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Calibration of the CMS Calorimeters

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Introduction

The calorimeters for CMS have two distinct structures. The electromagnetic compartment (ECAL) consists of a single crystal of PbWO4 which is read out by an avalanche photodiode (APD). The hadronic compartment (HCAL) is a sampling calorimeter where the absorber is brass while the active sampling is done by means of scintillators. The scintillator light is wave length shifted and read out by hybrid photodiodes (HPD).

Neither compartment is "compensating" in that in both cases the calorimetric response to deposited energy is different for electrons and hadrons [1]. Therefore, both devices are intrinsically nonlinear in energy response and have a component of the energy resolution due to this differing response.

Consider the generic case of a response ε to the deposition of energy E in either compartment. In general the energy has an electromagnetic and an hadronic fraction labeled by E_e and E_h respectively.. The calorimeter responds to those two components differently, indicated by the constants e and h respectively. The electromagnetic fraction of the energy deposited is defined to be F_o which is defined in Equation 1. In general the response relative to the incident energy is, $\varepsilon / E = e[F_o + h/e(1-F_o)]$. If we calibrate the response to electrons, then e = 1 by definition.

$$\begin{aligned} \varepsilon &= eE_e + hE_h \\ E_e &= F_o E,\ E = E_e + E_h \end{aligned} \qquad (1)$$

For electrons and photons incident on the calorimeter, F_o =1, and for electron calibration $\varepsilon = E$. For hadrons the neutral fraction at low energies is ~ 1/3, while at very high energies, since the electromagnetic part of the hadronic cascade "freezes out", the fraction becomes one [1]. An approximation to the behavior of the neutral fraction of a hadronic cascade as a function of the energy E of the primary hadron is;

$$F_o = a\log(E) \qquad (2)$$

The response to electrons/photons is then $\varepsilon_e = eE$, while the response to pions (hadrons) is $\varepsilon_h = Eh[1+F_o(e/h-1)]$. Therefore the ratio of the responses to electrons and pions is energy dependent, through the neutral fraction. Hence, a non-compensating calorimeter is inherently nonlinear in that it's energy response is a function of E.

$$e/\pi = \varepsilon_e / \varepsilon_h = (e/h)/[1+F_o(e/h-1)] \qquad (3)$$

The energy for a pion is simply related to the hadronic response of the calorimeter. In the case where the calorimeter is calibrated to electrons, e = 1, the factor is simply the electron to pion ratio.

$$E = \varepsilon_h (e/\pi)/e \rightarrow \varepsilon_h (e/\pi) \qquad (4)$$

Note that the electron to pion ratio is one independent of energy if the calorimeter is compensating, e = h. Note also that the average value of the neutral fraction is known but that there are hadron shower by shower fluctuations, indicated by dF_o . Those lead to errors in the measurement of energy even though the calorimeter is otherwise perfect.

$$d\varepsilon = Eh(e/h-1)dF_o \qquad (5)$$

Note that, if the calorimeter is compensating, e = h, fluctuations in the neutral fraction do not lead to errors in the measurement of the energy.

Calibration Techniques

Let us consider the calibration of the hadronic compartment first. The relevant techniques are described in a comprehensive article describing the CMS HCAL test beam data [2]. For the hadronic calorimeter the ECAL compartment was removed and the HCAL was illuminated first with electrons from a prepared test beam. The HCAL was found to be quite linear in it's response to electrons of different energies.

The HCAL compartment was then illuminated with pions of several different energies. Since the brass/scintillator calorimeter is not compensating the response was found to be non-linear. Data on the linearity of the device is shown in Figure 1. For pions interacting only in HCAL, the device has an electron to pion ratio between 92% and 100% for energies between 20 and 300 GeV.

These data are normalized such that the response is equal to the beam energy at for 300 GeV. The relevant plot is for pions interacting in HCAL only, because, in fact, these data were taken with ECAL in front of HCAL after the electron response of the HCAL had been measured separately.

