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Effect of Zero Suppression on Cosmic Ray Muon Energy Spectra in HCAL

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Abstract

In order to reduce event size during LHC running, it will be necessary to suppress readout of HCAL channels with energy below certain threshold. However, Zero Suppression (ZS) introduces bias to reconstructed energy in HCAL. In this note we evaluate and quantify effect of ZS (with firmware version 5A) on distribution of reconstructed energy deposition of cosmic ray muons. We conclude that cosmic ray data must be taken without zero suppression in order to have an unbiased sample, which can used to validate the HCAL energy calibration and to evaluate the effect of different possible options for zero suppression on HCAL calibration, muon ID and muon isolation algorithms.

1. Introduction

In order to reduce event size during LHC running, it will be necessary to suppress the readout of HCAL channels which have energy deposition below certain threshold.

However, Zero Suppression (ZS) will necessarily introduce a certain bias in the distribution of muon energy deposition as reconstructed in HCAL. In particular, HCAL energy spectra of cosmic ray muons are sensitive to such a bias. It is important therefore to quantify this effect and to understand to what extend one can use data collected with HCAL readout in ZS mode to validate the absolute scale, the relative energy calibration of Hadron Calorimeter, muon ID algorithms, and muon isolation algorithms.

In this note we evaluate the effect of ZS (with firmware version 5A) on the shape of the energy spectra of cosmic ray muons in HCAL.

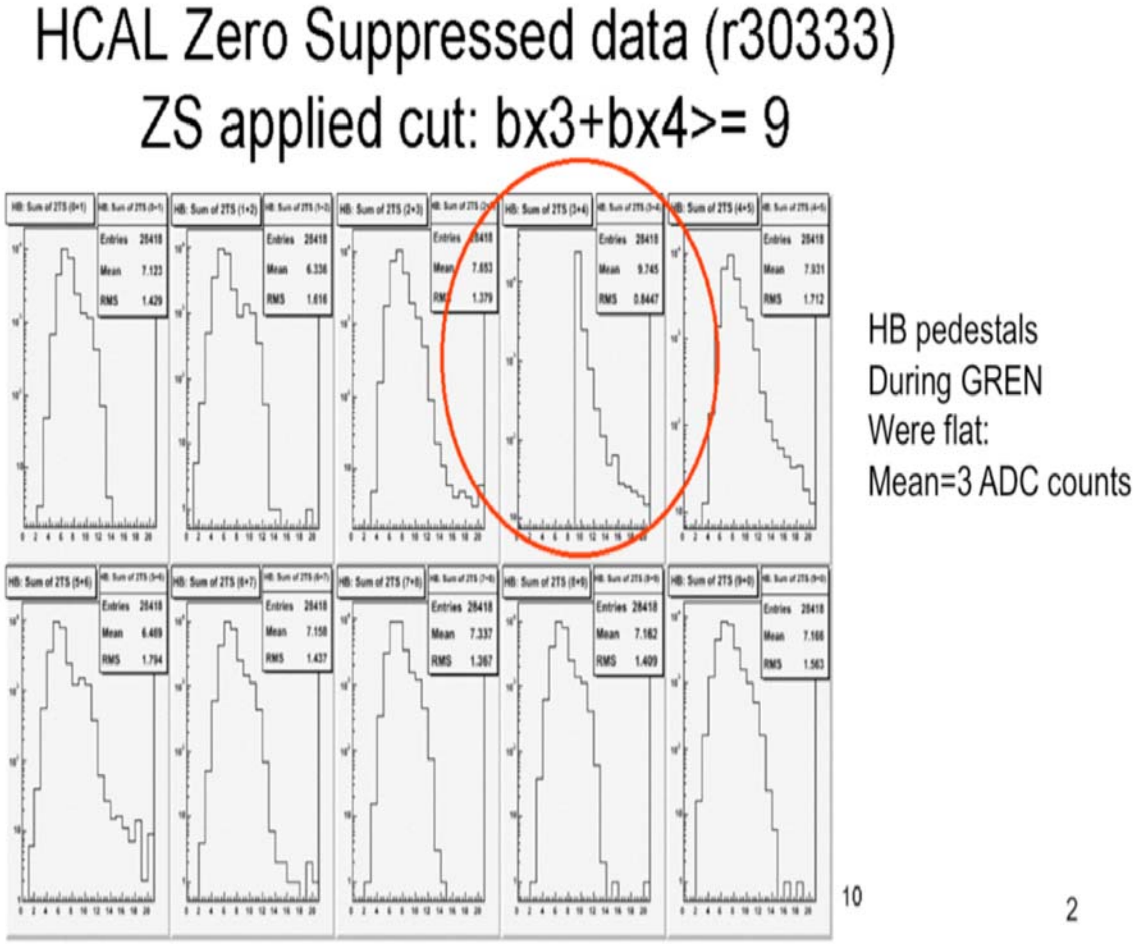


Figure 1: Sums of consecutive two time slices (raw ADC spectra) for Zero Suppressed (ZS) runs from GREN (R30333) data. Here ZS is based on the ADC values in two specific time slices (bx3+bx4) requirement >= 9 ADC counts. As is seen, there are no events with <9 ADC counts in bx3+bx4 (but the other time buckets are not biased).

2. HCAL Zero Suppression

Previously, we have reported [1-5] on the performance of HCAL in GREN and Cruzet1 global runs. Here we discuss in detail effects of zero suppression on HCAL readout. The Zero Suppression firmware (version 5A) checks if the sum of the absolute energy deposition (in ADC counts) in two consecutive time slices (in this particular case, bx3+bx4) is at greater than or equal to certain threshold. In GREN the threshold was set at 9 ADC counts. If this condition is not satisfied, it suppresses the readout of that particular channel. For HCAL Barrel channels, where the mean value of pedestals were adjusted to 3 ADC counts per time slice (within +/- 0.15 counts), this algorithm suppressed 99.7% of channels (passed ~ 0.3% of channels, effectively reducing number of channels acquired by factor of 300). Since the calibration of HCAL corresponds to approximately 0.200 GeV per ADC count, the requirement of 9 ADC counts in two time slices, corresponds to 3 counts above a pedestal of 6, or 0.600 GeV.

3. Pedestal settings in HCAL

The pedestals of HCAL QIE channels can be adjusted by sending appropriate value of the Digital to Analog (DAC) setting to the QIE card. Figure 2 shows three different pedestals settings. The lower left plot shows the distribution of pedestals where all pedestals were set with maximal value of DAC (norm7). For that setting, individual channels have mean pedestal values in range from 3 to 6 ADC counts, with an average value of 4.5 ADC counts. Changing the DAC setting by one unit, moves the pedestal mean by approximately 0.5 ADC counts.

