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Dynamic Range of the CMS HB and HE Electronics

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1 Introduction

The wide range of particle energies produced at the LHC requires that the CMS HCAL detectors measure values much larger than have been attempted before at colliders. At the same time, the detectors must maintain equivalent capabilities at the lower, more typical energies of current colliders. The electronics for the HCAL detectors must be able to measure signals as small as a minimum-ionizing muon, and as large as the showers produced by very energetic hadrons. In order to design the electronics for the HB & HE detectors, it is necessary to determine the maximum energy that a single channel in each detector should be expected to observe.

The physics process that produces the largest-energy particles at the LHC is not obvious. Two leading candidates are jets from the QCD production of quarks, and taus from the decay of new gauge bosons. In both cases, the amount of energy manifested in charged hadrons is always smaller than the original particle energy, so the amount deposited in a single tower of an HCAL detector is very often much less. To get a more accurate determination of the maximum energy per tower, therefore, it is necessary to use a Monte Carlo simulation of the physics process and detector.

In this note, we describe a study of the maximum tower energies expected in the CMS HCAL detectors from the QCD production of 2 jets at the LHC. We have chosen this process over the others since the physics can be simulated with some confidence, and the expected number of events is largest [1]. Also, one of the priority goals of CMS is to search for quark sub-structure at the highest jet energies available. Most probably, the two-jet process will produce the highest energy hadrons if no new physics beyond the Standard Model appears, and thus could be the basis for specifying the dynamic range of the HB & HE electronics.

2 Segmentation of the HB & HE Detectors

The barrel hadron calorimeter (HB) covers the pseudo-rapidity range ($|\eta| < 1.5$), while the endcap calorimeter (HE) covers the range ($1.5 < |\eta| < 3.0$). The barrel and endcap detectors are divided into towers in pseudo-rapidity and azimuth ($\Delta\eta \times \Delta\phi = 0.087 \times 0.087$).

The longitudinal segmentation of the HB & HE detectors is summarized in Table 1.

	HB	HE
EM	1.1	1.1
HAC1	0.11	0.5
HAC2	5.8	9.5
HO	3.5	0.0
Total	10.51	11.1

Table 1: Depth in interaction lengths of the HB & HE detectors

Each HCAL tower in the HB calorimeter is divided longitudinally into three compartments: HAC1, HAC2, and HO. The first compartment radially is HAC1, and consists of only a few layers of scintillator and absorber. Our study assumed the depth of HAC1 was 0.11 interaction lengths (the EM calorimeter was assumed to 1.1 interaction lengths). The main compartment of HB is HAC2, consisting of about 20 layers. Our study assumed the depth of HAC2 was 5.1 interaction lengths. The last compartment in HB is the outer detector (HO), located outside the CMS solenoid's coil. Our study assumed the depth of HO was 3.5 interaction.

The HE calorimeter is divided longitudinally into only two compartments: HAC1 and HAC2. Our study assumed the depth for the EM compartment was the same as for the HB calorimeter, but was 0.5 interaction lengths for HAC1 in the endcap, and 9.5 interaction lengths, for HAC2.

3 The Montecarlo Simulation

The study was conducted using the Montecarlo program ISAJET 7.16 to generate two-jet events with $P_T > 2.5 \text{ TeV}$, for the HB and HE detectors, at the center-of-mass energy of 14 TeV . The production cross section for this high P_T process provided by ISAJET was 11 fb . For an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$, collected for one LHC year (10^7 seconds), the integrated luminosity is 10^5 pb^{-1} . Thus, for a run of one year, CMS should expect about 1100 two-jet events with $P_T > 2.5 \text{ TeV}$.

A parameterized simulation of the CMS detector was used to estimate the amount of energy deposited in each tower of the calorimeters. This fast simulation has been used before to study other aspects of the CMS hadron calorimetry [2]. It tracks stable particles in the CMS magnetic field (which is assumed to be uniform) up to the calorimeter. The energy resolution is simulated by Gaussian smearing and is summarized in Table 2.

