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Feasibility of intercalibration of CMS ECAL supermodules with cosmic rays

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Abstract. The feasibility of using cosmic rays to make an intercalibration of the ECAL Supermodules before installation in CMS has been investigated. In a test with a single crystal a clear signal with a width of 15% rms was seen, with rates as expected. Simulations using a simplified detector geometry and a parameterisation of the vertical cosmic ray muon flux indicate that it is feasible to use the surrounding crystals as veto counters to ensure a longitudinal trajectory through the crystal, without introducing a large systematic error. The statistical error would be around 1% for one week of running.

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1 Introduction

The Compact Muon Solenoid [1] detector (CMS) will be one of the two general purpose detectors installed at the 14 TeV proton-proton collider LHC under construction at CERN. The Electromagnetic Calorimeter (ECAL) of the detector will be a hermetic homogeneous calorimeter [2] made of 61,200 lead tungstate ($PbWO_4$) crystals mounted in the central "barrel" part, closed by 7,324 crystals in each of the two end-caps. The ECAL will be mounted inside the superconducting coil of a 4 Tesla solenoid. The use of lead tungstate crystals leads to a compact calorimeter but the low light yield of this crystal requires that the light sensors have gain. In the barrel part the light emitted by each of the crystals will be measured using two type S8148 avalanche photodiodes (APDs) [3] specially developed by Hamamatsu Photonics for CMS, and in the end-caps with vacuum phototriodes. The aim of the CMS ECAL is to measure the energy of photons (and electrons) with as good resolution as possible, with the goal of 0.67% rms at 100 GeV.

In the barrel part of the ECAL the crystals are assembled into units called Supermodules, each containing 1700 crystals. In CMS 18 Supermodules will be mounted to form a cylinder covering the region of pseudorapidity, η, from 0 to 1.48 in one direction, and a further 18 will

cover the same region in the other direction. The barrel ECAL crystals are 23 cm long, slightly tapered with entrance and exit faces of about 2.2×2.4 cm and 2.4×2.6 cm respectively. APDs are paired in 5 V bins according to operating voltage, mounted in a "capsule" and subsequently glued onto the exit face of the crystals. A slice through a Supermodule is shown in Fig. 1.

Although the final calibration of the gains of each channel will be made using physics data it was intended to test and make a pre-calibration of all the Supermodules in a high energy electron beam at CERN. In order to be sure that a good calibration is obtained soon after the start of LHC it is important that such a pre-calibration have an accuracy of better than about 5%. However, due to delays in the construction and the absence of beam in 2005 and possibly 2006 this will not be possible for many Supermodules. This paper explores the feasibility of an alternative way to obtain an intercalibration of the channels using cosmic rays. Such measurements would also provide an additional check that each channel is working properly, and ensure that the gain monitoring system is maintained and functioning as it should. An initial feasibility test at PSI with a single crystal to check the rate and the signal quality gave a clear signal with a count rate in line with expectations. Simulations with a simple detector geometry and a parametrisation of the vertical flux of cosmic ray muons were then used to simulate the response of a crystal embedded in a matrix and to explore possible triggering modes. This paper outlines the considerations for

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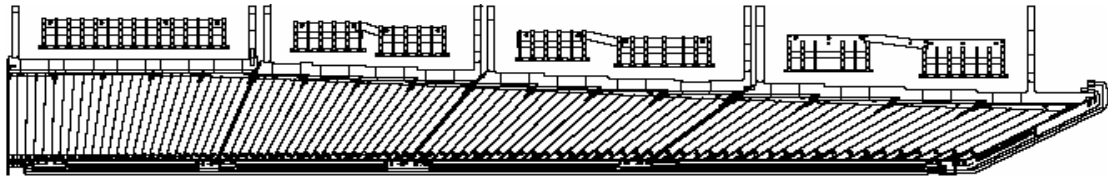
Fig. 1. A slice through a Supermodule, with the crystals pointing downwards towards the interaction region, and the electronics indicated schematically above the crystals. The front of the crystals is at a radius of 129 cm, while a plate closing the electronics (not shown, mounted on top) is at a radius of 175 cm. A Supermodule is 3 m long

a cosmic rate study of the Supermodules, and describes and gives the results from the test and the simulations.