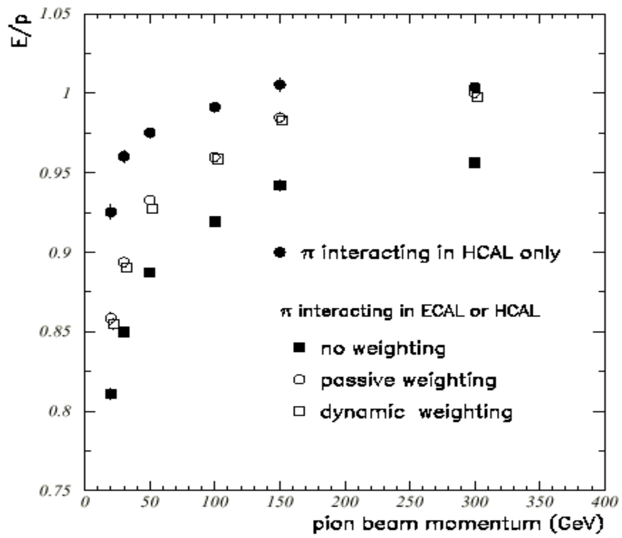

Figure 1: The response of the HCAL to pions of a given momentum in a test beam. The quantity plotted is the energy response divided by the beam energy (equal to the electron response assuming a linear calorimeter for electromagnetic energy deposits).

The energy in the ECAL compartment for 300 GeV incident pions is shown in Figure 2. Clearly there is a substantial fraction of events where the pion does not interact in the ECAL compartment. This implies that HCAL can be re-calibrated later, in situ, when the ECAL is installed in front. Thus, the HCAL compartment can be monitored during the course of CMS using incident tracks momentum analyzed by the tracking system.

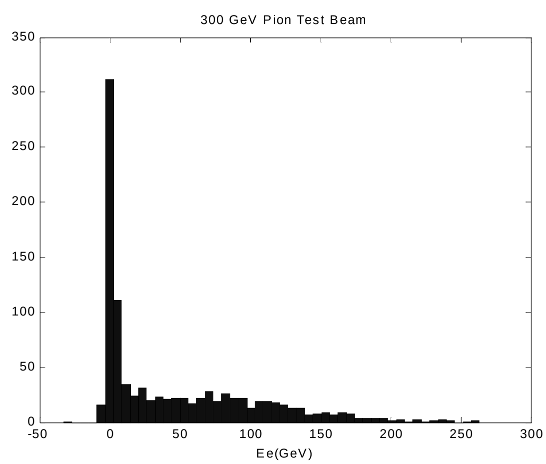

Figure 2: Energy in the ECAL compartment for 300 GeV pions incident on the ECAL + HCAL.

Data on the energy resolution of the HCAL are shown in Figure 3. Note that the best resolution occurs for pions interacting in HCAL alone. As will be shown the non-linearity of the two different compartments with different e/h values induces an additional energy error. The red dots are the final result when this effect is alleviated by the technique discussed below. Clearly, we essentially fully restore the behavior to that of pions interacting in HCAL only.