		$ \eta < 1.5$	$1.5 < \eta < 2.6$	$2.6 < \eta < 3.0$	$3.0 < \eta < 5.0$
EM	a	0.02	0.02	0.36	1.55
	b	0.005	0.005	0.03	0.01
HCAL	a	1.17	1.17	1.17	2.84
	b	0.066	0.066	0.066	0.08

Table 2: Energy Resolution of the calorimeters (in GeV)

$$\left(\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b\right)$$

The longitudinal parameterization of the hadron shower is given by [3]:

$$\begin{aligned} dE &= \frac{E_0}{\Gamma(a)} [f_0 \Gamma(a, bt) d(bt) + (1 - f_0) \Gamma(a, b'D) d(b'D)] \\ &= \frac{E_0}{\Gamma(a)} f_0 [(bt)^{a-1} e^{-bt} d(bt)] + \frac{E_0}{\Gamma(a)} (1 - f_0) [(b'D)^{a-1} e^{b'D} d(b'D)] \end{aligned}$$

where f_0 is the fraction of the shower's energy that goes into electromagnetic energy, t is the depth in units of radiation lengths, and D is the depth in units of nuclear interaction lengths. The constants are:

$$a = 0.62 + 0.32 \ln E_0 \quad b = 0.22 \quad b' = 0.91 - 0.024 \ln E_0$$

Although the electromagnetic fraction (from π^0 's) goes up as a function of the energy of the shower, we use the fixed value $f_0 = 0.46$ from ref. 3.

Since this fast program does not include a full simulation of the shower development, we must use an approximation to calculate the energy deposited in each longitudinal compartment. We first consider the depth at which the initial interaction of the hadron shower occurred. If the hadron first interacted in the HO, then the energy in the other compartments is obviously zero. If the hadron first interacted in HAC2, then to obtain the energy in the HO, we first calculate the energy deposited in HAC2. Next, we assume a new depth for HAC2 that includes the depth of

HO, and finally assign the difference of these two determinations to be the energy deposited in the HO compartment. Similarly, we use the same subtraction scheme for initial interactions in HAC1 and the EM calorimeter. The ratio of electron to pion response was assumed to be:

$$\frac{e}{\pi} = \frac{A}{1 + B \cdot \ln E \cdot (A - 1)}$$

where $A = 1.49$ and $B = 0.15$.

The transverse shower shape is modeled assuming an RMS width of 3.4 cm for the hadronic component of the shower, and 1.2 cm for the electro-magnetic. The lateral parameterization of the hadron shower is given by the function [3]:

$$f(d) = 0.7 e^{-\frac{|d|}{2}} + 0.3 e^{-\frac{|d|}{3}}$$

where d is the distance from the point of incidence in centimeters.

4 Results

For the study, we generated 20,000 two-jet events with $P_T^j > 2.5 \text{ TeV}$, which represents about 20 years of LHC running at an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$. The results of the study are summarized in Figures 1-6. Figure 1 is a histogram of the energy deposited in each tower of HAC1 for the barrel hadron calorimeter.