2 Outline

The basic requirements for a cosmic ray study to be feasible are that there is a clear enough signal to be able to compare the channels with a useful accuracy, that any systematic errors are small and that the rate is practical. Cosmic rays crossing the crystals transversely deposit about 25 MeV on average (normal incidence), too small to be useable. However, those passing longitudinally through the full length of the crystal deposit about 250 MeV, which should give a clear signal, but with a rather low count-rate. The crystals produce around 4.5 photoelectrons in the pair of APDs per MeV, so that an energy deposit of 250 MeV would give 1125 photoelectrons. In addition to the crystal response there will be a contribution from the so-called nuclear counter effect due to muons passing through an APD, which we have estimated to be 90 MeV for APDs operating at gain 250, used in the test reported here. However, the area of the two APDs sensitive to traversing particles, including a region outside the optically sensitive area, is only about 10% of the area of the crystal back face and so this should not significantly interfere with the measurements.

A Supermodule would be supported lying horizontally, as in Fig. 1, such that crystals which will be at the centre of CMS ($\eta \sim 0$) would be oriented nearly vertically. However, those at the other end of the Supermodule (large η in the detector) would be at angles up to 64 degrees to the vertical. At such large angles the rate of cosmic ray muons is significantly lower, and the spectrum is harder than the vertical spectrum [4]. Thus the average energy deposited in the crystals in a Supermodule lying horizontally will change with the angle of the crystal, but not by a large amount. The expected background from electrons and protons appears to be negligible [4]. Triggering would be provided by scintillators above and below the Supermodule.

In order to have a clean signal, it is necessary to restrict the data to muons passing through the entrance and exit faces of the crystals, or entering or leaving the side of the crystals close to the end. This could be ensured by mounting tracking devices such as drift chambers above and below the Supermodule, but because of the large size and range of angles to be covered this did not appear to be practical. An alternative which is discussed here is to use the crystals surrounding that where the muon passed as veto counters.

2.1 Count rate

The cosmic muon rate at the ground passing through a horizontal plane is 80 per (m^2 sr sec) for "hard" muons [4]. The total flux is about 25% higher. For a crystal 23 cm long, with a 2.2 × 2.4 cm front face and a 2.4 × 2.6 cm back face placed vertically, the hard rate should then be $3600 \times 80 \times 2.2 \times 2.4 \times 2.4 \times 2.6/(23 \times 23 \times 10^4) = 1.8$ per hour, or 300 per week. The angular distribution is expected to follow a cos^2 distribution so that crystals at an angle of 64 degrees would have a rate a factor 5.2 lower.

2.2 APD gain

With the APDs operated at the planned mean gain of 50 for each capsule, the ECAL read-out electronics has been demonstrated [5] to have noise levels equivalent to around 40–50 MeV rms. In order to improve the signal to noise ratio and thus reduce the sensitivity to channel-to-channel variations of light output and noise, the APDs can be operated at a higher mean gain. Each APD has been qualified for use in CMS by testing that they behave without problem up to gain 300 [3]. Higher gain also increases the sensitivity to energy deposited in adjacent crystals, allowing a lower level veto in adjacent crystals to be applied. In the test reported here, gain 250 was used. However, in order that neither APD of a pair in a capsule be operated at a gain over 300, a mean gain of 200 is assumed in the simulations reported here. This requires an increase of the bias voltage of about 29V (compared to an increase of 40–50 V to reach breakdown). Since channel to channel variations in the change in gain of a few per cent may be expected, the actual increase in gain of each pair of APDs relative to the operating gain must be determined by the laser monitoring system [2]. The reliability and characteristics of the APDs at high gain are discussed in Sect. 5. In order to verify that a clear signal could be achieved and was not substantially degraded by running the APDs at high gain a test set-up with a single crystal was installed.
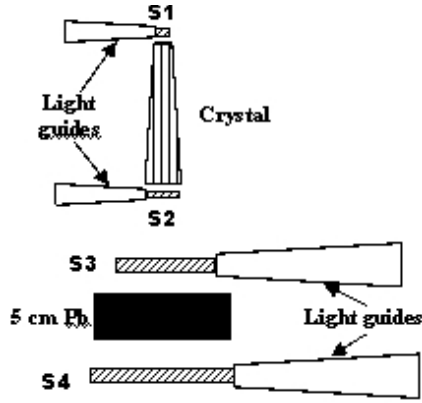
Fig. 2. Schematic of the set up for the test with a single crystal. S1 and S2 were plastic scintillators with transverse sizes 2 mm smaller than the end of the crystal they were positioned above or below. S3 and S4 were large scintillators, not included in the hardware trigger

