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25 February 2008

Study of CMS HCAL response to muons using data collected during Global Run in September, 2007 and Integration Run in October 2007

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Abstract

We used the data collected with Drift Tube (DT) muon chamber triggers and central DAQ to study HCAL response to muons. The data was collected in two periods: global run at the end of September (GRES) and integration run taken on Monday, October 22, 2007 (iromo22). Using GRES data, we established timing in the HCAL readout with respect to DT trigger. We also performed analysis of energy, timing and geometric occupancy distributions for muons observed in HCAL. Using iromo22 data we confirmed correlations between eta and phi distributions of muon signals in HCAL and muon tracks reconstructed in DTs. We also studied the energy spectrum of muons passing through Hadron Outer (HO) subsystem. Using muon events from iromo22, we have also studied the optimal value for the energy threshold for HCAL muon trigger.

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1. Introduction

The HCAL subsystem has participated in the CMS global runs starting in May 2007. At that time, random trigger and LED triggered events in HFplus were recorded. Commissioning of HCAL Barrel (HB) wedges, using HCAL local DAQ system, started on September 17, 2007. At the end of September, there were seven fully tested HB wedges on the + z side (HBplus wedges 15-18 and 1-3). Global run at the end of September (GRES) provided the first opportunity for HCAL to record cosmics in the underground cavern. HCAL readout was timed in with respect to DT triggers and muon signal was identified in HB wedges.

However, further analysis of HCAL data indicated a problem of HCAL event fragments that were not matching DT event fragments. The problem was traced to different interpretation of trigger rules by Global Trigger (GT) and HCAL groups. GT used trigger rules, which allowed up to three triggers within 25 bunch crossings, not two. On other hand, HCAL readout would follow the rule allowing only two triggers within 25 bunch crossings and would not accept the 3rd trigger within 25 bunch crossings. This caused loss of synchronization in the HCAL event readout. As a result, for most of the runs recorded during GRES, HCAL event fragments did not match DT event fragments. A special, one day integration run was organized on Monday, October 22 (iromo22) in order to collect synchronized HCAL/DT data. In this note, we summarize analysis of the data collected in both GRES and iromo22 run periods.

2. GRES data set

Figure 1 shows schematic of CMS detector with parts of DT and HCAL systems participating in the Global Run at the end of September (GRES). Only Central wheel (YB0) detectors participated in that run. DT provided triggers using chambers on sectors S10 and S12. At that time, only seven HCAL Barrel wedges on the +z side were fully commissioned and connected to the readout (HBplus wedges 3 through 15).

Events in global runs triggered by DT trigger used _OR_ of four sectors: (S10/YB0, S12/YB00, S10/YB+1, S11/YB+1). DT Track Finder (DTTF) required a track in at least two chambers to generate a trigger for a sector. According to local DT runs, rates on YB+1 were ~ a factor of 2 or 3 lower than on YB0. Trigger rates from DT (requiring two out of four chambers to report segments) were at the level of 10-15Hz (S10, S12 on YB0).

At the time of data taking, we also attempted to include HO/YB0, sectors S4, S10, S11 and S12 in the readout. Unfortunately, due to lack of a cooling system for the HO subsystem, we could only power up HO front end electronics for a very limited time (less than a half an hour at a time). Therefore data taken with HO is statistically very limited.

We have connected the following HO sectors for the global run:

Sector 10 Spigot 0, 1, 4, 5 DCC = 730 Official mapping scheme
Sector 12 Spigot 4, 5, 8, 9 DCC = 731 Official mapping scheme
Sector 4 Spigot 6, 7, 8 DCC = 730 Only 1-to-1 RM-to-HTR cabling
Spigot 6 = Phi 17, 18
Spigot 7 = Phi 19, 20
Spigot 8 = Phi 21, 22

The table below summarizes GRES runs with HCAL readout included.

Run	events	trigger	HCAL PLD	comments
20565	7371	DT	80 bx	Some muons in HCAL in TS=0
20570	8958	DT	70 bx	
20571	18449	DT	90 bx	Muons appear in HCAL in TS=8
20575	1737	DT	100 bx	
20580	3409	DT	110 bx	
20599	5724	DT	120 bx	
20602	4361	DT	130 bx	
20603	13468	DT	140 bx	After r20695 DT trigger delayed (by 13bx?)
20729	1902	DT, RPC	98 bx	85bx +13bx =98bx, but muons in TS=8 ! ?
20734	17000	DT, RPC	93 bx	Adjust PLD to 93bx and get muons in TS=3
20734	130450	DT, RPC	93 bx	HCAL synchronization lost
20977	7741	DT, RPC	93 bx	Low HVsetting:4kV instead of 8kV
20981	40000	DT, RPC	93 bx	Low HVsetting:4kV instead of 8kV
20994	19126	DT, RPC	93 bx	HO/Yb0:S4, S10, S12 on, HCAL synchronization OK