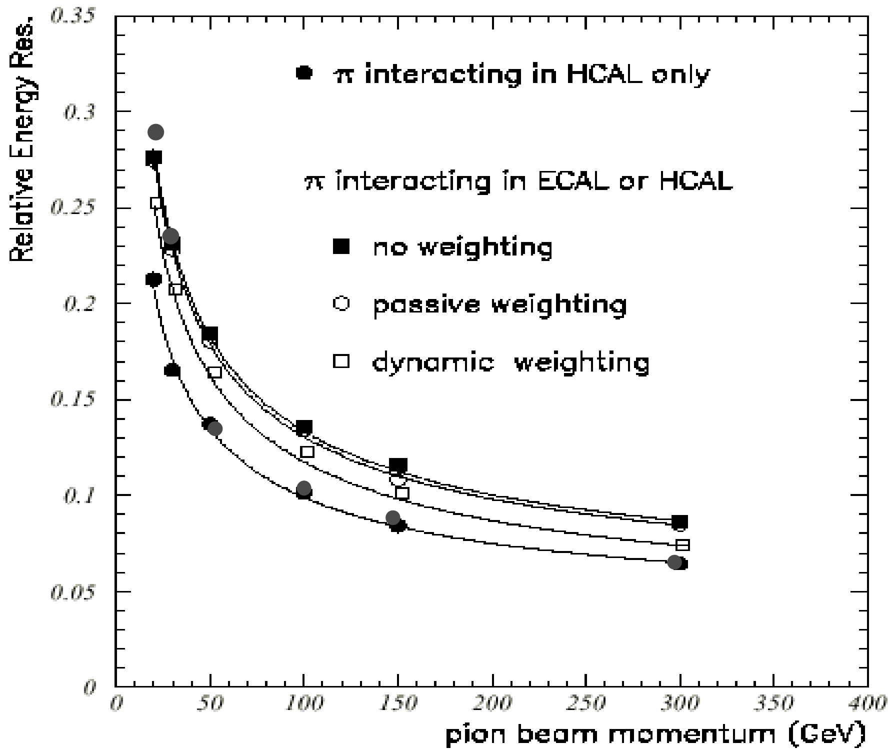

Figure 3: Data taken on the fractional energy resolution of the HCAL. The HCAL response by itself is indicated by the data points where the incident pion did not interact in the ECAL compartment in front of the HCAL.

The pion response of the HCAL was used then to extract the e/h value of the HCAL compartment. Basically Equation 3 was used with the parametrization for the neutral fraction given above to fit the pion data to e/h. The results are shown in Figure 4. The data are clearly consistent with the hypothesis if e/h = 1.39 and Fo = 0.11 * ln(E).

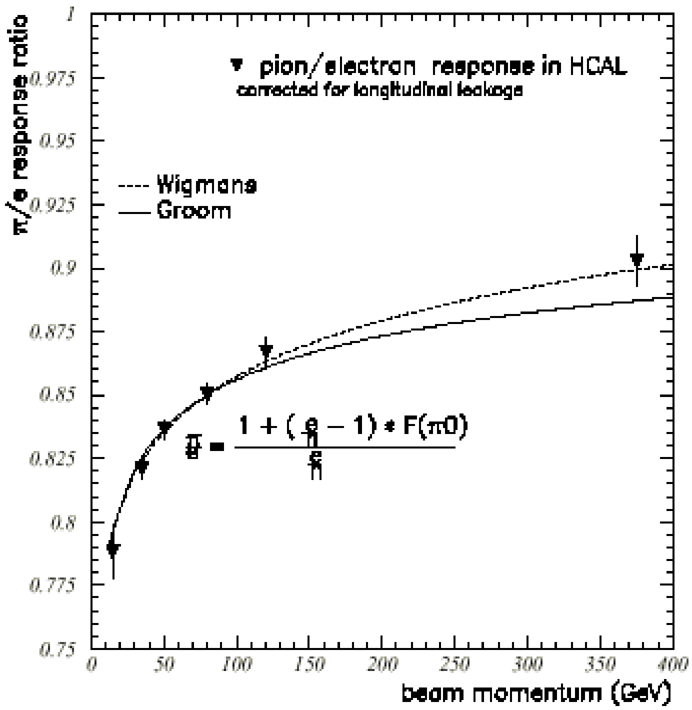

Figure 4: HCAL pion energy response (mean) as a function of test beam energy and the fit to that response using e/h = 1.39. Note that the data shown here is normalized such that the pion to electron response at 300 GeV is ~ 0.90 and not = 1 as it was in Figure 1.

The ECAL is a linear device. Data taken in the test beam with an ECAL followed by the HCAL are shown in Figure 5 for an incident electron beam. Note that there are some hadrons in the beam. Since the ECAL crystals are more than 20 radiation lengths deep, we calibrate the ECAL to electrons by taking the energy in the crystal array to be 100 GeV with an electron beam of 100 GeV incident. In what follows the calibration of both ECAL and HCAL is done with electrons. For the HCAL, the pion response at 300 GeV is then ~ 0.91 with respect to the electron response.