3 Test with a single crystal

Measurements were made with the crystal placed vertically (0 degrees) and at about 13 and 67 degrees. The crystal was a standard ECAL crystal, with a pair of APDs mounted on the crystal in a capsule in the standard way, but operated at mean gain 250. The crystal was wrapped in Tyvek. Figure 2 shows the set-up schematically. Trigger scintillators (S1 and S2) of widths 2.0×2.2 and 2.2×2.4 mm were mounted about 1 cm from the crystal's front and the back faces, respectively. These scintillators were 2mm narrower than the crystal ends in both dimensions, to restrict the tracks to those passing through the end faces of the crystal. Larger paddles (S3 and S4) of 22×22 cm and 15×15 cm (13×13 cm for the off-vertical measurements) were mounted below the crystal. 5 cm of lead was placed above S4. The trigger for the data acquisition was a coincidence between S1 and S2 and a coincidence register recorded hits in S3 and S4. The APDs were read-out through a preamplifier and an Ortec type 450 shaping amplifier with a shaping time of 100 ns and gain 5 feeding a Lecroy 2249 W ADC with a 100 ns wide gate to simulate a peak-sensing ADC. The noise at the ADC input was measured to be about 6 MeV equivalent rms.

Initial tests gave many triggers with no data from the crystal and it was concluded that there were a lot of coincidences from Cerenkov signals from the trigger counters' plexiglas light guides. As a result thresholds were increased, which reduced these bad triggers but appears also to have reduced the efficiency of the paddles for real tracks by some 5%. The efficiencies of S1 and S2 may therefore have been similarly reduced.

The temperature was not stabilized but recorded with each event. Figure 3 shows the correlation between the signal and temperature for the 0 degree data. The line is a linear fit to the data giving a temperature dependence of the crystal plus APD of about -8.5% per degree, as expected, which was used to correct the data.
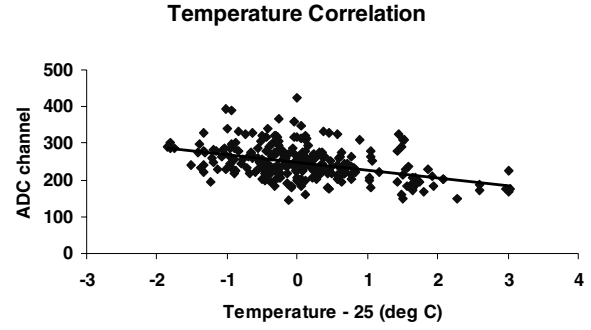
Fig. 3. The correlation between temperature and ADC channel for data between channels 150 and 450
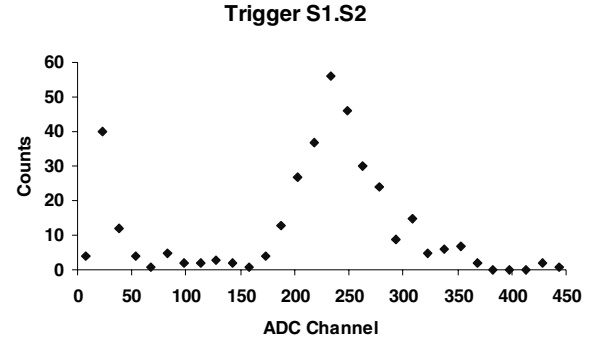
Fig. 4. The data at 0 degrees for events with coincidences in the counters S1 and S2 only. The data are binned in 15 ADC channels
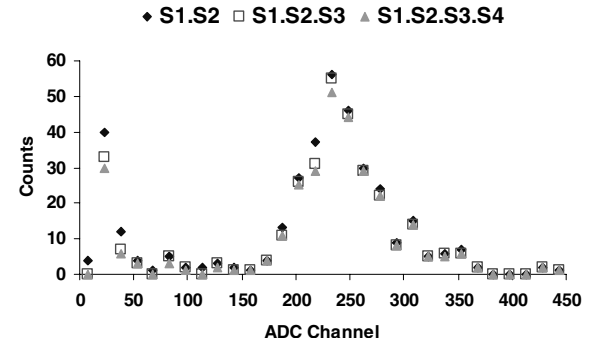
Fig. 5. The data at 0 degrees with the three different coincidence conditions, binned in 15 ADC channels

