration constant) were the only free parameters in the fit. Figure 6 shows, as an example, the fitted energy distributions for two channels.

3.3 Comparison with test beam data

In order to evaluate the precision obtainable with cosmic muons on the inter-calibration constants, a comparison between cosmic and test beam data was performed. Unfortunately, test beam calibration constants were available only for a fraction of module 1 crystals. Furthermore, some of the crystals had particularly low statistics in the cosmics sample, due to the limited angular acceptance of the scintillator trigger. The comparison between cosmic and test beam data was thus restricted to those crystals for which the test beam calibration constant was available, which corresponds to 156 channels in total. To reduce the statistical uncertainties, a minimum of 50 good cosmic events per channel was also requested, which further reduced the analyzed sample to 130 crystals. These channels were characterized by an initial mis-calibration of 6% (rms), as obtained from the spread of their test beam calibration constants.

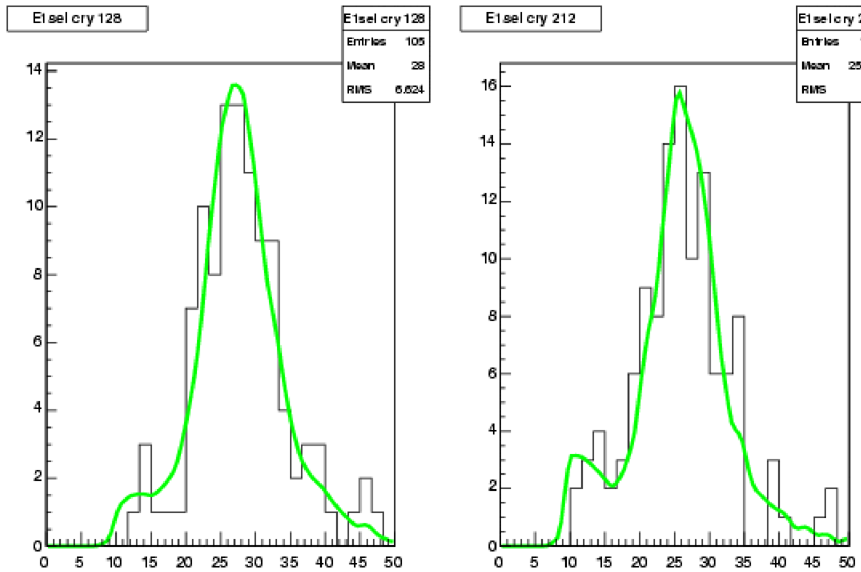

Figure 6: Two examples (channel 128 and channel 212) of single-channel spectra fitted with the reference functions. The units of the horizontal axis are ADC counts.

The comparison between cosmic and test beam calibration constants in the 130 selected channels is shown in Figure 7 (right). The gaussian fit to the observed distribution has a standard deviation of $(3.2 \pm 0.2)\%$. Figure 7 (left) also includes a plot showing the correlation between cosmic and test beam constants.

The statistical uncertainty affecting the cosmic calibration constants was estimated as follows. The peak of the energy distribution released by well aligned cosmic muons in one crystal (shown, for example, in Figure 6) can be approximated with a gaussian curve having a standard deviation of 15%-20%, depending on the channel. Given that, on average, 95 cosmic events per channel were collected, the statistical contribution to the cosmics calibration precision could be roughly estimated to be $(1.8 \pm 0.2)\%$. The statistical and systematic uncertainties associated to the test beam calibration values were assumed to be negligible.

After subtracting (in quadrature) the statistical contribution, a systematic uncertainty of $(2.6 \pm 0.3)\%$ was obtained. This result strictly applies only to crystals in module 1 not belonging to edge rows. This estimate necessarily includes, among others, contributions coming from possible dis-uniformities in the (non)linearity of the electronics and from the spread introduced by the change in the APD gain, which could be measured independently and subtracted from the uncertainty. In the framework of the present analysis, however, no attempt was made to correct the data for these two effects.