Clearly, we also need e/h for the ECAL in order to complete the calibration procedure. At first blush this seems to be impossible because the ECAL is only about one interaction length deep. Therefore, on average only a small fraction of the hadronic shower will be deposited in the ECAL. Viewed this way, we would need crystals ~ 10 times deeper in order to contain the pionic shower completely if we wanted to measure the pion response of ECAL. Fortunately, this is not strictly necessary. Data for 300 GeV incident pions is shown in Figure 6.

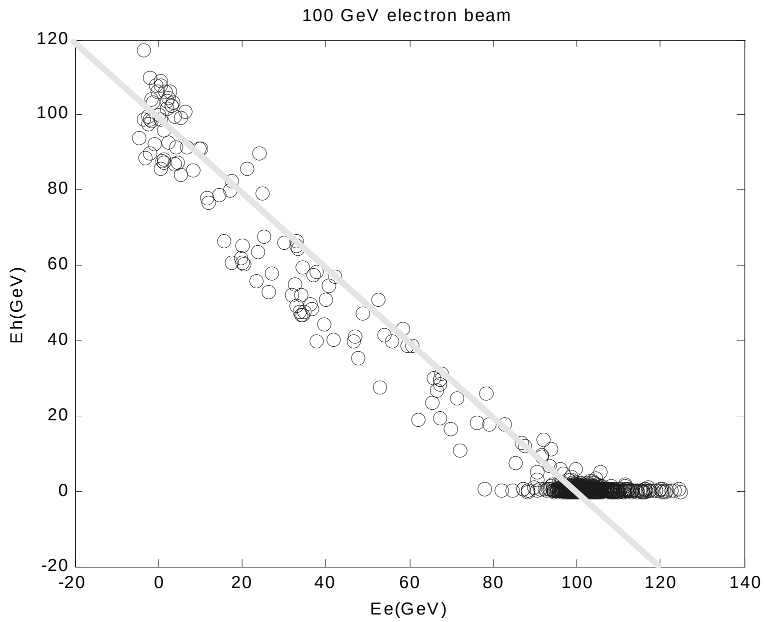

Figure 5: Data on the ECAL and HCAL response to a beam of 100 GeV electrons. The line indicates the response expected for a linear calorimeter. Aside from the pion contamination in the beam, the full beam energy is deposited in ECAL.

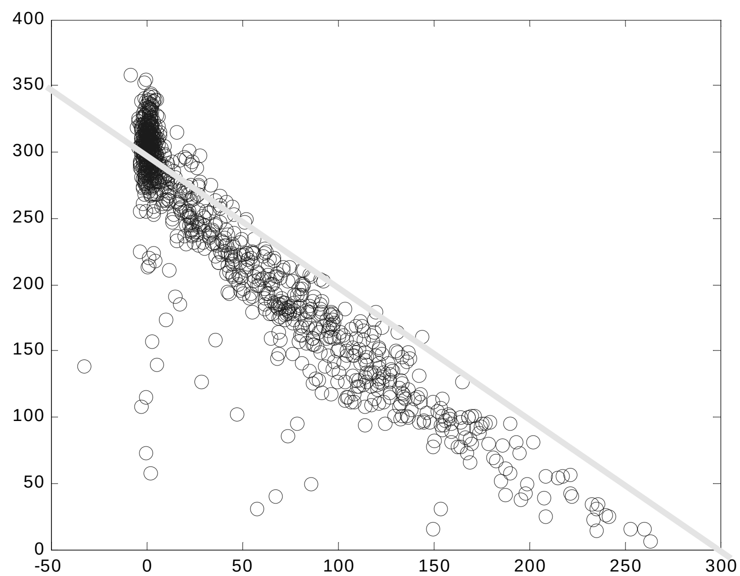

Figure 6: Data on the ECAL and HCAL response to a beam of 300 GeV pions. The line indicates the response expected for a linear calorimeter. Clearly, there is a mismatch in e/h between the 2 compartments. This mismatch projected onto the total energy response induces additional error.

The data shown in Figure 6 indicate the problems that exist when we have two compartments both of which are non-compensating. Although the pions which deposit almost all their energy in HCAL are approximately centered at the beam energy, the combined device is quite non-linear. Since the mean of the response depends then on the fraction of energy deposited in ECAL, we have another error caused by the fluctuation in that fraction. Note that this data is normalized such that pions interacting only in HCAL have 300 GeV response for a 300 GeV beam (see Figure 1).