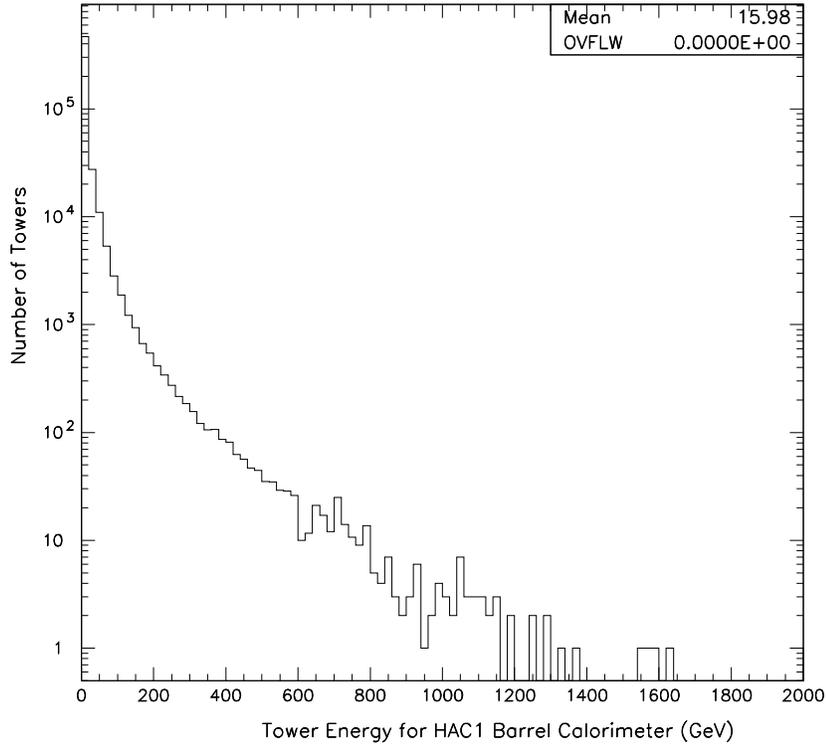


Fig. 1

Only if the energy in the tower exceed 100 MeV is the tower included in any of these histograms. We note that even for this extremely long running period, there is never more than 2 TeV of energy deposited in any tower of HAC1 for the barrel hadron calorimeter.

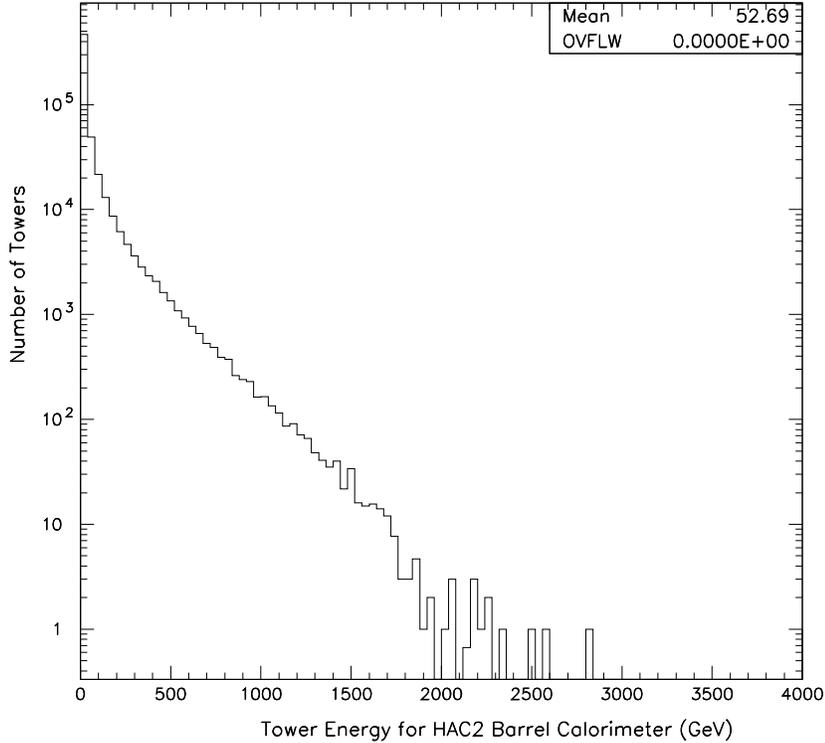


Fig. 2

A similar plot can be found in Figure 2 for HAC2 of the barrel calorimeter. We again see that the energy never exceeds 3.5 TeV in any single tower of HAC2. The results for HAC1 and HAC2 are similar despite the disparity in the number of layers in the two compartments. This can be explained by the large shower fluctuations that can occur in hadron calorimeters. (Sometimes most of the energy is deposited in only a few layers of the calorimeter.) However, the average energy in HAC2 of the barrel calorimeter is considerably larger than HAC1, as we would expect from the larger number of layers and larger number of interaction lengths.