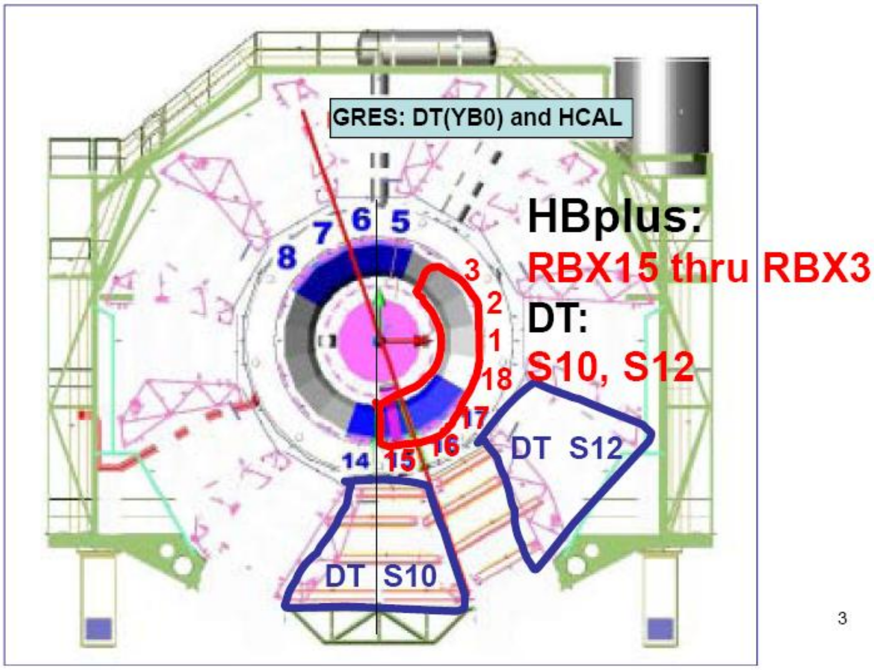

Figure 1: Schematic of CMS detector with parts of DT and HCAL systems participating in the Global Run at the end of September (GRES). DT provided triggers using chambers on sectors S10 and S12 on the central wheel (YB0). At that time, only seven HCAL Barrel wedges were fully commissioned and connected to the readout (HBplus wedges 1 through 3 and 15 through 18).

3. Timing in of HCAL readout with respect to DT trigger

HCAL data is stored at every bunch crossing (bx, 25ns) in a pipeline which is 256 bx long. Once the Level_1_Accept (L1A) is issued, data for ten bunch crossings is recorded. It was necessary to time in the readout of HCAL with respect to arrival of L1As from DT triggers. In order to accomplish this we have recorded several runs with various values of PipelineDelayLength (PDL). This parameter defines how far back in time one needs to look to obtain HCAL data corresponding to the DT trigger. For example if it takes longer to generate L1A decision, one needs to use larger values of PDL.

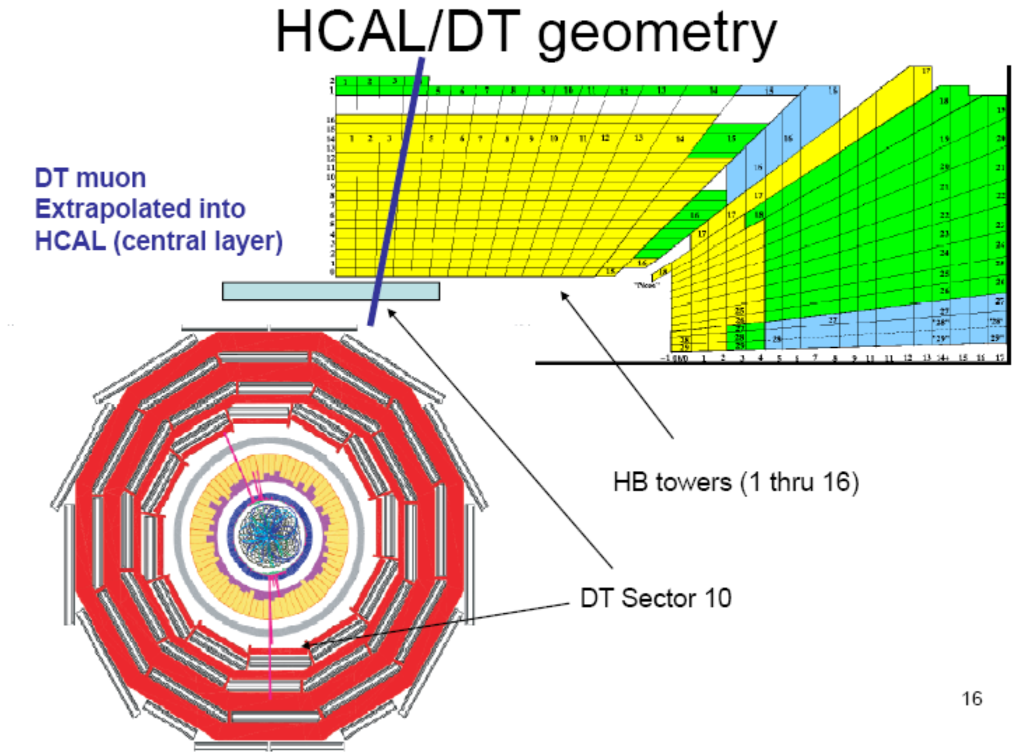

Figure 2: Schematic view of HCAL/DT geometry in CMS.

In order to select muon candidate events, we required the energy deposition in a single HCAL tower to be at least 7.5fC above pedestal. The energy was defined using sum of QIE values from ten recorded time slices (bunch crossings). Timing of each individual event was defined using an energy weighted sum of bunch crossing numbers (0 through 9).

Figure 2 shows the details of HCAL/DT geometry in R-phi and R-z view. Note that the DT chambers in the central wheel (YB0) extend only up to the HCAL tower with eta index=4 (eta<0.35). In order to increase the signal to noise ratio, we have only considered HCAL towers in wedge 15 from HBplus half-barrel (phi = 55, 56, 57, 58). This particular wedge overlapped sector S10 of DTs which provided 40% of the triggers. To further reduce the background, we did not consider HCAL towers with the four highest values in eta (eta > 1.05).