During the GREN data taking period, HB channels had their pedestals adjusted in order to make the pedestal of all channels as uniform as possible. DAC setting values of 4, 5 or 6 were chosen individually for each QIE channel. As a result of this ‘tuning’ the average pedestals values for all channels were in the range from 2.5 to 3.5 ADC counts. The upper left plot in Figure 2 shows the distribution of pedestals taken with during GREN (flat pedestals).

Unfortunately, during the GRuMM data taking period, wrong DAC settings were sent to QIE channels. As a result, the pedestal means of HCAL QIE channels were in the range from 1 to 5 ADC counts (un-flat pedestals, as shown on the right plot of Figure 2). Note that ZS firmware (version 5A) uses raw ADC values (without pedestal subtraction) to make decision to suppress or not suppress the readout of particular channel. Therefore there was a significantly wider spread of pedestals during the GRuMM period (these un-flat pedestal settings had a RMS of 0.7 ADC counts per time slice) affected the performance of data taken with ZS.

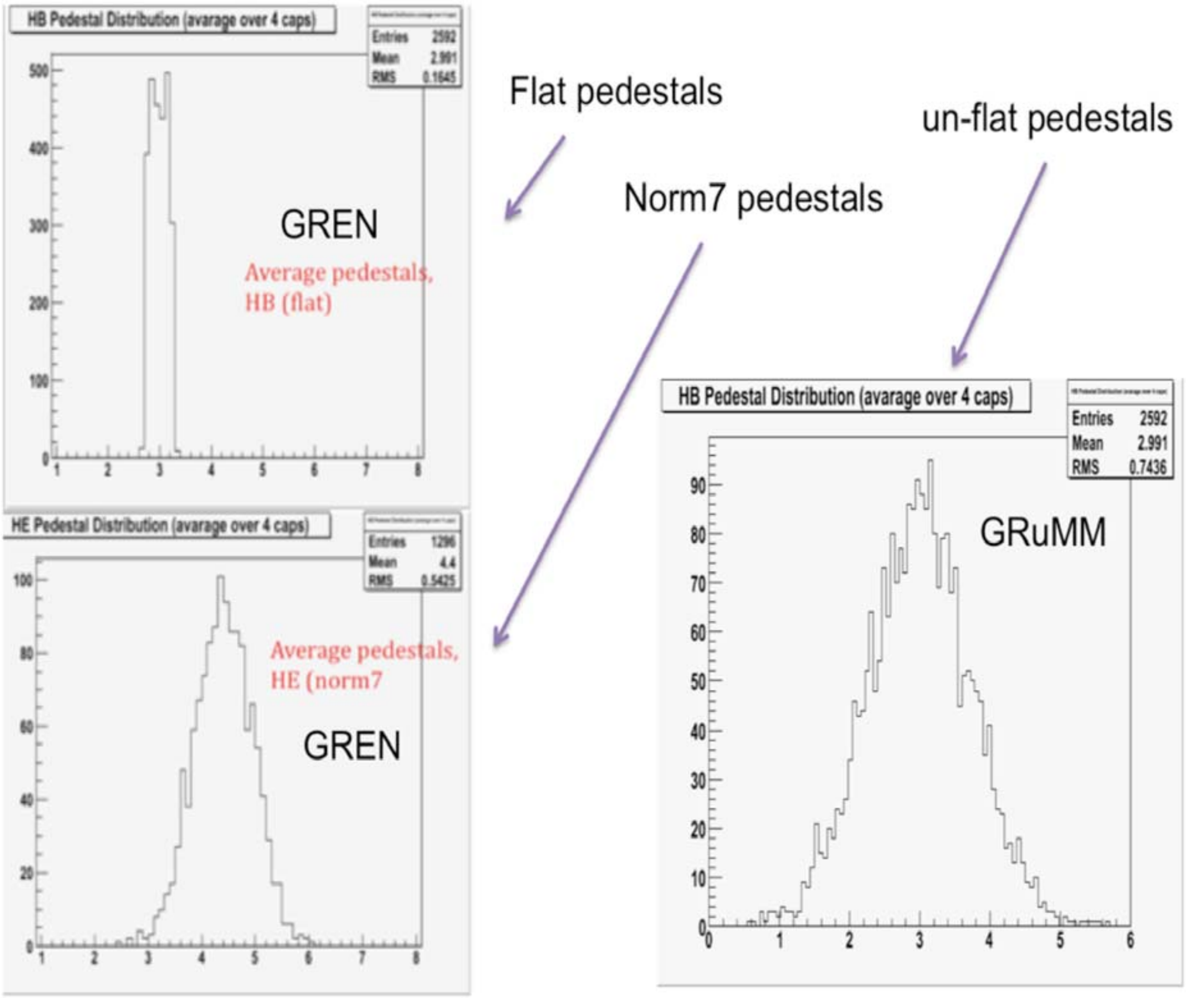
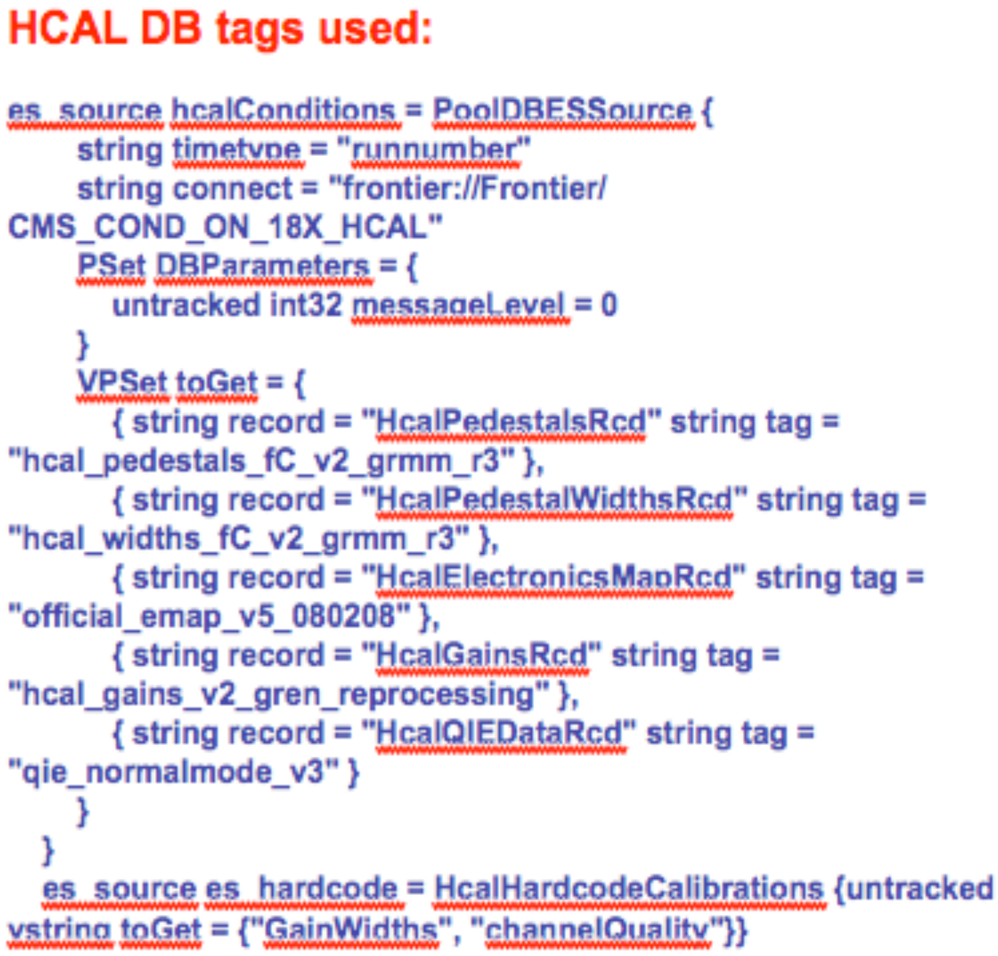