Figure 4 shows the temperature corrected data at 0 degrees after 12 days for the raw trigger, with a clear signal visible. The peak around channel 30 is the pedestal, indicating that the triggering was still not very clean.

Figure 5 compares these data with those when coincidences in S3 and in S3 and S4 are also required. Requiring these extra coincidences principally reduces the number of bad triggers (histogram entries below channel 160), with a reduction of counts in the peak of about 5% per additional coincidence, which we attribute to inefficiencies in these detectors. There is no obvious effect on the spectrum shape of the lead absorber placed above S4. Taking the data shown in Fig. 4 between channels 160 and 400 as the signal, the rate was 1.0 per hour or 168 per week,
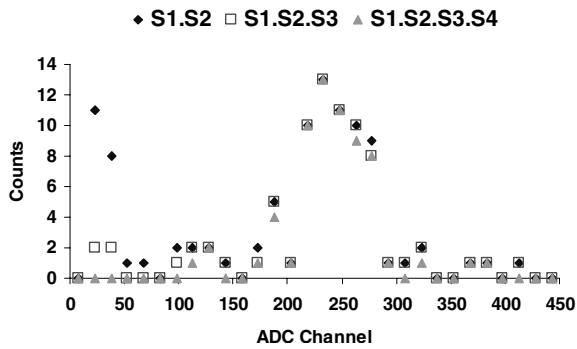
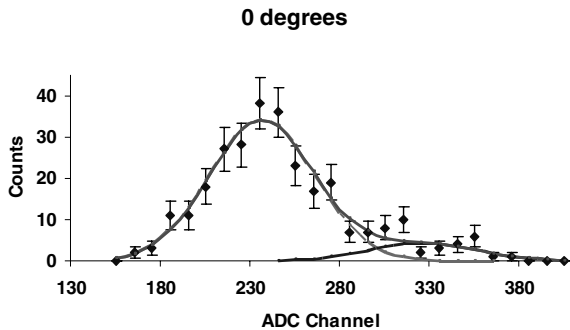**Fig. 6.** As for Fig 5 but for the data at 67 degrees

Fig. 7. The 0 degree data in channels 150 to 410 for the S1.S2 trigger, in 10 ADC channel bins. The lines are best fit Gaussians (see text) and the errors statistical

compared to 180 per week expected for hard muons in this geometry.

Figure 6 shows the results for the run at 67 degrees which lasted 15 days. The conclusions are the same as for the 0 degree run except that the rate, 4.4 per day, was a factor of 5.4 lower than at 0 degrees compared to the expected $(1/\cos^2(67°))$ factor of 6.6. The more striking removal of data at low channels with the 4-fold coincidence may reflect an improved geometry of the set-up with the light guides oriented differently to reduce coincidences from Cerenkov signals in them.

Figure 7 shows best fits of Gaussians to the 0 degree data binned in 10 ADC channels. First a Gaussian was fitted to the data in channels 150 to 300, and then a second Gaussian was added with the widths of both fixed to that found in the first fit. The rms width of the fitted Gaussian is 29.5 channels or 14.6% of the pedestal subtracted mean channel (202). If the main peak is assumed to correspond to 250 MeV energy deposit, then the second, smaller Gaussian is centered 115 MeV higher, with an area 12.5% of the main peak. Our estimate of the size of the nuclear counter effect was 90 MeV, with a magnitude of about 10% of the main peak. However, the simulations indicate (see Fig. 9) that the energy deposit spectrum itself has a tail towards higher energies and so the nuclear counter effect cannot be considered to be the only source of the observed high energy tail. A similar fit to the 67 degree data gave exactly the same rms width as that at 0 degrees, which is fortuitous given the statistical accuracy. The position of

the main peak at 67 degrees is 3.6 ± 2.1 % higher than that at 0 degrees.