Figure 3 shows the timing distribution of HCAL events with signal above 7.5fC threshold with respect to DT triggers. The plot illustrates the search procedure that was carried out to ascertain the location of the HCAL signal with respect to DT trigger. The data corresponds to a set eight runs (20565 – 20603), taken with value of PDL from 70 to 140 bunch crossings, in steps 10 bx. Since in HCAL we record ten time slices for every event, each run covers ten non-overlapping bunch crossings, as shown by the arrows extending for 10 bx counts.

The plot indicates that for two values of PDL: 90bx and 80bx, we see an increase in the number of events with energy deposition above 7.5fC. For all other settings of PDL, we observe on average less that one event per run. However, for PDL=90bx (r20571) we observe 18 muon candidate events. Candidate events appeared late (TS=8) within HCAL 10bx window. For PDL setting of 80bx (r20565), we 12 muon candidate events. In r20571, In this run events appeared early (TS=0) within HCAL 10bx window. From this we concluded that best choice of PDL was 85bx. This would place candidate events in the middle (TS=4) of HCAL 10bx window.

Note, that starting from run 20695 onwards, DT trigger was delayed to match RPC trigger. We have therefore adjusted HCAL timing accordingly, by increasing PDL to 93bx.

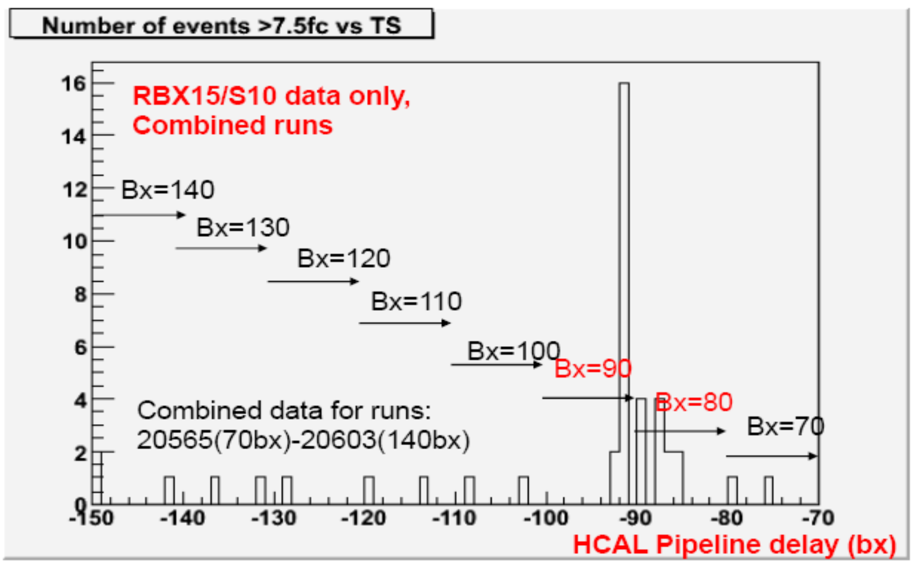

Figure 3: Timing of HCAL events with signal above 7.5fC threshold with respect to DT triggers. The data corresponds to set of runs (20565 – 20603) taken during September global run (GRES) with various values of PipelineDelayLength (PDL). Values of PDL varied from 70 bunch crossings to 140 bunch crossings. The plot indicates that for two values of PDL: 90bx and 80bx, we see an increase in the number of events with energy deposition above 7.5fC.

Figure 4 shows an example of CMS event display for event triggered by DT, Sector 10/YB0. In this run (R20571), the PipelineLengthDelay (PLD) was set to 90 bx. Note that in this particular run, HCAL readout was properly synchronized with the rest of the event fragments. Muon track hits, seen in both R-z and R-phi views, match energy depositions in HCAL. Note, that during GRES wheel YB+1 which was also included in the readout, was displaced from its nominal position by 6.5m in the +z direction.

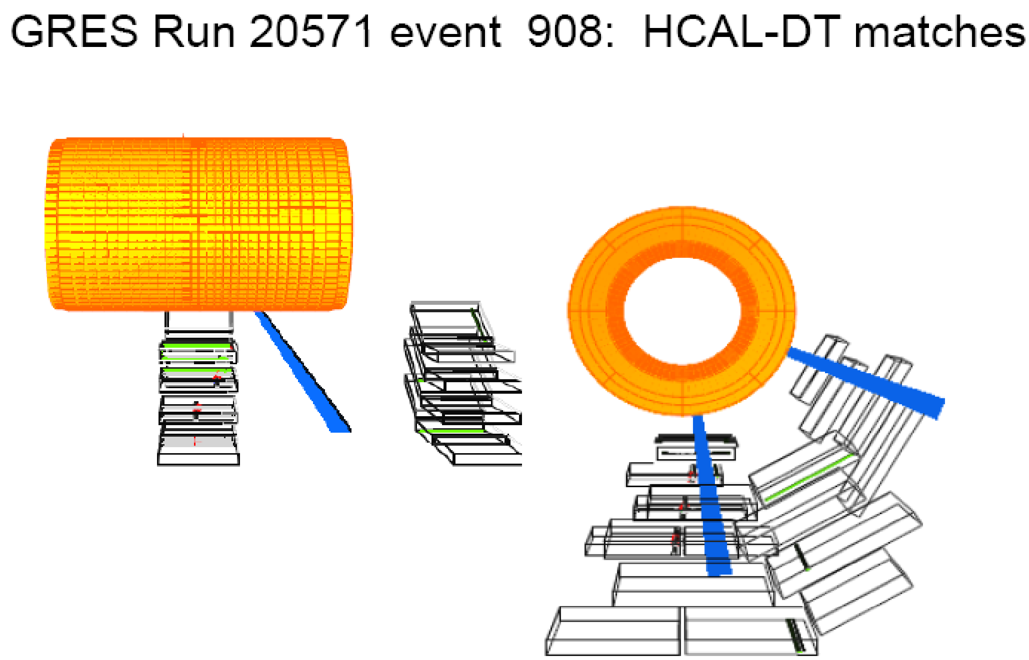

Figure 4: Example of event display from global run in September (r20571). Event was triggered by DT Sector S10 on YB0 (central wheel) . Muon passed HCAL leaving energy in two HB towers.