Figure 2: Example of pedestal distributions for HCAL during GREN (flat pedestals, “tuned” using a different DAC setting for each channel, top left) , norm7 (using a single DAC setting for each channel, bottom left) and GRuMM (un-flat pedestals, bottom right) data taking periods.



HCAL DB tags used:

```
es_source hcalConditions = PoolDBESSource {
      string timetype = "runnumber"
      string connect = "frontier://Frontier/
CMS_COND_ON_18X_HCAL"
      PSet DBParameters = {
         untracked int32 messageLevel = 0
      }
      VPSet toGet = {
         { string record = "HcalPedestalsRcd" string tag =
"hcal_pedestals_fC_v2_grmm_r3" },
         { string record = "HcalPedestalWidthsRcd" string tag =
"hcal_widths_fC_v2_grmm_r3" },
         { string record = "HcalElectronicsMapRcd" string tag =
"official_emap_v5_080208" },
         { string record = "HcalGainsRcd" string tag =
"hcal_gains_v2_gren_reprocessing" },
         { string record = "HcalQIEDataRcd" string tag =
"qie_normalmode_v3" }
      }
   }
   es_source es_hardcode = HcalHardcodeCalibrations {untracked
vstring toGet = {"GainWidths", "channelQuality"}}
```

Table I: The list above shows HCAL DB tags used in this analysis. In particular the HCAL gain file was: "hcal_gains_v2_gren_reprocesing". Note that the calibration coefficients in this file are multiplied by factor 1.12 with respect to the calibration coefficients in file "hcal_gains_v2_cosmics_magoff" [6].

4. Data set : GRuMM run 38426

We have investigated one of the cosmic ray runs recorded during GRuMM (Global Run in the Middle of March 2008). Data for Run 38246 were collected on Friday, March 14, 2008 using DT and CSC triggers. During Run 38246 HCAL ZS firmware (version 5A) was not enabled. We have analyzed a sub-sample of 10k events from Run 38426.

Figure 3 shows the unbiased signals of individual HB towers for cosmic ray triggers (DT). The upper plot shows the pedestal subtracted sum of digis (ACD) for 10 bunch crossings, in fC. The RMS of this distribution is 1.45 fC. The lower plot in Figure 3 shows the same distribution, but now in terms of RecHit energy in GeV. Here the RMS =0.23 GeV. The RMS of this distributions reflects the noise of single HCAL channel (1.45fC or 0.23 GeV). Note that the distributions would be narrower if 8 time slices (instead of 10) were used, and even narrower if only four time slices were used (since there are 4 capacitors in each QIE which have anti-correlated pedestals, a sum of 4 time slices yields the most stable pedestals).

We have analyzed the muon timing and energy deposition distributions using the DT track as an unbiased seed. The Muon DT track is extrapolated to the inner and outer HCAL radia. The upper plot in Figure 4 shows the distribution of timing for a muon signal in HCAL. The timing of the muon signal as defined here is the energy weighted center of mass of bunch crossings for events with pedestal subtracted ADC sum of 3 bunch crossings above 10 ADC counts:

$$t_{\mu} = \frac{\sum_{i=\max-1,\max+1} E_i * i}{\sum_{i=\max-1,\max+1} E_i} ,$$

where the sum is over three bunch crossing, around the one with maximum energy deposition in HCAL. The red curve corresponds to timing for muons crossing the upper wedges, and the blue curve corresponds to timing for muons crossing the lower wedges.

The difference in timing between muons crossing the top and bottom wedges is consistent with the time of flight of muons. The observed multipeak structure in the average time of the signal in the HCAL towers is caused by the lack of phase adjustment in the HCAL Trigger and Readout cards (HTRs), and in the Clock Control Modules (CCM) in the front-end Readout Boxes (RBX).