Combining the rms width of the peak and the number of counts gives statistical accuracies of 1.2 and 2.6 % at 0 and 67 degrees, respectively, in one week.

Much of the vertical cosmic ray muon spectrum has a momentum of less than 1 GeV/c. In passing through 23 cm of lead tungstate they suffer multiple scattering on the scale of 1 cm lateral displacement. Therefore for a crystal embedded in a matrix the possibility should be considered that significant numbers of muons might scatter out of the crystal, and then rescatter in an adjacent crystal back into the original one. This would then give a tail in the spectrum to lower energies corresponding to the energy deposited in the neighbour. To investigate this, data were taken with and without the crystal wrapped in 3 mm of lead (excepting 2.8 cm at each end), in this case with the crystal at 13 degrees to the vertical. The run with the lead gave essentially the same result as that without, with at most about 5% more counts in the 70 channels below the peak. This indicates that re-scattering should not be significant for crystals embedded in a Supermodule.

4 Simulations

In practice, for a Supermodule test, it is barely feasible to define the incident and exiting track with the millimetre precision used in the test. The size of a Supermodule is such that any tracking device such as drift chambers would need to be metres long. Those found to be readily available typically either could not provide the resolution or were themselves sufficiently massive to cause significant multiple scattering, degrading the resolution of track projections. Further, it is not possible to get very close to the back face of the crystals because of the read-out electronics, compounded by the range of crystal angles. Therefore it was decided to explore the possibility of using the surrounding crystals as veto counters to ensure proper trajectories, using Monte Carlo simulations.

The APDs are paired in the capsules according to the operating voltage, in 5 V wide bins, such that the mean operating voltage of the pair is always at the bin centre. However at gain 250, the change in gain with voltage (dM/dV) is so large that individual APDs at the edge of the 5V bin would be operated at gains of over 300, the maximum gain at which the APDs were tested to be noise-free. Therefore in the simulations, an APD gain of 200 was assumed. Then the effective read-out electronics noise is "reduced" from around 45 MeV to 11 MeV rms.

In order to use the adjacent crystals as vetoes without large losses due to accidental vetoes from the noise, the veto level cannot be much below 3 times the rms value of the noise; in this case if the noise distribution is Gaussian and all eight surrounding crystals are used as vetoes the accidental veto rate would be 2.2%. However, a veto level of 3 times the rms noise would be 33 MeV, which is about 13 % of the signal size. This means that about 13 % of each end of the crystal is effectively exposed without adjacent vetoes, for the vertical geometry in the Supermodule
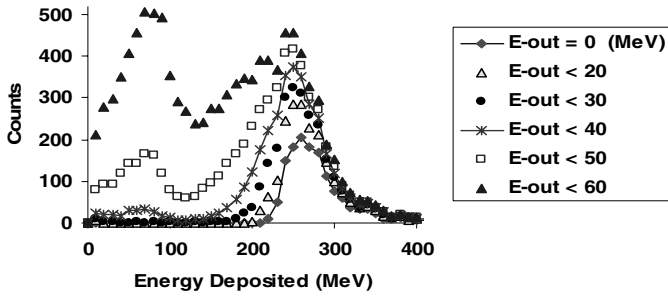
Fig. 8. The energy deposited in the target crystal in the simulations, for various values of the permitted maximum energy deposited (E-out) in any of the surrounding 8 crystals. The lines through the E-out = 0 and < 40 MeV are to guide the eye. No additional cuts on the generated incident muon distribution were applied


Fig. 9. Top: the same as Fig. 8, except that muons with large exit angles or positions far from the target crystal have been excluded. Bottom: as for the top panel, except that the muon was required to have an energy of at least 380 MeV on leaving the crystal

where the end faces are co-planar. Solid angle considerations then indicate that there would be about the same number of muons entering or leaving (or both) through the "exposed" sides of the crystal at the ends, which would not trigger a veto in an adjacent crystal, as muons with correct trajectories through the entrance and exit faces; these would deposit up to 26% less mean energy in the crystal than muons with the proper trajectories. The geometry at larger angles is more complicated with a tooth-edged profile, and will not be considered here.