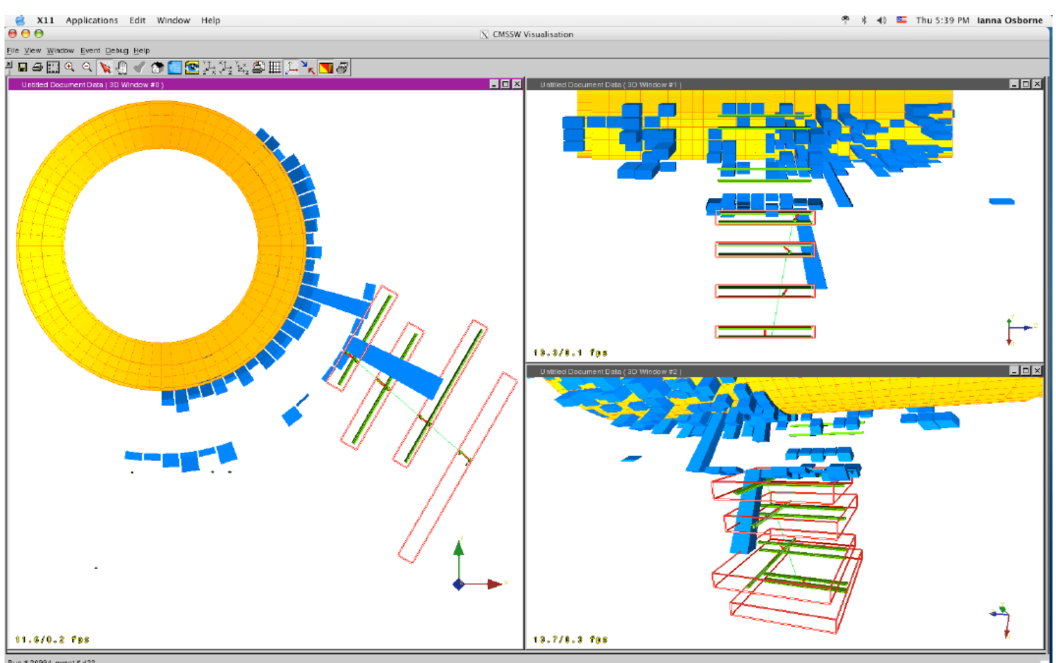

Figure 5: Example of event display from global run in September (r20994). Event was triggered by DT Sector S12 on YB0 (central wheel) . Muon passed HCAL leaving energy signals in HB and HO. This event was selected by Yanna Osborne.

4. Muon signal distributions

Following a set of short runs to establish proper timing of HCAL readout, a large statistics run was recorded (130k triggers) with DT and RPC triggers and with DT and HCAL in the readout. RPC provided triggers on Sectors S10 and S11 on wheels YB+1 and YB+2. Note however, that since YB+1 and YB+2 were not on the solenoid, the muon tracks triggered by RPC (mostly vertical) would not intercept HCAL Barrel.

Figure 6 shows a set of distributions of signals observed in HCAL for r20734. The PDL was set at 93 bx. Events with pedestal subtracted energy above 7.5fC in a single HCAL tower were selected. Only events in HCAL wedge HB+15 (with phi towers 55 through 58) are included in the plots. The plots show that indeed observed signal in HCAL has characteristics consistent with the signal of cosmic ray muons, both in timing and geometrical (eta-phi) distributions. A total of 550 events passed these selection cuts. Considering the fact that only one third of S10/YB0 overlaps with wedge HB+15, we find that in the fiducial volume of this wedge approximately 5.5% of DT triggers contain events with HCAL energy deposition above 7.5fC.

The upper left plot shows average event energy distributions (average energy deposition vs bunch-crossing) for events passing 7.5fC cut (sum of ten time slices). The events are typically two bx wide. This distribution is consistent with muon event distributions observed earlier in the TestBeam data.

The upper right plot shows average event time observed in HCAL with respect to L1A trigger time. Here the HCAL event time was defined as energy weighted sum of bunch crossing numbers. The sum was calculated over four buckets: by using the bucket with maximum energy deposition and -1 (proceeding bucket), +2 (two buckets following the bucket with maximum energy).

The distribution has a narrow (RMS ~ 1bx) peak in bx=3. However, one can also see a long tail, extending beyond bx=4. Approximately 20% of events event time larger than 4bx. Similar distribution was observed during August Global run for ECAL-DT timing. This effect was caused by DT trigger firing too early (assigning too early bx to the trigger). In effect that made HCAL signal appear late with respect to DT trigger. Note that this effect was corrected in the November run.

The lower left plot shows eta tower distribution of events in HCAL with E> 7.5fC cut: The red line indicates that HB+15 overlaps with S10 over first four eta towers (up to eta= 0.35). The observed distribution is consistent with expectation, i.e. it peaks at eta=0 with over 70% of events having HCAL signal in eta tower <= 4. Since the trigger did not require that muons pass through Interaction Point (IP), the observed eta distribution of signal events in HCAL is consistent with angular distribution of muons from cosmics.

The lower right plot shows phi tower distribution of events in HCAL. Only events in RBX+15 were selected. RBX+15 overlapped with S10 of DT/YB0 which was providing triggers.