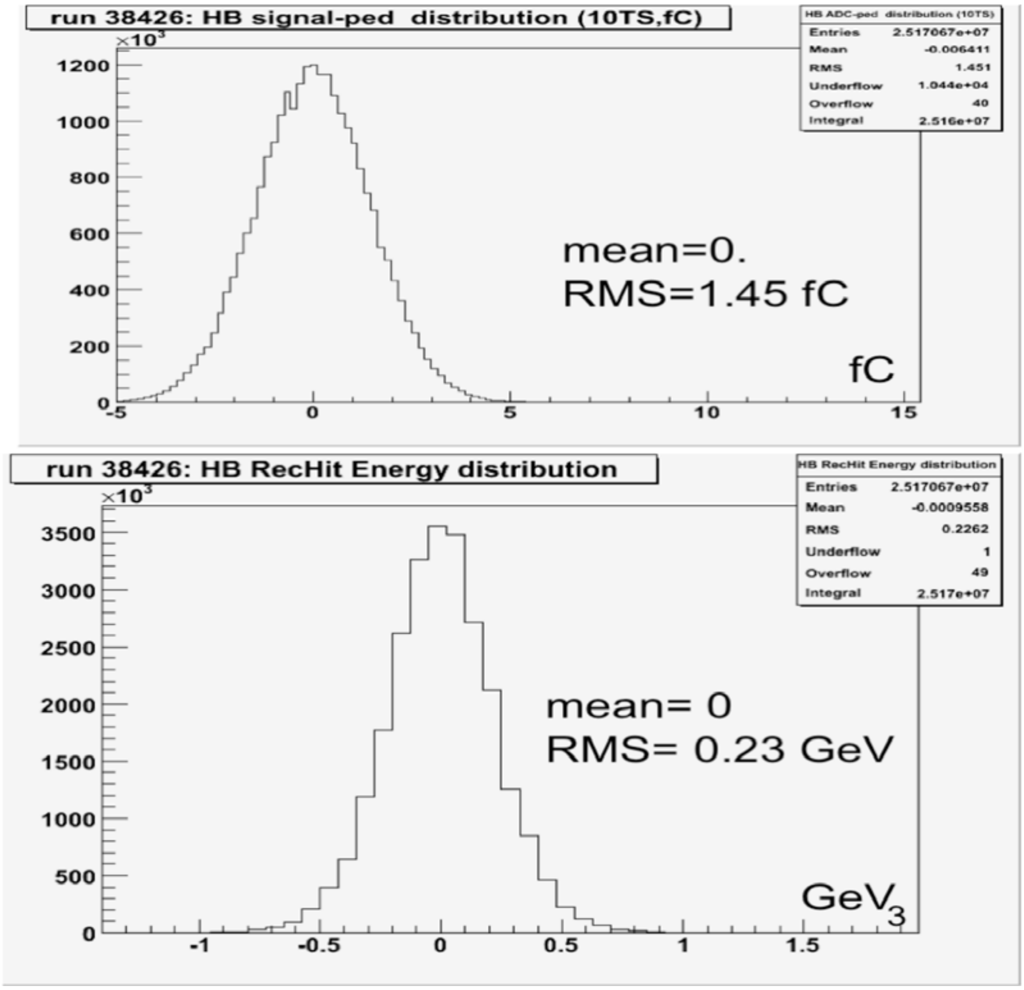


Figure 3: The HB signal, pedestal subtracted (for each channel), using 10 time-slice sums in fC: RMS=1.45 fC (upper plot). The same spectrum shown as the reconstructed (RecHit) energy distribution for HB channels in GeV: RMS= 0.23 GeV (lower plot). Note that the distribution would be narrower if 8 time slices were used, and even narrower if four time slices were used (since there are 4 capacitors in each QIE). (since there are 4 capacitors in each QIE which have anti-correlated pedestals, a sum of 4 time slices yields the most stable pedestals).

The energy deposition of the muon is defined as the energy sum over all HCAL tower crossed by muon track. Note that in this definition the muon energy deposition is NOT corrected for the angle of incidence:

$$E_{\mu} = \sum_{phi} \sum_{eta\,\min-1, eta\,\max+1} E(phi, eta)[GeV]$$

Typically, a muon track crosses two to nine HCAL towers. A single tower has electronic noise of approximately 0.23 GeV. This implies that the RMS of electronic noise is at the level of 0.3 GeV – 0.75 GeV for two to nine HCAL towers. The muon signal in HCAL is about 2 GeV (without angle of incidence correction).

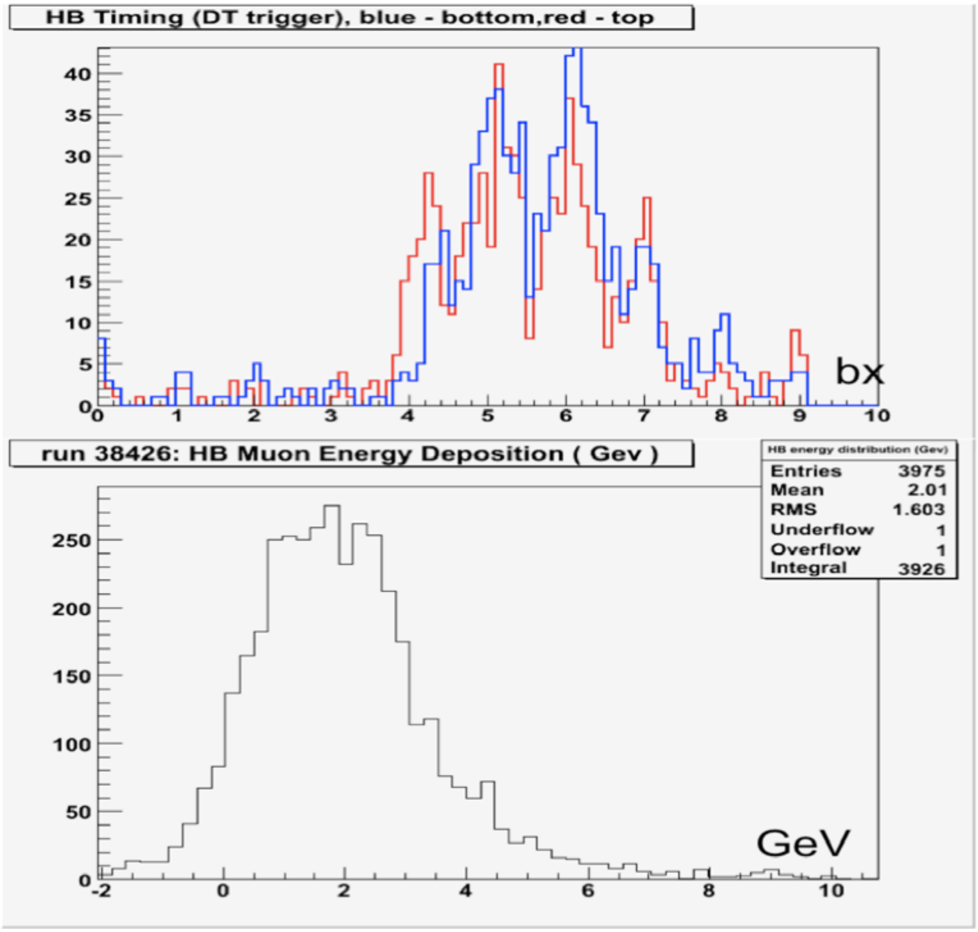


Figure 4: The timing of muon signals in HCAL (upper plot). The red curve corresponds to timing for muons crossing the upper wedges, and the blue curve corresponds to timing for muons crossing the lower wedges. The distribution of muon energy deposition in HCAL (lower plot). Data taken without Zero Suppression.