In order to remove the error due to the different e/h response in the different compartments we first need to measure e/h in ECAL since we clearly need to correct the ECAL response for pions interacting in ECAL. If we simply choose pionic events with a substantial energy in the ECAL and if we have previously calibrated HCAL, then we can determine the e/h for the ECAL. The data shown in Figure 6 for 300 GeV pions indicate that these types of pionic interactions are relatively rare.

Consider the ECAL and HCAL compartments. We treat them as independent objects and sum their energies, E_E, E_H respectively, to obtain the pion energy. The measured response of ECAL and HCAL to pions is $\varepsilon_E, \varepsilon_H$ respectively. We assume both compartments are calibrated to electrons, $e_E = e_H = 1$.

$$\begin{aligned} \mathrm{E} &= \mathrm{E_E} + \mathrm{E_H} \\ \mathrm{E} &= (\mathrm{e}/\pi)_\mathrm{E}\,\varepsilon_\mathrm{E} + (\mathrm{e}/\pi)_\mathrm{H}\,\varepsilon_\mathrm{H} \end{aligned} \tag{6}$$

The HCAL e/h ratio is easily determined. Equation 7 simply indicates in symbols what was shown in Figure 4 above. Note that the neutral fraction is evaluated using the energy response in the appropriate compartment. In what follow we make the first approximation, E ~ ε, which is sufficient given the logarithmic dependence of the neutral fraction on the energy.

$$\begin{aligned} &\mathrm{ECAL/HCAL\ calib\ to\ electrons} \\ &(\mathrm{e/h})_\mathrm{H}\ \mathrm{from\ mip\ in\ ECAL\ and}\ (\mathrm{e}/\pi)_\mathrm{H} \\ &(\mathrm{e/h})_\mathrm{H} = (\mathrm{e}/\pi)_\mathrm{H}(1-\mathrm{F_o})/[1-\mathrm{F_o}(\mathrm{e}/\pi)_\mathrm{H}] \\ &(\mathrm{e/h})_\mathrm{H} = 1.39 \end{aligned} \tag{7}$$

The energy prepared test beam, E_{beam}, and the HCAL calibration allows us to use a "beam constraint" and to correct the response of the HCAL event by event in determining E_H, $E_H = \varepsilon_H (e/\pi)_H$, $F_{oH} \sim 0.11[\ln(\varepsilon_H)]$.

$$(\mathrm{e}/\pi)_\mathrm{E} = [\mathrm{E_{beam}} - \mathrm{E_H}]/\varepsilon_\mathrm{E} \tag{8}$$

The event by event distribution of the electron to pion ratio for 300 GeV incident pions which deposit more than 100 GeV energy in ECAL is shown in Figure 7. The mean is ~ 1.225 and there is a substantial width, r.m.s ~ 0.15 caused by the fluctuations in the neutral fraction quoted above. The mean will be corrected, but the fluctuations are not redeemable and will remain.

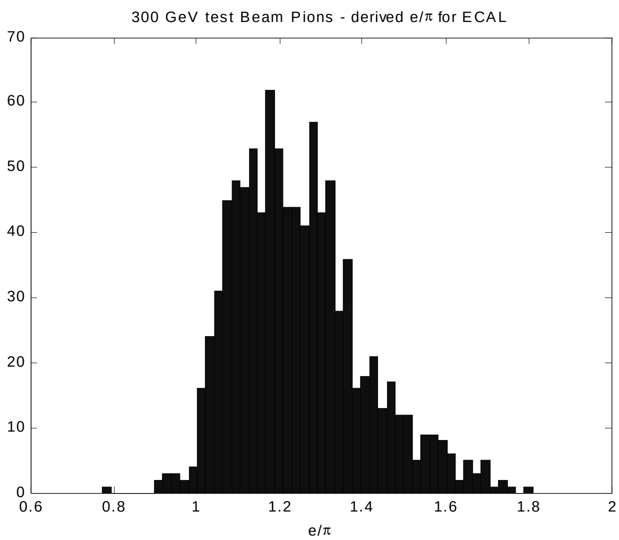

Figure 7: Derived value of the electron to pion ratio for the ECAL compartment for 300 GeV pion events which deposit > 100 GeV in the ECAL compartment.