The simulations used the standard GEANT 3.21 package [6] together with programs developed to simulate similar cosmic ray tests for an experiment at PSI [7]. The "target" crystal was defined as a 2.4 cm square (untapered) rod at the centre of a 23 cm thick large (400 cm square) block of lead tungstate. The target crystal was surrounded by eight similar crystals. An event was vetoed when the energy deposit in any one of the eight surrounding crystals exceeded the veto level. In addition, trajectories could be confined with loose geometrical cuts to be approximately correct, such as might be imposed if a CMS muon Drift Tube chamber were mounted below the Supermodule. Simulations were also made with a minimum outgoing energy of 380 MeV, corresponding to the range in 30 cm of iron, to examine whether such a filter before the lower trigger counter could be helpful. The incident momentum spectrum of muons was that measured for vertical cosmic ray muons [4], with a cut-off at 10 GeV/c (removing about 5% of the flux), and no angular dependence. The lead tungstate block was uniformly illuminated at its centre over an area of 10×10 cm, and with the cosmic ray $\cos^2$ azimuthal angular distribution over the range 0 to 20 degrees. For the results presented here 1 million events were generated.

Figure 8 shows the energy deposited in the target crystal with no additional geometric cuts beyond those of the incident distribution, as a function of the assumed veto level. E-out is the maximum energy deposited in one of the surrounding eight crystals. The condition E-out = 0 MeV thus corresponds to muons entering and leaving the target crystal's front and back faces, and without an excursion out of the crystal en route. If E-out was set to 33 MeV it
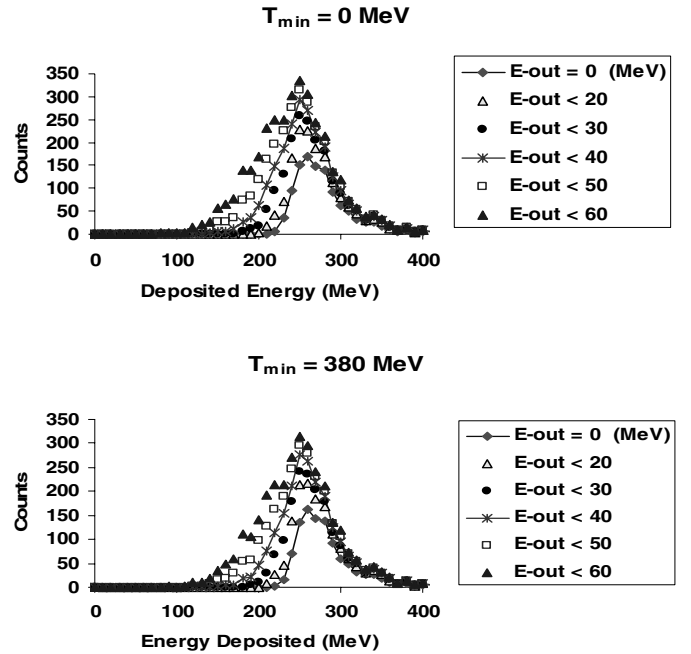
would correspond to the veto being 3 times the rms noise as discussed above. The peak around 75 MeV which grows as the veto level is increased is due to muons traversing the crystal at relatively steep angles and depositing energy in around four of the neighbouring crystals.

Figure 9 shows the same spectra as in Fig. 8, but with the assumption that there is a wire chamber below the Supermodule which is used to remove tracks at steep angles and with exit coordinates well outside the target crystal exit face. The two figures show the spectra without constraint on the outgoing muon energy and with the requirement that it should be at least 380 MeV. There is no obvious significant difference between the two plots.

Figure 10 shows the mean energy of the spectra of Fig. 9 between 100 and 500 MeV, as a function of the veto level in the neighbouring crystals (E-out), expressed as the ratio to that for E-out = 0 MeV. The effect of requiring a minimum of 380 MeV for the outgoing muon is not significant. The slopes of these curves at a veto level around 33 MeV indicates that no great care need be taken to ensure that each channel has an identical veto level, to achieve a precision in the per cent range.