Figure 3 shows the sensitivity to the parameterization of the transverse development of the hadron shower. The solid histogram is the same as Figure 2, while the dashed curve is the same but with the modeling of the transverse shower shape turned off. There are more events at larger tower energies, but they still do not exceed about 3.5 TeV.

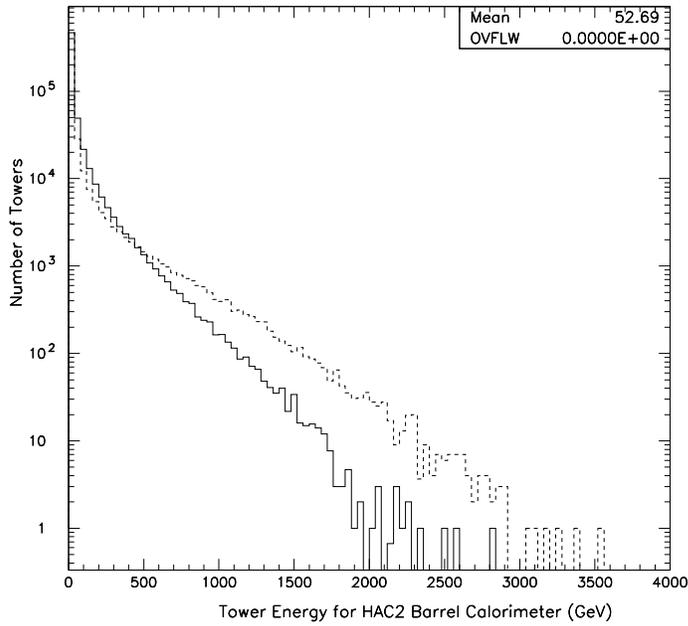


Fig. 3

Figure 4 shows the same plot for the HO of the barrel hadron calorimeter. As expected from the smaller number of interaction lengths and location of this longitudinal compartment, the energy deposited in a tower is often less than for HAC1 and HAC2. Nevertheless, sometimes hadrons will not interact in the EM or HAC1 compartments, and interact deeply into HAC2, or even penetrate all the way to the HO of the barrel calorimeter before they interact, depositing a large amount of energy. From this study, we can see that even for a long CMS run, the energy in the HO of the barrel calorimeter hardly exceeds 1 TeV.