5. Emulation of Zero Suppression firmware (5A)

We have then emulated ZS in the offline analysis and re-analyzed same data set (10k events, r38426) in order to make direct comparison of muon energy deposition distributions after the ZS (firmware 5A) algorithm is applied.

Figure 5 shows the raw ADC sums for two consecutive time slices for r38426, prior to application of the ZS (firmware 5A) algorithm. The circled histogram (bx5+bx6) is the unbiased distribution.

Figure 6 shows the same distributions for the raw ADC sums with emulation of standard ZS (firmware 5A) algorithm :

$\mathrm{ADC}(bx5) + \mathrm{ADC}(bx6) >= 9$,.

This ZS (firmware 5A) algorithm implicitly assumes that pedestals have mean values of 3 ADC counts. However, in the GRuMM period, the pedestals were not set properly (un-flat pedestal setting). Here the ZS algorithm passes (acquires) approximately 3% of channels, (as opposed to acquiring 0.3% channels for the flat pedestal setting).

Therefore alternative emulation algorithm was chosen, with mean values of pedestals subtracted channel-by-channel:

ADC-ped(bx5) + ADC-ped(bx6) >= 3.

Figure 7 show the resultant distributions for this ZS (firmware 5A with flat-pedestals) simulation.   Only 0.3% of channels pass (are acquired) in this flat-pedestals ZS emulation.

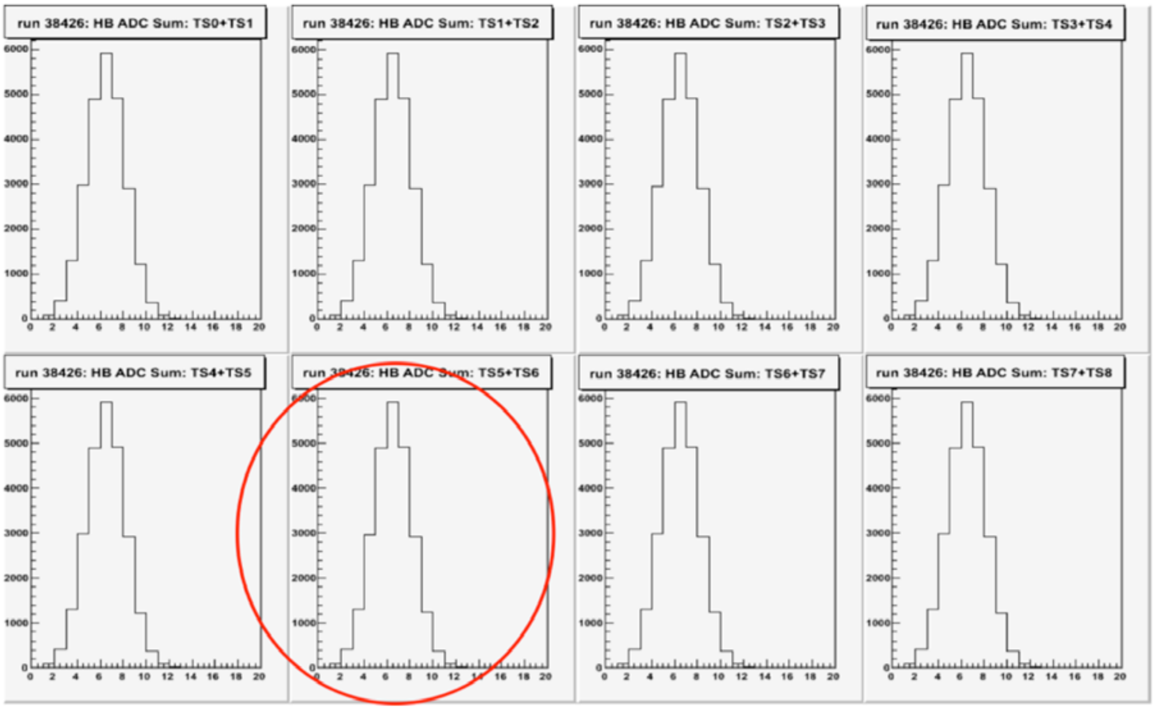


Figure 5: Run 38426: Digi sum for two consecutive bunch crossing without ZS (firmware 5A) emulation: The horizontal axis in ADC counts. Pedestal sums for bx5+bx6 are unbiased.

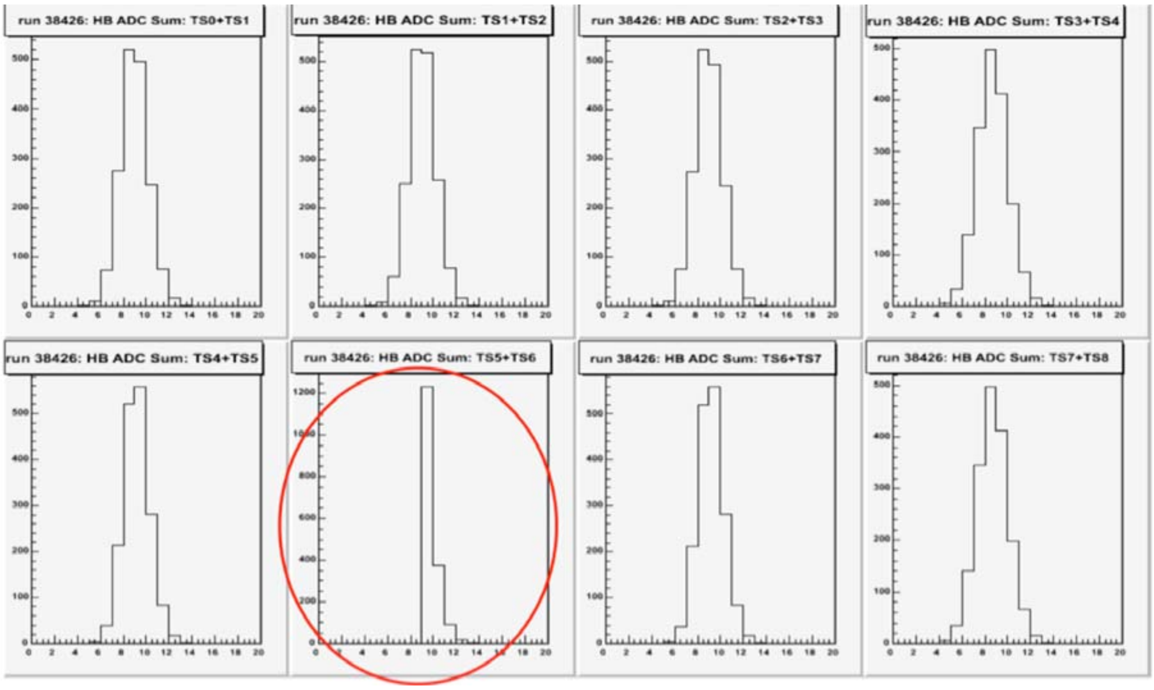


Figure 6: Simulation of ZS (firmware 5A), r38426 acting on raw ADC values: ADC(bx5)+ ADC(bx6) >= 9. Sharp threshold is seen.