Figure 11 shows the total number of counts between 100 and 500 MeV in the spectra of Fig. 9 as a function of the veto level. For a veto level of 33 MeV the number of counts is nearly double that for E-out = 0 MeV, as expected from solid angle considerations. Together, Figs. 10 and 11 suggest that having a non-zero veto level allows a significant improvement in statistical accuracy with little extra systematic uncertainty. Indeed, further studies may be helpful to ascertain the optimum veto level.

Ratio Mean ch / Mean ch Veto Level = 0 MeV
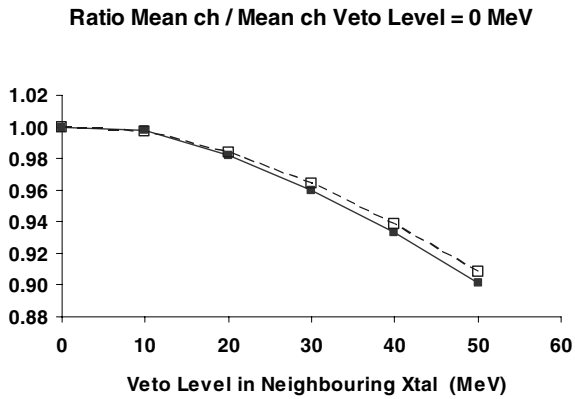
Fig. 10. The mean energy deposited between 100 and 500 MeV as a function of the veto level, divided by that for a veto level of 0 MeV, for the data of Fig. 9. The full line is for all muons and the dashed line for muons leaving the crystal with at least 380 MeV

Counts E = 100 - 500 MeV
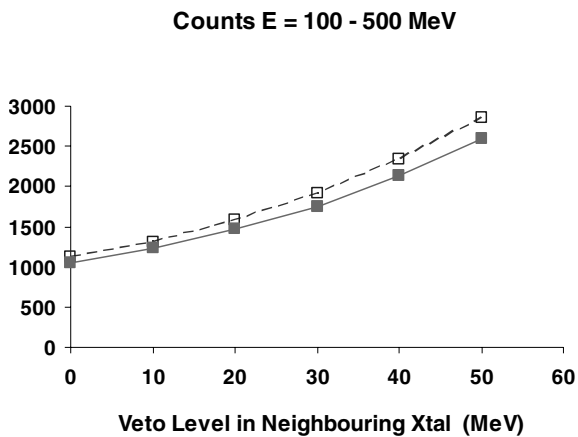
Fig. 11. The number of counts in the spectra between 100 and 500 MeV as a function of the veto level for the data of Fig. 9. The full line is for all muons and the dashed line for muons leaving the crystal with at least 380 MeV

5 APD Reliability and characteristics at high gain

All APDs installed in the CMS ECAL have been powered up to breakdown many times during the screening procedure for acceptance for ECAL [3]. Furthermore, many tests over many years, especially during the development phase, have indicated that the Hamamatsu APD is a very robust device, which survives even accidental gross mistreatment without any change in its electronic characteristics. It is therefore thought unlikely that running all the APDs in the ECAL at gains around 200 for a period of around a week would cause any damage, although it could possibly identify any weak APDs which slipped through the screening. Nevertheless to confirm this, 39 APDs were run at gains between 160 and 320 for 24 days. Their dark currents and their operating voltage for gain 50 as well as their breakdown voltages were measured before and afterwards. There was no measurable change in either the operating or the breakdown voltage of any APD, but the

dark current at gain 50 was reduced for all APDs, by typically 30%, indicating that some remaining small defects may be annealed by running them at raised gain for a period.

All APDs delivered by Hamamatsu were required to be fully depleted at gain 50, which was checked for all APDs upon receipt of their test data. Thus at higher gains there is no change in the capacitance, and the only expected significant changes in the APD characteristics are increased excess noise factor, and voltage and temperature coefficients [8], which become 3, 8% per Volt and -5% per °C respectively at gain 200. However, these changes are not sufficient to impinge on measurements with a Supermodule, as the single crystal test at PSI confirmed.