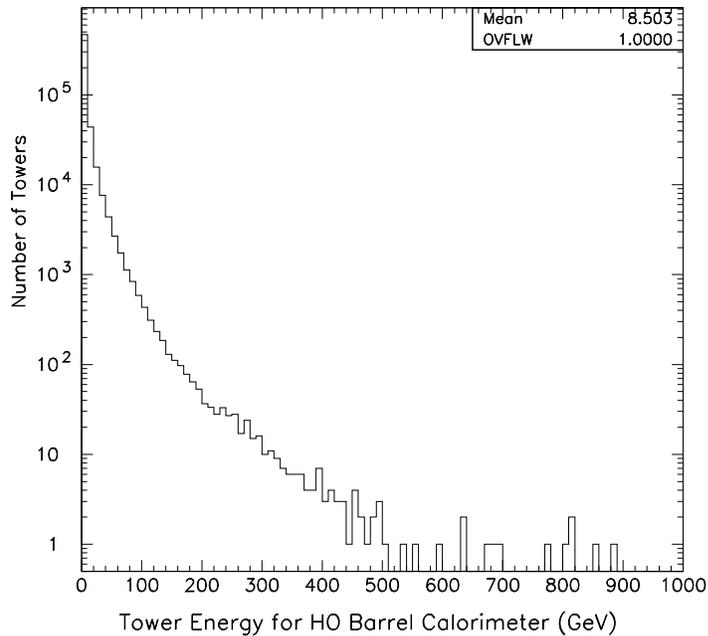


Fig. 4

For the endcap hadron calorimeter, the two-jet process used in this study produces fewer events. This is evident in Figures 5 & 6, histograms of the tower energies for HAC1 and HAC2 of the endcap hadron calorimeter. It is not obvious that this is the determining process to set the maximum energy for this calorimeter. However, until a better candidate is established, this study should provide the current basis for specifying the dynamic range in the endcap hadron calorimeter.

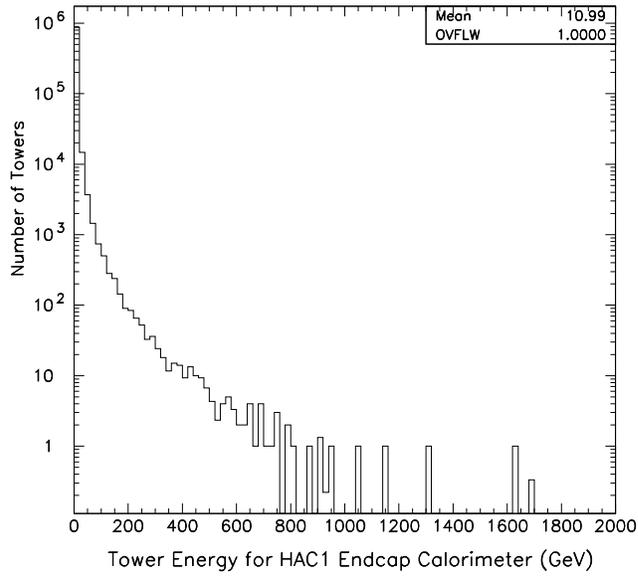


Fig. 5

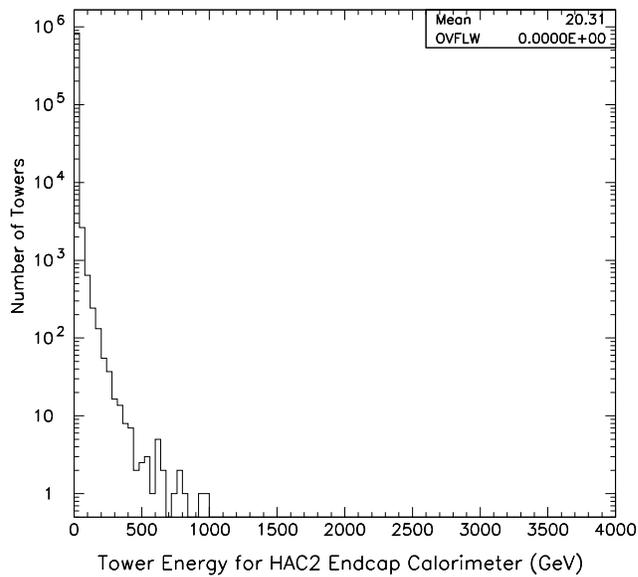


Fig. 6

To complete this part of the study, Figures 7 & 8 are histograms of the energy deposited in each tower of the EM calorimeter for the barrel and endcap detectors. The segmentation of the barrel and endcap EM calorimeters was assumed to be 6x6 EM towers per HCAL tower.