The expected value of the mean electron to pion ratio at this energy is 1.20 for e/h in ECAL of 1.6 since the mean energy in this case is 146 GeV in ECAL, and thus the mean neutral fraction is ~ 0.548. The spread in the electron to pion ratio due to fluctuations in the neutral fraction is;

$$d(e/\pi) = -(e/h)/[1+F_o(e/h-1)]^2 \, dF_o(e/h-1) \qquad (9)$$

For the data shown in Figure 7, the sensitivity is $\sim d(e/\pi) = -0.55 dF_o$.

Results on Linearity and Resolution

Test beam data was taken at 20, 30, 50, 100, 150 and 300 GeV. Using the now determined value of e/h for ECAL that data is corrected using Equation 6 and determining the neutral fraction for ECAL and HCAL event by event. The result for 300 GeV pions is shown in Figure. 8. Note that the two compartments now make an overall linear device. Clearly, the energy resolution will then decrease compared to the calibration procedure shown in Figure 6. Data for a beam energy of 20 GeV are shown in Figure 9. Note that, in this case a larger energy fraction appears in ECAL and therefore the correction to the ECAL compartment is more important. The negative values of the ECAL energy have to do with experimental problems with signal readout noise.

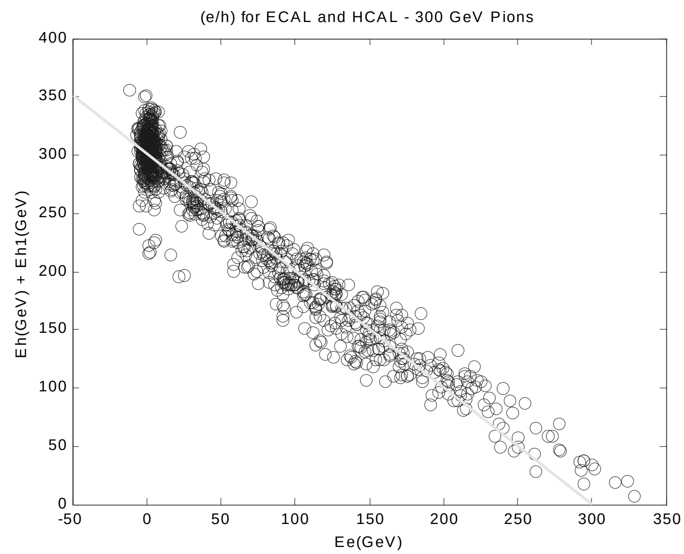

Figure 8: Data for 300 GeV pions using the determination of e/h for both the ECAL and HCAL compartments and correcting the response for the electron to pion ratio in both compartments event by event.

The sum of the energies of the two compartments after correction is shown in Figure. 10. The sample mean and r.m.s. are indicated for each of the data sets with a distinct energy. The distributions are quite Gaussian. Fits were performed to the data and the resulting Gaussian mean and standard deviation were essentially the same as the sample mean and r.m.s.