6 Discussion and conclusions

The results of the tests with a single crystal and of the simulations indicate that it should be possible to obtain intercalibrations of the crystals in ECAL Supermodules with statistical accuracy in the per cent region, in one week.

The results of the test with the single crystal showed a clear signal, with a possible contribution from the nuclear counter effect in line with expectations. The rates were consistent with those expected. The statistical uncertainty for one week of running based on the geometry used in this test would be between 1 and 3% depending on the crystal angle. The test indicated that there does not appear to be a need to have a thick absorber to remove slow cosmic rays from the trigger. There was some evidence of a few per cent increase in signal size at 67 degrees, but the statistical accuracy is poor. A mean APD gain of 250 was used for these tests.

The simulations have indicated that it should be possible to achieve a clean and reliable signal in a Supermodule by using the surrounding crystals as veto counters. The rates with such a configuration would be with significantly higher than if a "perfect" geometrical cut on the trajectories was applied, without a large increase in systematic uncertainty due to possible channel-to-channel variation in the veto level. This relative insensitivity to the precise veto level is important because the read-out electronics feeds the ADC with a scale (for APD gain 200) of 9 MeV per channel. Thus veto levels of either 27 or 36 MeV are probably the only options, and there will be no possibility to fine-tune the level within this step to account for any inherent channel-to-channel variations. The simulations included neither noise nor the nuclear counter effect, but these should not change the main conclusions of these studies. The simulations confirmed that there appears to be no need for a heavy absorber above the lower trigger scintillator. They assumed that a mean gain of 200 would be used for the pair of APDs on a crystal, to avoid individual APDs running at gains over 300.

There will be systematic changes as a function of η in such a test, due to change in the cosmic ray spectrum and to geometrical effects. The pointing geometry leads to the development of a saw-tooth profile at the front and the

back of the detector as η increases. At maximum η on one side of a crystal 15% of its length is then "exposed" at one end, making the veto less effective; at the other end of this crystal the neighbour on the same side projects beyond the end of the crystal by the same amount, providing a more effective veto. Thus in a first approximation there is no net effect on the overall veto effectiveness. On the opposite side of the crystal the situation at the two ends is reversed, again with little net effect. (On the two other sides the adjacent crystals line up as at $\eta = 0$ and so there is no change.) Even if these end effects do not exactly cancel, they should be small compared to the ca 6% shift in the peak position resulting from the veto level effectively exposing 15% of all sides of the crystal at both ends (see Fig 10, with a 40 MeV veto level). We have not explored these effects in more detail, but any systematic error as a function η should be the same for all Supermodules and so should be correctable with a uniform and reasonably smooth function. We have also not explored how useful the signal obtained from crystals at the edges of the Supermodule would be, where three of the eight neighbouring vetoes would be missing, but even if these cannot be intercalibrated properly this would be only a minor drawback.

Another source of possible systematic error is any nonlinearity in the electronics since the effective signal of 1 GeV needs to be extrapolated $1-2$ orders of magnitude to be useful in CMS. Cosmic ray muons generate light in the crystal as a uniformly bright single line passing through it, while electron and photon showers produce light with a very different distribution, which could also introduce systematic differences. However, both of these effects are only significant for an intercalibration to the extent that they vary from channel to channel.

It is proposed to relate the calibration coefficients determined at gain 200 to those at gain 50 by using the actual change in gain measured by the laser monitoring system. This may be checked against the gain curves of each APD measured and supplied by Hamamatsu, but which need to be scaled from 25 °C to the 18 °C to be used in CMS and in the proposed pre-calibrations. Since the laser monitoring system should track changes in the experiment with a precision in the per mil range this ought not to be a significant source of error.

Nevertheless, the best test of the reliability of such an intercalibration will be comparison with results from calibrations using high energy electron beams. Preliminary results of such a comparison for part of a Supermodule near $\eta = 0$ indicate that an accuracy of about 3 % was achieved in less than 2 days of running with a cosmic ray trigger [9]. As a result it is intended that all Supermodules produced while there is no test beam at CERN will be tested and intercalibrated with cosmic rays.

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