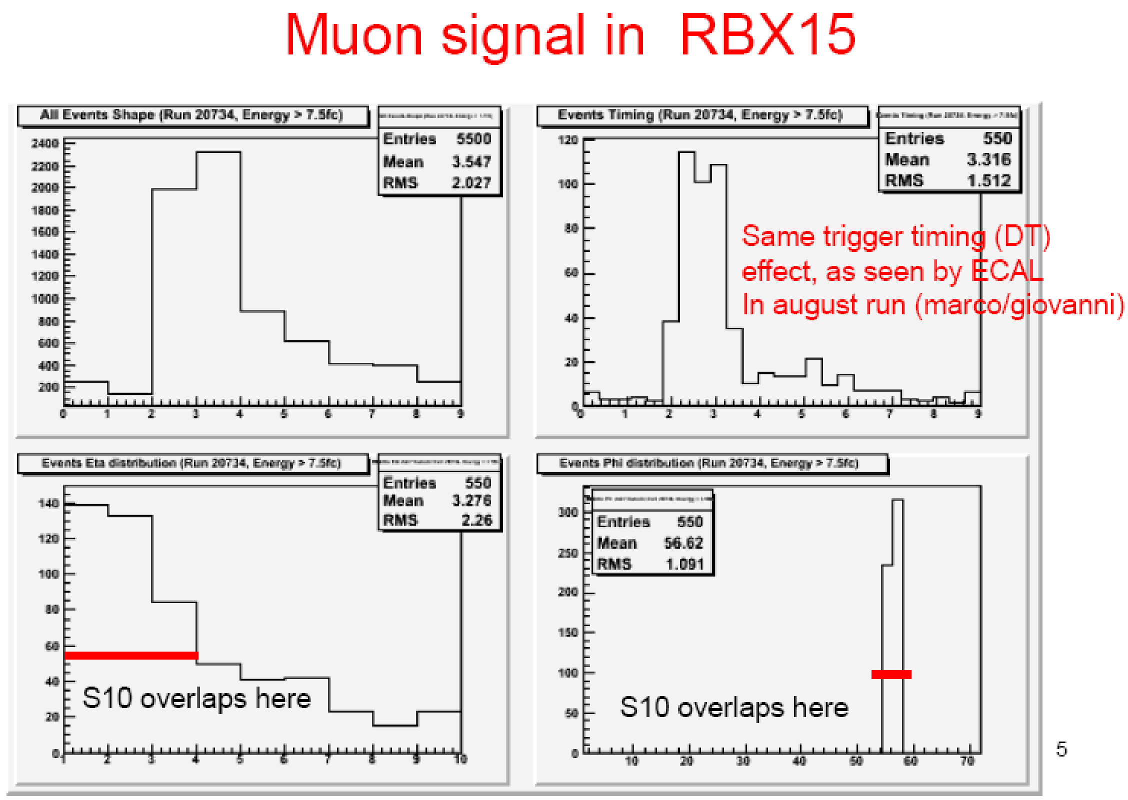

Figure 6: Muon signal distributions for GRES run R20734 :

a) Average event energy shape vs time (average energy deposition vs bunch-crossing) for 550 events with energy deposition above 7.5fC cut (sum of ten time slices).
b) Average event time distribution. The event time was defined as energy weighted sum of bunch crossing numbers. The sum was calculated over four buckets: using the bucket with maximum energy deposition and -1 proceeding bucket, +2 following the bucket with maximum energy.
c) Eta tower distribution of events in HCAL with E> 7.5fC cut: The red line indicates that HB+15 overlaps with S10 over first four eta towers (up to eta= 0.348).
d) Phi tower distribution of events in HCAL with E> 7.5fC (after phi=55-58 cut).

5. Top-Bottom muon coincidence events

Timing and geometrical (eta-phi) plots of signal (energy > 7.5 fC) in HCAL are consistent with cosmic ray muon distributions and not with random noise. In order to provide another verification that observed signal is indeed coming from cosmics, we have looked for events, where muon would cross the HCAL detector in two separated sections. The topology of such events would be two energy depositions above certain threshold, one in the top section of HCAL and the other in the bottom section of HCAL.

As only seven (20 degree in phi) HB wedges were operational, all located on +z side, we have assigned, somewhat arbitrarily, wedges 1 through 3 (phi index 1-10) as TOP wedges and wedges 15-18 (phi index 55-70) as BOTTOM wedges. Two 5 degree phi sectors (phi=71, 72, belonging to wedge 18), were used as separation zone). In order to increase statistical power of this analysis, we have lowered the energy cut from 7.5fC for single muon events to 6.0fC for each top and bottom energy cut.

Figure 7 shows an example of such event, selected from r20734. In the top section, signal above 25fC is present in eta tower=5 and in the bottom section signal is present at eta tower=3 at about 15fC. The absolute energy scale in HCAL is such that 1fC corresponds approximately to 160 MeV. H2 Test Beam results show an average energy deposited by muon is ~1.5 GeV. Note however, that in the testbeam, muons cross a single HCAL tower along tower axis, so that energy spectra are expected to be different.