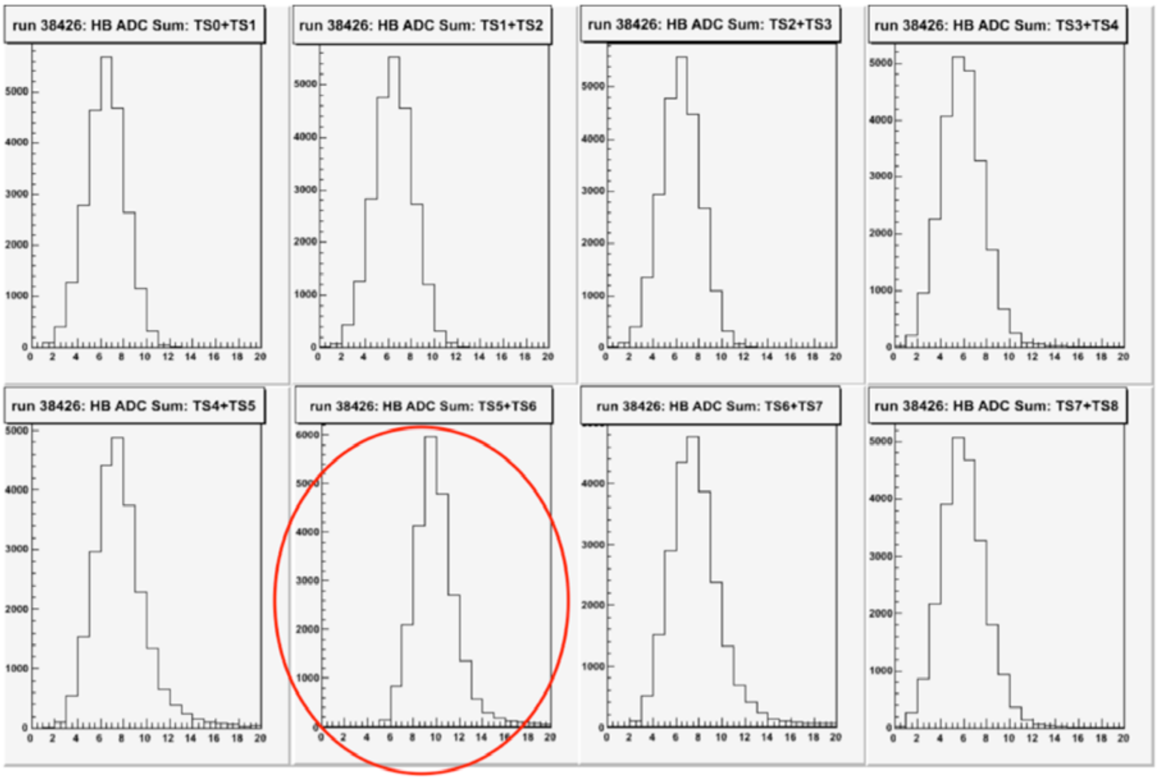


Figure 7: Simulation of ZS (firmware 5A), r38426 acting on pedestal subtracted ADC values: ADC-ped(bx5) + ADC-ped(bx6) >= 3. Threshold is not sharp, as we plot raw ADC sum, but cut is applied on pedestal subtracted sums.

6. Muon timing and muon energy deposits with emulation of Zero Suppression

Figure 8 shows muon timing and muon energy deposits with emulation of firmware 5A Zero Suppression: ADC-ped(bx5) + ADC-ped(bx6) >= 3. Equivalent plots for analysis without Zero Suppression are shown on Figure 4. As expected, the timing distribution on upper plot of Figure 8 is narrower than the corresponding plot on Figure 4. Events with timing other than bx=5 or bx=6 are suppressed.

The energy deposition spectrum of muons with ZS (firmware 5A) is significantly different from the one without ZS. For more than 50% of events (2000 events out of approximately 4,000 events selected based on DT track trajectory) all RecHits (reconstructed energy) for the HCAL towers crossed by the muon are completely suppressed, not acquired. The majority of the remaining events have reconstructed energy deposition of muons much below 2 GeV. As can be seen on the lower plot on Figure 4, without ZS, the reconstructed energy deposition of muons has an average value of approximately 2 GeV.