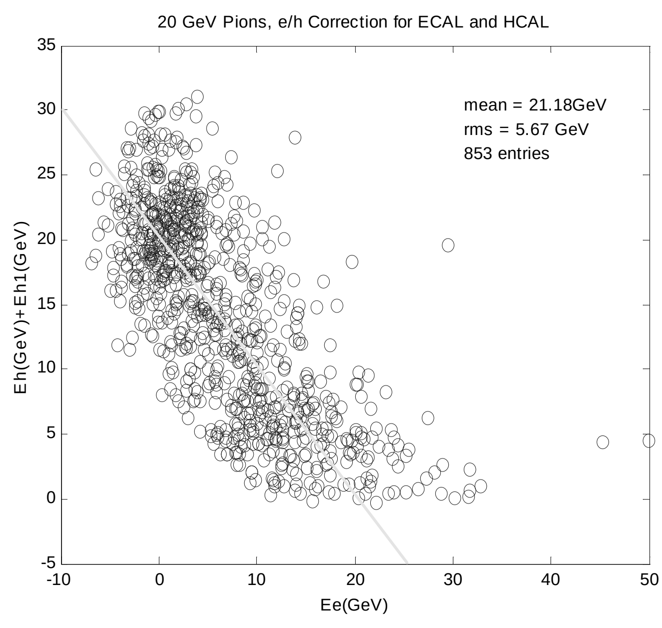

Figure 9: Data for 20 GeV pions using the determination of e/h for both the ECAL and HCAL compartments and correcting the response for the electron to pion ratio in both compartments event by event. The line indicates the response of a linear overall device.

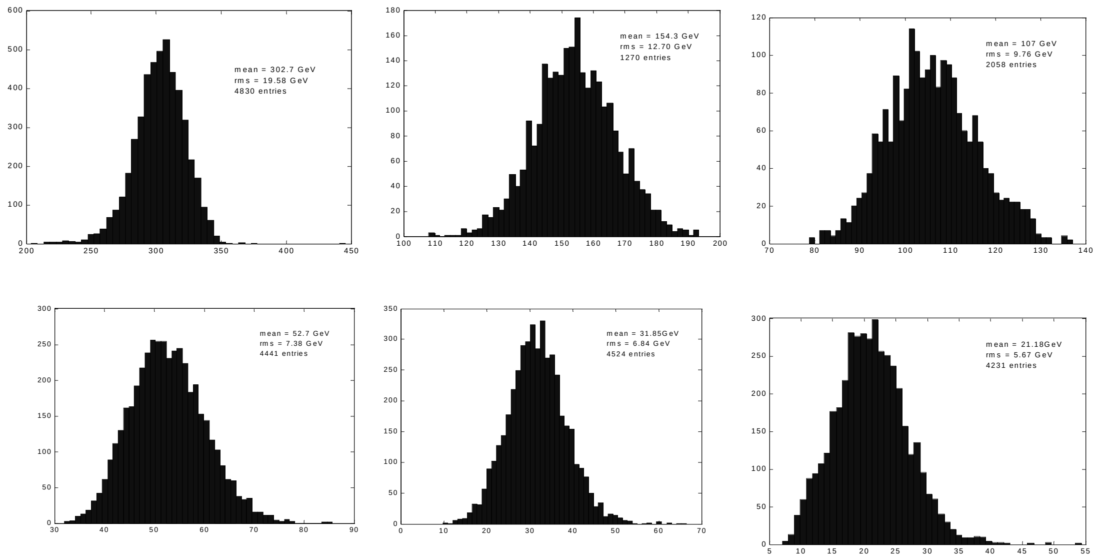

Figure 10: Distributions of the sum of the corrected energies for ECAL plus HCAL for incident pion beams of 20, 30, 50, 100, 150, and 300 GeV.

The sample means for the 6 pion energies are plotted in Figure 11. The linearity is rather good. In comparison, for events with interactions everywhere in the compartments, there is a ~ 15% variation in energy response from 20 to 300 GeV – see Figure 1. In contrast there is only a ~ 8% variation in the energy response contained in the data of Figure 10. This is comparable to the behavior of HCAL by itself – see Figure 1.

The sample r.m.s for the 6 pion energies are plotted in Figure 12 as a function of the pion energy. The line represents a resolution, $dE/E = 1.1/\sqrt{E}$. This behavior is considerably better than that reported previously [2]. In fact, the present resolution has been plotted in Figure 3 for comparison. For 50 GeV and above the resolution has been restored to the value obtained for a homogeneous calorimeter composed of HCAL alone. Below 50 GeV the resolution is somewhat worse. However, the impact of ECAL readout noise on the resolution has neither been quantified nor subtracted.