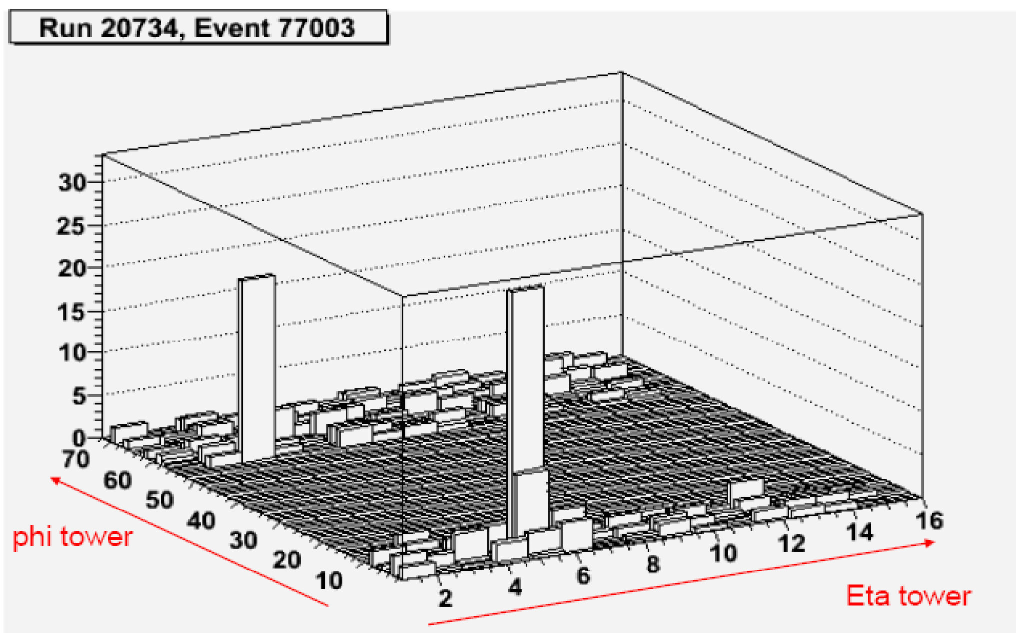

Figure 7: Lego plot in eta-phi space for HCAL energy distribution one of the events from GRES: r =20734/ev=77003. This event was selected using the requirement that one of the BOTTOM towers (phi = 1-10) and one of the TOP towers (phi=55-70) are above the 6fC threshold.

Figure 8 shows a view of the HBplus detector indicating the eta and phi segmentation of towers. The left-hand side picture shows the y-z view of the detector. The right-hand side picture shows the x-z view of the detector. The insert scatter-plot shows correlation between phi of the signal tower in top and bottom wedges.

The lengths of HCAL signal cables between front end QIE cards installed on the detector and FrontEndDevices (called FEDs in the case of HCAL HTRs) located in the S2F row of the USC cavern have the same length. Therefore one can use the time difference between arrival of signal from Top and Bottom sections into HTRs to see if it is consistent with signal arriving from a single muon crossing HCAL at two points.

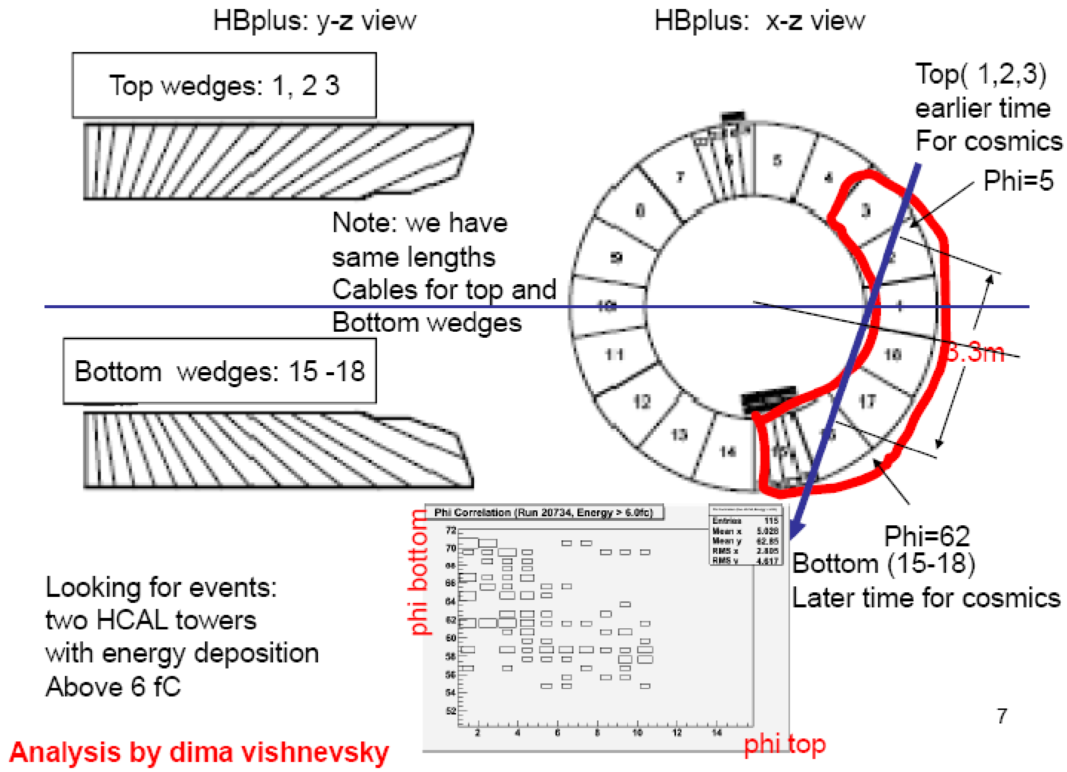

Figure 8: Illustrates looking for events with two HCAL towers with energy deposition above 6fC. During September run, seven HBplus wedges were powered up and read out. In this analysis, wedges 1-3 (phi=71, 72, 1- 10) were designated as ‘top’ wedges and wedges 15-18 (phi=55-70) were designated as ‘bottom’ wedges. The scatter-plot shows correlation between phi of the signal tower in top and bottom wedges.