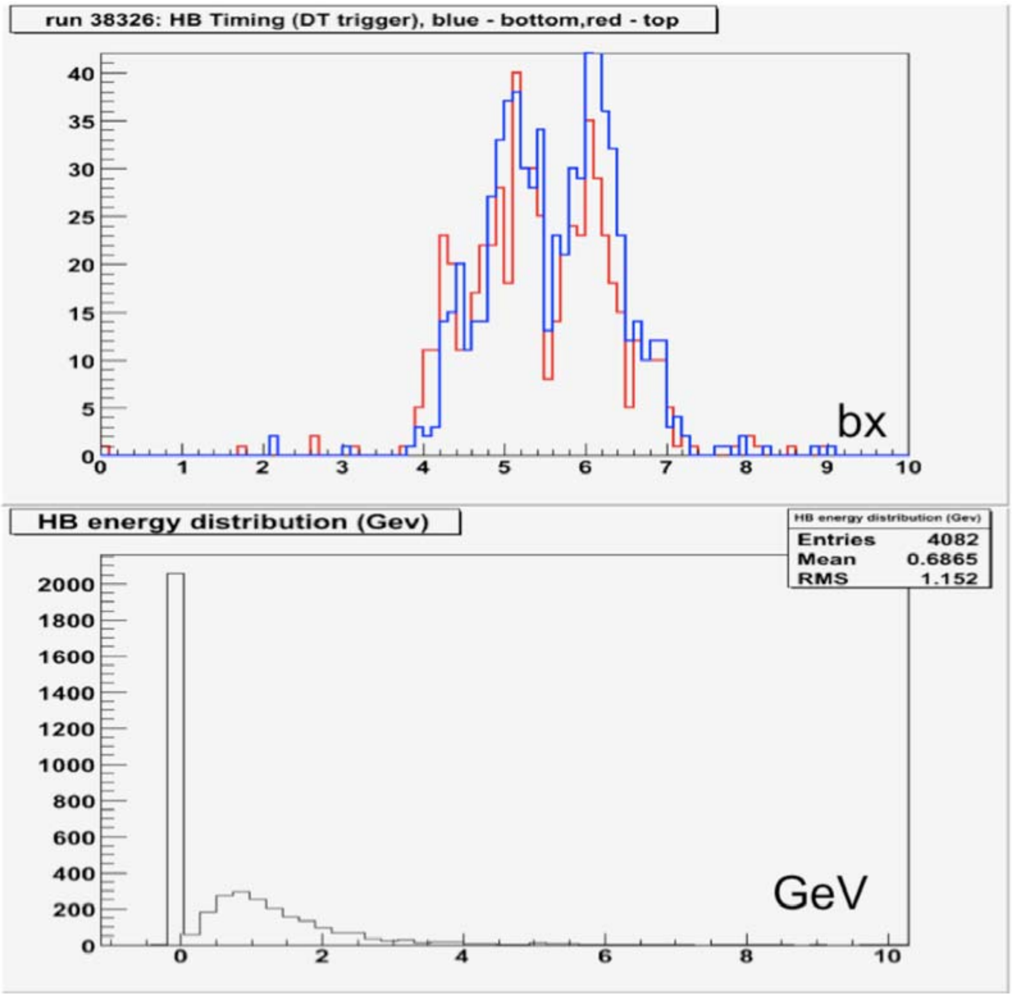
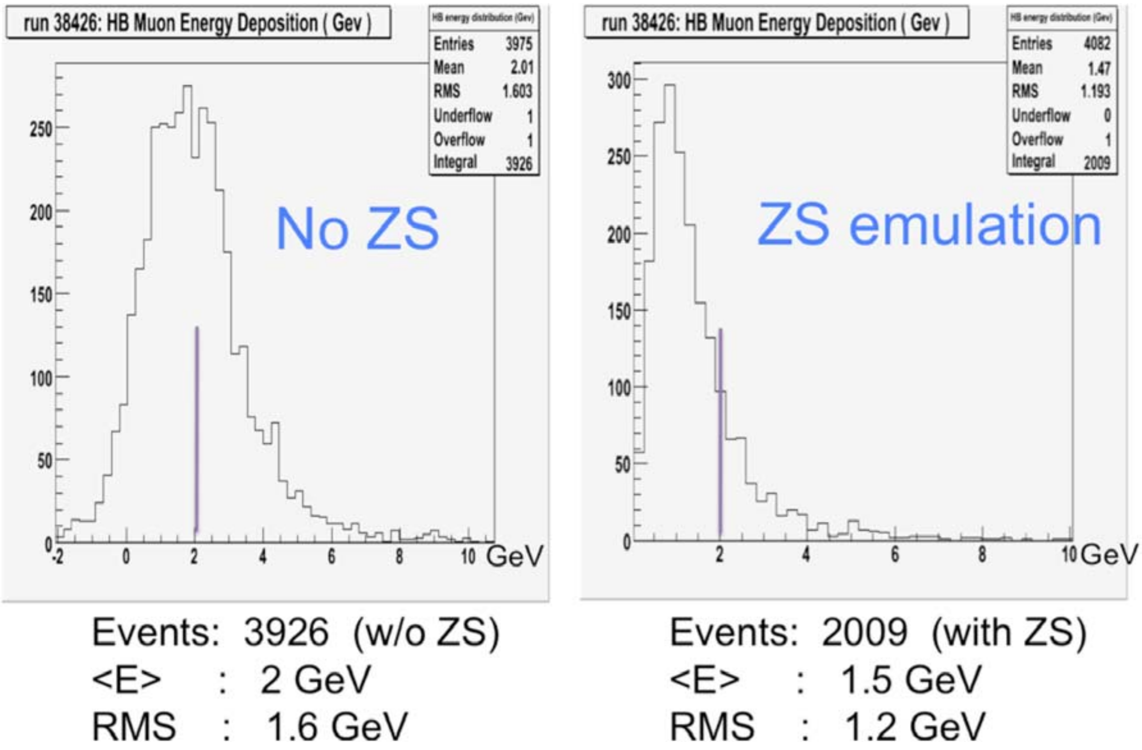


Figure 8: Timing and muon HCAL energy deposition distributions for events passing ZS (firmware 5A) simulation (to be compared to figure 4, which is without ZS).

Figure 9 shows comparison of the HCAL energy deposition spectra for muons without ZS and with ZS emulation. A total 10k events from DThcal filter were analyzed. Further selection requiring the muon track to cross the inner and outer HCAL radia was imposed. Out of 10k events, 4k pass the HCAL event selection criteria. The average muon energy deposition in HCAL is about 2 GeV, with RMS of 1.6 GeV (see figure 4 and figure 9 (left)).

Once emulation of ZS firmware 5A is included as part of the offline analysis, 50% of the muon events (2000 out of 4k sample) do not have reconstructed HCAL energy.



Events: 3926 (w/o ZS)
<E> : 2 GeV
RMS : 1.6 GeV

Events: 2009 (with ZS)
<E> : 1.5 GeV
RMS : 1.2 GeV

Figure 9: Comparison of cosmic ray muon HCAL energy deposition distributions. Left plot: spectrum without Zero Suppression (firmware 5A). Right plot: spectrum with emulated ZS emulation.

It is interesting to compare the muon energy deposition spectrum in HCAL obtained in the 2006 Test Beam. Figure 10 shows the test beam muon HCAL energy deposition spectrum for HB tower, eta index =9. The muon signal has a mean of 12 fC above pedestal, while the RMS of noise is less than 1 fC. Note that in the test beam, muons always traverse HCAL parallel to tower axis. The timing of the muon signal with respect to LA1 is very sharp, thus it is sufficient to use sum of energy registered in only two bunch crossings to define a muon signal. In effect, the signal-to-noise ratio of muons in the test-beam is significantly higher than for cosmic ray muons collected in UX5.