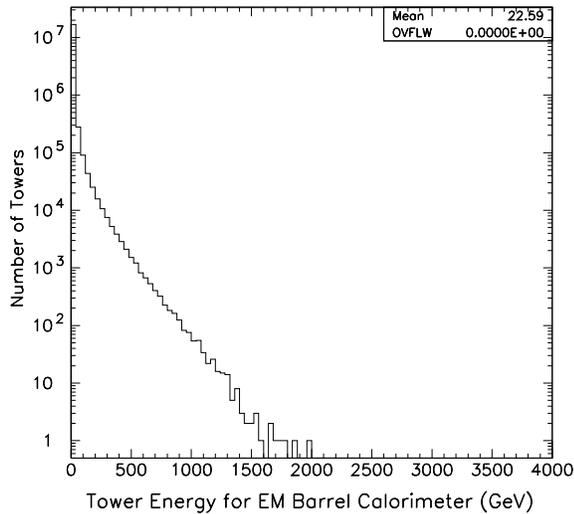


Fig. 7

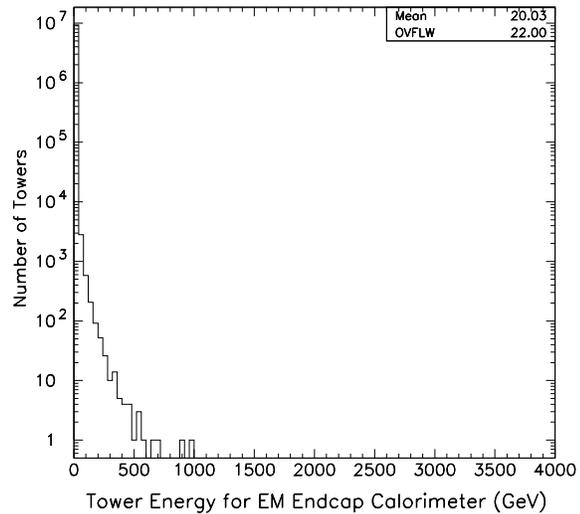


Fig. 8

5 Conclusions

This study shows that the maximum tower energy from the QCD production of two jets for the expected lifetime of CMS at the LHC should never exceed 3.5 TeV in any compartment of the barrel or endcap hadron calorimeter. These results can form the basis for specifying the dynamic range of the HB & HE electronics.

The current proposal for the front-end electronics for the barrel and endcap hadron calorimeter includes an auto-ranging QIE device [4]. This device could provided as many as 7 energy ranges or more (see Table 3). Since it would be easier to use a single type of electronics for each longitudinal compartment of both the barrel and endcap calorimeter, it is important to know whether this is feasible in terms of the required dynamic range. This study shows that a single device with a maximum energy range up to 3.5 TeV would accommodate both the barrel and endcap hadron calorimeters.

We would like to thank the CMS Simulation Group at Fermilab for useful discussions on these results, and in the preparation of this note.

Range	Current	Min E	Max E	#bins	bin size
1	I	0.0	2.8	28	0.1
2	I/3	2.8	11.2	28	0.3
3	I/9	11.2	36.4	28	0.9
4	I/27	36.4	112.0	28	2.7
5	I/81	112.0	338.8	28	8.1
6	I/162	338.8	792.4	28	16.2
7	I/324	792.4	1699.6	28	32.4
8	I/648	1699.6	3514.0	28	64.8

Table 3: An example of the QIE ranges (in GeV)

References

- [1] For a luminosity of 10^5 pb^{-1} , only a few $\tau\nu$ events are expected from a W' -boson with mass $> 6 \text{ TeV}$. Since the τ typically gets half the energy of the W' , and since the hadrons coming from the decay of the τ typically get less than half the energy of the τ , we believe the maximum tower energy in the hadron calorimeter from this process will always be less than from the two-jet process (see M.C. Cousinou, ATLAS-PHYS-No-059, December 1994).
- [2] I. Gaines et al, "Missing E_T plus Jets Signals for Supersymmetry in the CMS Detector at the LHC", Fermilab-FN-642, CMS-TN/96-058
- [3] R.K. Block, T Hansl-Kozanecka and T.P. Shah, Nucl. Instr. and Meth. 186, 533(1981); W. Wu et al, Fermilab-FN-579, January, 1992.
- [4] R.J. Yarema et al, Nucl. Instr. and Meth. A360, 150(1995)