Figure 9 (left) shows a scatter-plot of timing with respect to DT trigger of HCAL signal in bottom section (y axis) vs timing of HCAL signal in top section (x axis). There is a clear correlation between bottom and top HCAL timing, with most of the events having Time_bottom> Time_top. The right hand side plot shows time difference of HCAL signal, Delta_t = Time_bottom – Time_top. The average time difference observed for 115 events passing selection cuts (E_top> 6fC, E_bottom> 6fC) is 0.5 bx.

Assuming an average radius of HB wedges, R = ~ 2.5m and an average phi angle difference between top and bottom towers crossed by the muon to be 75 deg , the average distance between top and bottom towers is 3.3m. This value is consistent with muon 'time-of-flight' of 0.5bx (12.5ns) which corresponds to a distance of ~3.8m.

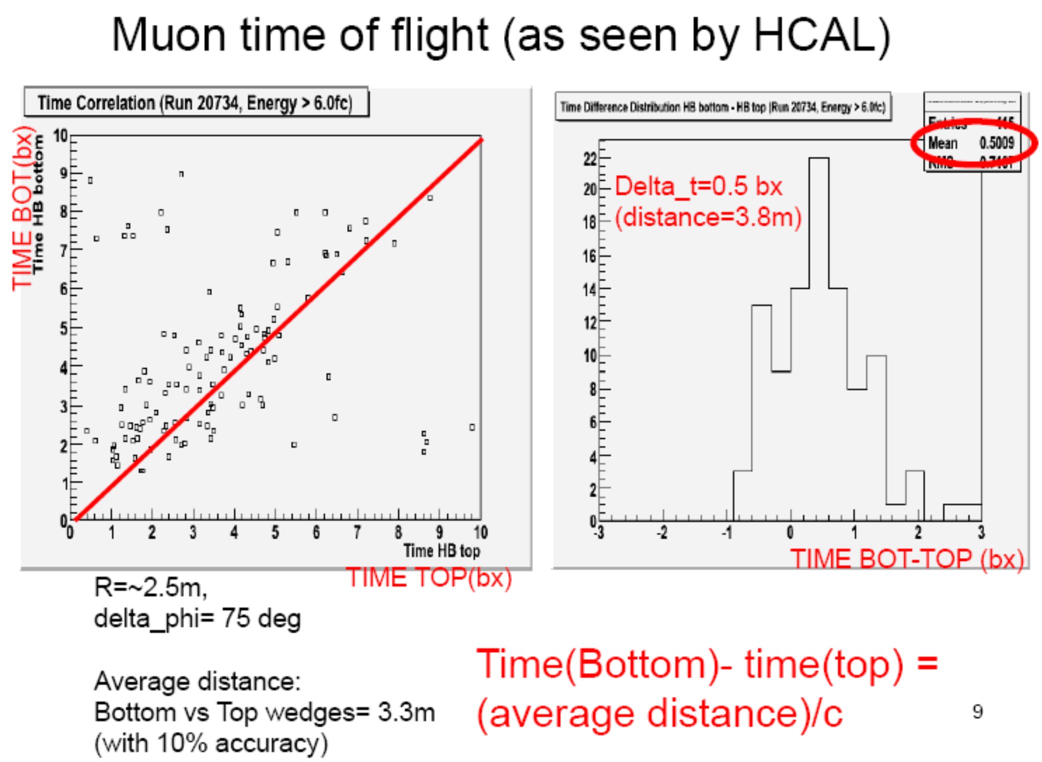

Figure 9:
a) Scatter-plot of event time in bottom wedges vs event time in top wedges.
Top events arrive systematically earlier (below y=x line).
b) Time difference (Bottom-Top). The average difference is ~ 0.5 bunch crossings, corresponding to 3.8m. (1 bunch crossing = 25ns). The average distance between top and bottom phis is ~ 3.3m. The time difference is consistent with time of flight of muons.

6. Iromo22 data set

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Data collected during GRES provided very useful information. Using GRES data, we have established timing in HCAL readout with respect to DT trigger. We have also performed analysis of energy, timing and geometric occupancy distributions for muons observed in HCAL. Unfortunately, due to a loss of synchronization between DT and HCAL event fragments, one could not use the high statistics DT/HCAL run taken at the end of GRES to check correlations between the position of muons as seen by DTs and position of towers with muon signal in HCAL. Therefore, a special, one day integration run was organized on Monday, October 22 (iromo22) in order to collect well synchronized HCAL/DT data. In the remaining part of this note, we summarize analysis of the data collected in the iromo22 run period.

Figure 10 shows a schematic view of the HCAL and DT detector elements participating in the iromo22 run. At that time the entire z- side half-barrel (18 HBminus wedges) was commissioned and included in the HCAL readout. In addition, ten HBplus wedges were fully commissioned and connected to the readout (HBplus wedges 6 through 15). The readout also included four sectors of HO on YB0; S4, and sectors S10-S12. Three DT sectors on YB0 were read out; S10, S11 and S12. However, DT trigger was provided only by sector YB0/S10.