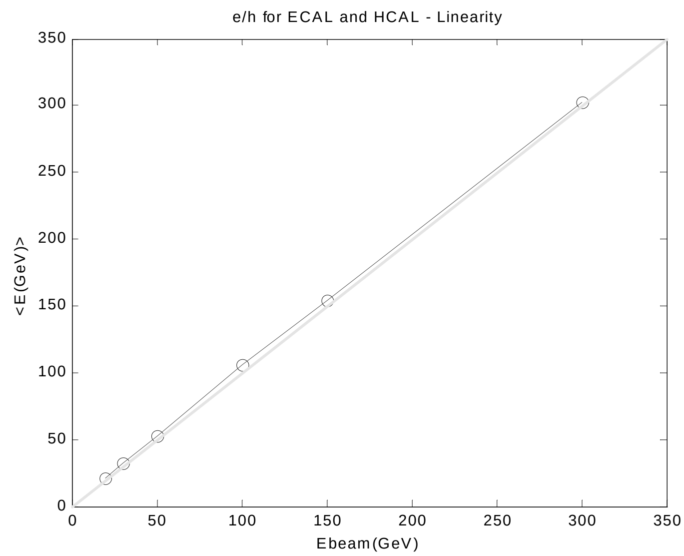

Figure 11: Mean of the energy detected in ECAL + HCAL after correction for the e/h of the two compartments. The line is a linear detector response.

Note that the baseline calibration is to set ECAL to electrons and HCAL to some energy for pions interacting only in HCAL. It is clear that this procedure introduces non-linearity and degraded energy resolution. However, it is safe in that the ECAL compartment responds accurately to electrons and photons. For jets, we have outlined an alternate procedure. Implementing that procedure requires that the energy deposit in both the ECAL and HCAL be used to determine the event by event electron to pion ratio. Clearly, this works for single particles. However, for a complex interaction in CMS one must decide if a localized energy deposition is a photon/electron or a pion/hadron. This identification requires fine transverse segmentation. The luminosity should be such that the CMS transverse towers are only sparsely occupied. In a jet environment, where the core is densely occupied, it remains to see if this technique is applicable

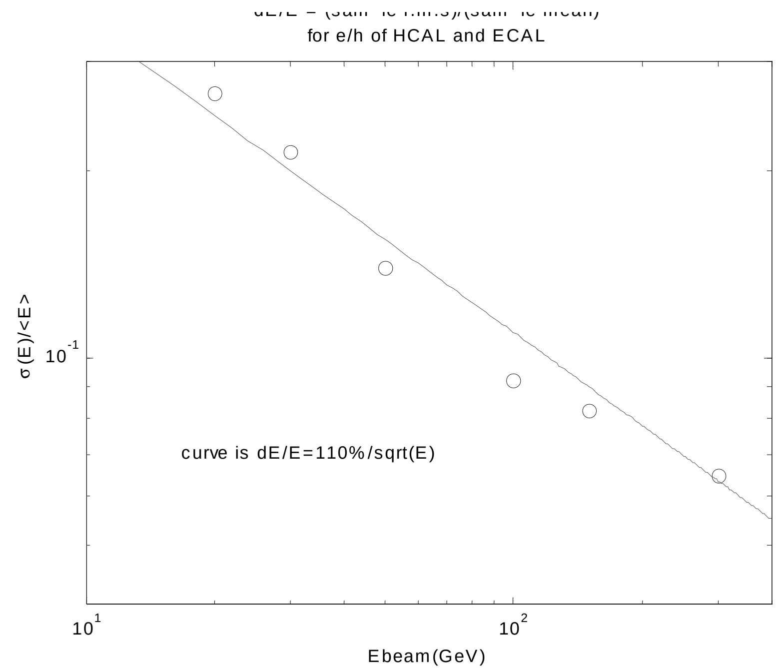

Figure 12: Sample r.m.s of the energy distribution divided by the mean for pions detected in ECAL + HCAL after correction for the e/h of the two compartments. The line represents a stochastic coefficient of 110%.

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References:

1. C. Fabjan paper in “Experimental Techniques in High Energy Physics” Ed. T. Ferbel Addison-Wesley Pub. Co. (1987).

2. Nucl. Inst. & Meth. in Physics, 75-100, A(457), 2001.