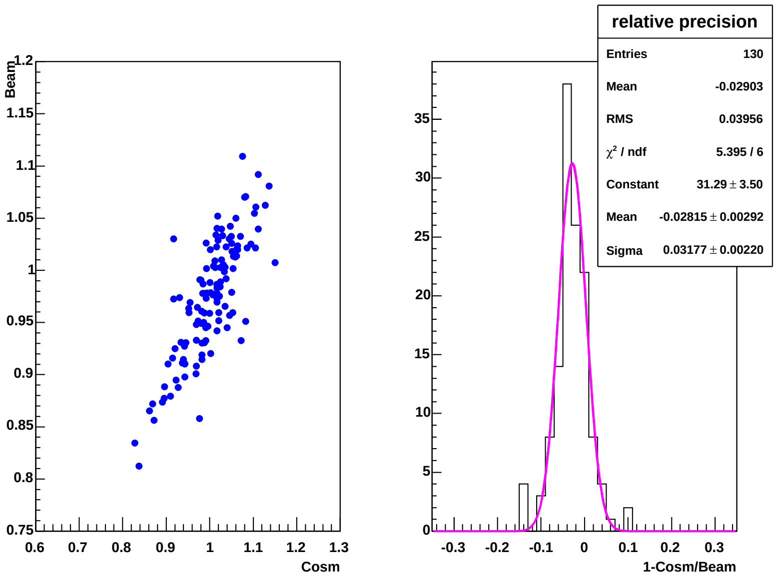

Figure 7: Left: correlation between test beam coefficients and cosmic data coefficients. Right: relative precision of the cosmic calibration constants. Only those channels with more than 50 cosmic events are considered.

4 Simulation of the calibration setup

The analysis of real cosmic events shows that the inter-calibration of ECAL crystals with cosmic rays is possible and that is affected by a relatively small systematic uncertainty, of order 2.6% for crystals in module 1 not belonging to edge rows. For the rest of the super-module only the simulated data can be used to estimate the achievable precision. Given the good agreement observed between real and simulated data and the simplicity of the analysis, the results of the simulation should be considered as reliable.

By applying the same analysis to the simulated data in modules 2 to 4, it was possible to conclude that, for what concerns internal crystals, no dramatic deterioration of the systematic precision should be expected compared to module 1. This is demonstrated by Figure 8 (left), where the cosmic peak in the selected sample is shown for all four modules after rejecting edge crystals. Considering a data taking period of one week, the statistical contribution would be 0.9% in module 1, 1% in module 2, below 1.2% in module 3 (which guarantees an overall precision better than 3%), but could exceed 2% at the extreme of module 4. In any case, one should expect a calibration precision better than 3.5% for all internal crystals.

For edge crystals the situation is different as shown in Figure 8 (right). Clearly a different analysis procedure and a more refined setup are necessary to obtain calibration constants with sufficient precision, given the inefficiency of the veto cut based on the neighboring crystals, as it will be discussed in the following sections.

4.1 Calibration of module 4

As already mentioned, the difficulty of calibrating module 4 is related to the small rate of cosmic rays reaching the earth surface at large angle. Clearly this cannot be modified. The statistics can only be increased by inclining the super-module itself, possibly at an angle which maximizes the total flux of muons traversing the crystals along their longer size. Unfortunately, constraints related to the mechanical structure of the super-module do not permit an inclination larger than about 10-20°. In the horizontal position, the average rate of good cosmic muons in module 4 is about one third the rate in module 1. For example, with 20° inclination the rate in module 4 would increase by roughly 30% in relative terms, while the rate in module 1 would decrease by 20%. In simple words, the situation of module 1 and 4 in the inclined position would be close to the situation of module 2 and 3, respectively, in the horizontal position. This alone would

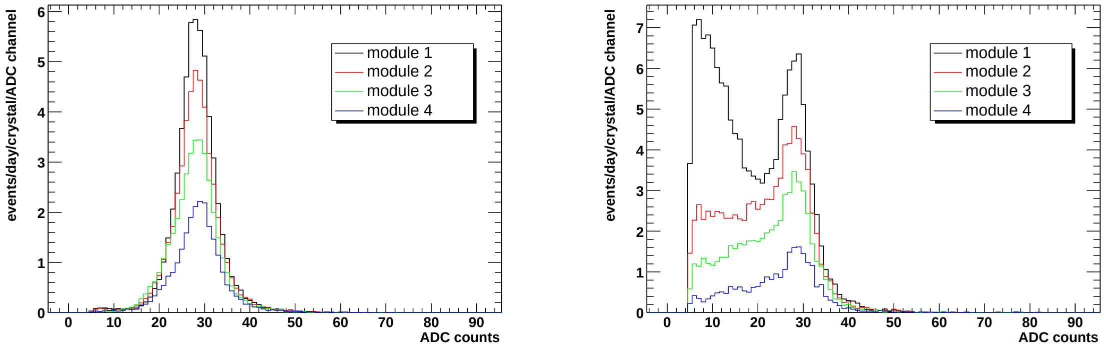

Figure 8: Energy released in ECAL crystals by cosmic muons selected by the simple two-plane trigger setup and passing the calorimetric selection. The four curves correspond to crystals in the four modules. Internal crystals are shown in the left plot, edge crystals in the right plot.

reduce the statistical uncertainty in module 4 by a non-negligible 15%.