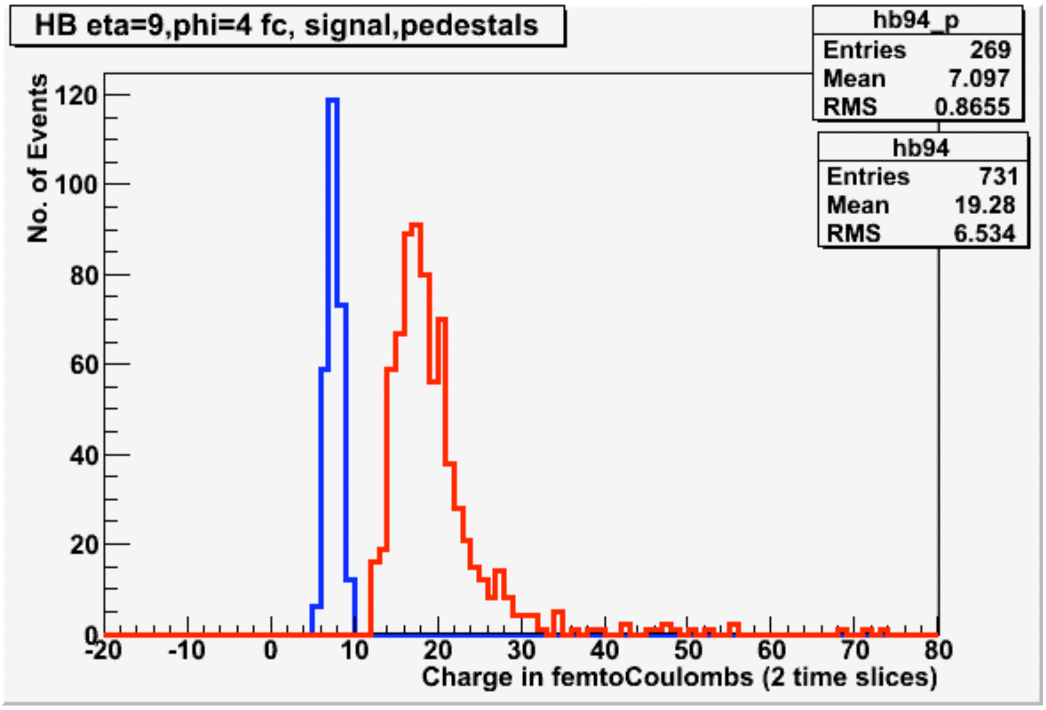


Figure 10: Test beam muon energy spectrum for HB tower, for eta index =9. The red histogram corresponds to the muon HCAL signal with a mean ~ 12fC above pedestal. The blue histogram corresponds energy distribution for pedestal events (two bunch crossing sums), with a pedestal mean of 7 fC, and RMS less than 0.9 fC. (This plot has been provided by Sudeshna Banerjee and Nancy Marinelli).

7. Conclusions

The Zero Suppression firmware 5A in HCAL checks if the sum of raw ADC values for two consecutive time slides (bx3 and bx4) is above certain threshold. During GRuMM, the cut required that signal is at least 9 ADC counts. For flat pedestals with mean value of 3 ADC counts per time slice, the ZS requirement suppresses 99.7% of channels.

However, this ZS cut introduces a strong bias in reconstructed energy deposits of cosmic ray muons. Approximately 50% of cosmic ray muons have no reconstructed energy deposition in any of the HCAL readout towers in the eta-phi region where muon passed. The HCAL energy deposits for the remaining 50% of events (where not all of the HCAL RecHits are suppressed) has significantly different mean (1.5 GeV instead of the 2 GeV for the unbiased sample), and RMS of 1.2 GeV instead of 1.6 GeV for the unbiased sample.

There are two main reasons why ZS (firmware 5A) introduces such a strong bias in the cosmic ray muon HCAL energy spectrum:

1. Cosmic ray muons pass through HCAL, but most of the tracks are not projective with respect to the HCAL tower axis. In effect the muon HCAL energy is deposited not in a single tower, but is shared by number of towers (between 2 and 9 towers per event, and 4 on average). Thus in order to

calculate the energy deposited by muon, one must include several HCAL towers. Since the muon signal is spread among multiple towers, individual channels are likely not to cross the required ZS (firmware 5A) threshold (which is 3 ADC counts or about 0.6 GeV).

2. The timing of the muon signal within 10 bunch crossing window of HCAL readout is not stable: HCAL readout moves +/- 1 bx with respect to L1A trigger, as the phases in HTRs and CCMs have not been yet adjusted. In addition, the muon time-of-flight introduces systematic shift of up to 1 bunch crossing for top versus bottom wedges. The ZS firmware 5A checks energy in HCAL towers based on sum of two specific buckets. Shifts in timing imply that even large signals than above 0.6 GeV threshold may be suppressed.

The study presented here implies that for Cosmic Run at Zero Tesla (CRuZeT) high rate readout tests with enabled Zero Suppression (firmware 5A) are not compatible with taking meaningful muon calibration data for HCAL. The GREN experience shows that one can collect ~ 500k DT/RPC triggers in 10 hrs of running. This gives ~ 100-500 muons per 5 degree phi section in the HCAL phi regions close to detector vertical axis.

Increase by order of magnitude in statistics of cosmic ray muons (5M muons in CruZeT vs 500k muons in GREN) would be very useful from point of view of the HCAL calibration exercise. It should be possible to collect such a sample in ~100 hrs of running without ZS in CRuZeT. It will be also interesting to collect some cosmics with ZS to check and understand the bias it introduces.

Note that the noise in the pedestal would be much narrower and even narrower if four time slices were used instead of two time slices in ZS with firmware 5A. This is because there are 4 capacitors in each QIE which have anti-correlated pedestals. Therefore, the sum of 4 time slices yields the most stable pedestals. For such a sum, a Zero Suppression level of only 1 ADC channel above pedestal (0.2 GeV) may be possible. With a four-time slice zero suppression firmware, the muon HCAL energy spectra would be less biased. This has implication not only for HCAL energy calibration with cosmic ray muons, but also for muon identification in HCAL, and the use of HCAL for muon isolation. For the identification of mouns form W and Z bosons, a muon isolation requirement of about 2-3 GeV has been used in Tevatron experiments. The current ZS firmware 5A, with a ZS threshold of 0.6 GeV introduces a significant bias not only in the muon HCAL energy deposit spectrum, and muon ID in HCAL, but also in the use of HCAL for muon isolation requirement.

In contrast, the sum of 4 time slices yields the most stable pedestals. For such a sum, a Zero Suppression level of only 1 ADC channel above pedestal (0.2 GeV) may be possible. This is comparable to what was possible at the Tevatron, where muon isolation included ECAL and HCAL towers with energies greater than 0.1 GeV.

The study of proposed alternative ZS firmware algorithm is the subject of another CMS internal note which we are currently writing.

Acknowledgements

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