While the inclination of the super-module would increase the signal rate, a contemporary reduction of the background of misaligned muons could be obtained by means of a more selective trigger, based on properly positioned additional scintillators.

Taking into account the quasi-pointing geometry of ECAL crystals, the most economic scintillator configuration for a selective trigger would consist of two trigger planes of different size, both to be placed below the super-module. One plane should be positioned as close as possible to its internal surface, with proper dimensions to cover completely the super-module acceptance. A second, smaller plane should be positioned close to the focal point in η of the crystals quasi-pointing geometry. With reference to Figure 9, the coordinates of the scintillators edges would be defined by (X is along η and Z along ϕ):

- $(-217 < Z < 217)$ mm and $(0 < X < 2680)$ mm in the upper plane;
- $(-350 < Z < 200)$ mm and $(-300 < X < 500)$ mm in the lower (focal) plane;

The asymmetry in Z is due to the non-pointing geometry of the crystals.

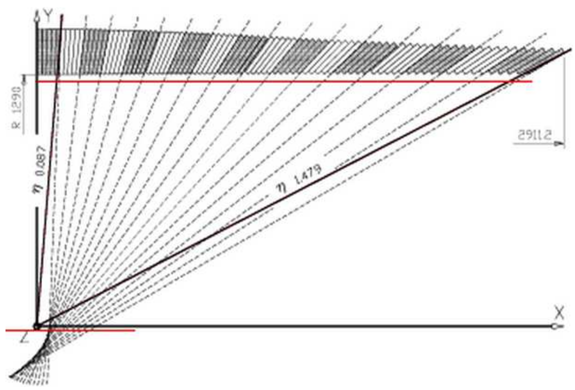

Figure 9: View of the two-plane trigger setup in the XY plane, where Y is the radial coordinate and X the coordinate along η

4.2 Calibration of edge crystals

The cumulative E_1 spectra observed in edge crystals belonging to all four modules assuming the trigger setup described above are shown in Figure 8 (right). The figure demonstrates that a simple two-plane

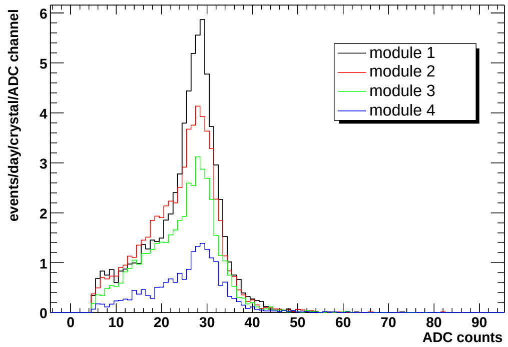

Figure 10: Same as Figure 8 (right) but after introducing an additional tagger plane of scintillator slabs positioned above the super-module to improve the definition of the edge crystals acceptance.

trigger telescope is insufficient and that some additional information on the muon direction is needed to obtain a clear peak. An additional trigger plane, if properly shaped, would certainly reduce the difficulties related to the calibration of edge crystals, by rejecting badly aligned cosmic events passing near the edges.

This additional trigger plane could consist of several scintillator slabs, positioned above the super-module (as close as possible to the crystals to minimize its surface) and parallel to the module edges in order to define precisely the acceptance borders. Their signal, when combined with those of the other scintillator planes, could be used to tag muons that do not exit/enter from the sides of the module. To give an idea, the external dimensions of such a scintillator frame would be 3720 mm in X and 650 mm in Z if, for example, it could be placed precisely on top of the super-module. The effect of such an additional plane of taggers is simulated in Figure 10, which should be compared with Figure 8.

5 Conclusions

The response of ECAL barrel crystals to cosmic muons was studied with samples of real and simulated data. A good agreement was found between data and simulation. For each crystal, well aligned cosmic muons could be selected, even without an external tracking device, by applying a simple veto on the neighboring channels after increasing the APD gain by a factor four to enhance the sensitivity to small signals. This study indicates that the internal crystals of ECAL barrel super-modules can be successfully inter-calibrated with cosmic rays before their installation in CMS, using a simple two-plane scintillator telescope. The overall precision achievable in one week, based on extrapolations from the results obtained in module 1, should be better than 3% for modules 1 to 3 and better than 3.5% for module 4 (which could be improved by inclining the super-module).

The simulation shows that additional information on the muon direction is needed for crystals positioned at the edges of the super-module, where the veto on neighboring channels becomes inefficient. In this note an economic solution is suggested based on the addition of a third scintillator plane, which would increase the signal-to-background ratio by improving the selectivity on the cosmics direction.

Acknowledgments

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