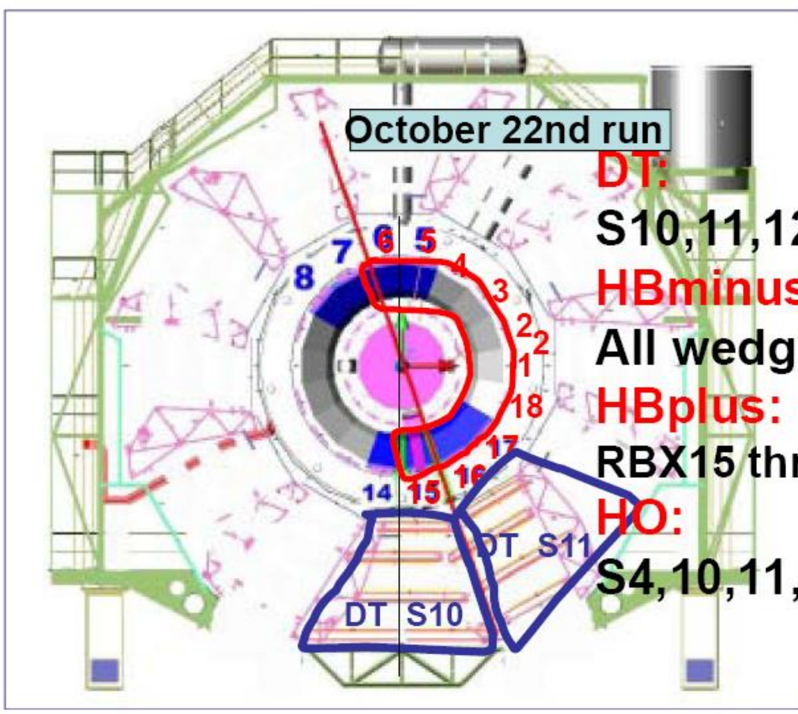

Figure 10: Schematic of CMS detector with parts of DT and HCAL systems participating in the Integration Run on Monday October 22nd (iromo22).

Figure 11 shows details of HO scintillators on the YB0 wheel. There are two layers of scintillator. The first layer is installed immediately outside of the outer vacuum tank of the magnet. The second layer is installed on the outside of the innermost iron yoke plate, approximately 23 cm away from the first layer. Light signals from both layers are combined into a single readout.

A single HO megatile, 30 degree in phi matching DT sectors, is subdivided into six 5 degree towers in phi and 8 towers in eta, delta_phi x delta_eta = 5deg x 0.087. Ring 0 eta coverage extends +/- 0.696 in eta. Note that during October run, moving wheels (Ring +/-1 and +/- 2) were positioned away from Ring 0 (not over the magnet).

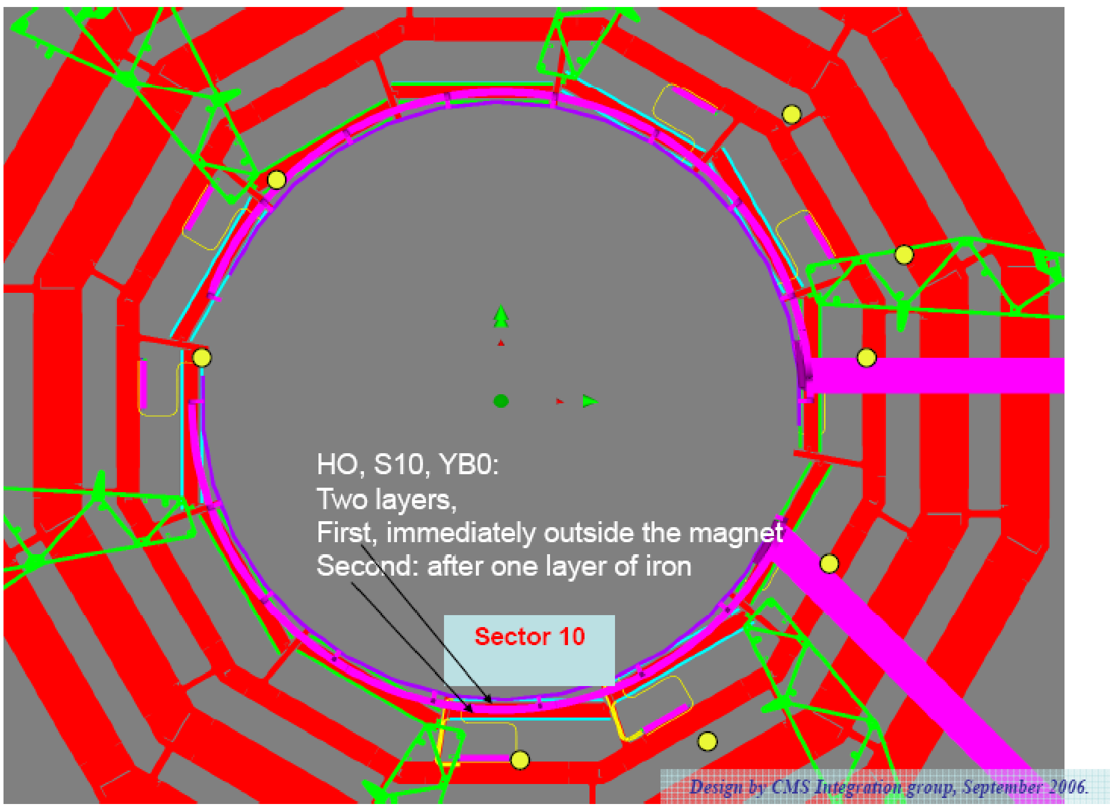

Figure 11: Details of HO detector on YB0 wheel.

Figure 12 shows a diagram of DT sector S10, HO/YB0 Sector10 (S10) and two HB wedges (HB14 and HB15). HB14 covers phi=51, 52, 53, 54. HB15 covers phi= 55-58. HO/S10/YB0 covers six phi's = 53 thru 58.

The scatter plot on the right shows the x-y distribution of hits in four S10 chambers (MB1, MB2, MB3 and MB4). Note that R values on the drawing do not agree with values corresponding to the edges of individual chambers on the plot (most likely obsolete/old picture).

At the end, only one high statistics, 35k events, run was recorded during iromo22, r25179. The trigger included only DT/S10 on YB0 and the trigger rate was ~ 7Hz. As was later verified, there was good synchronization between DT and HCAL fragments.

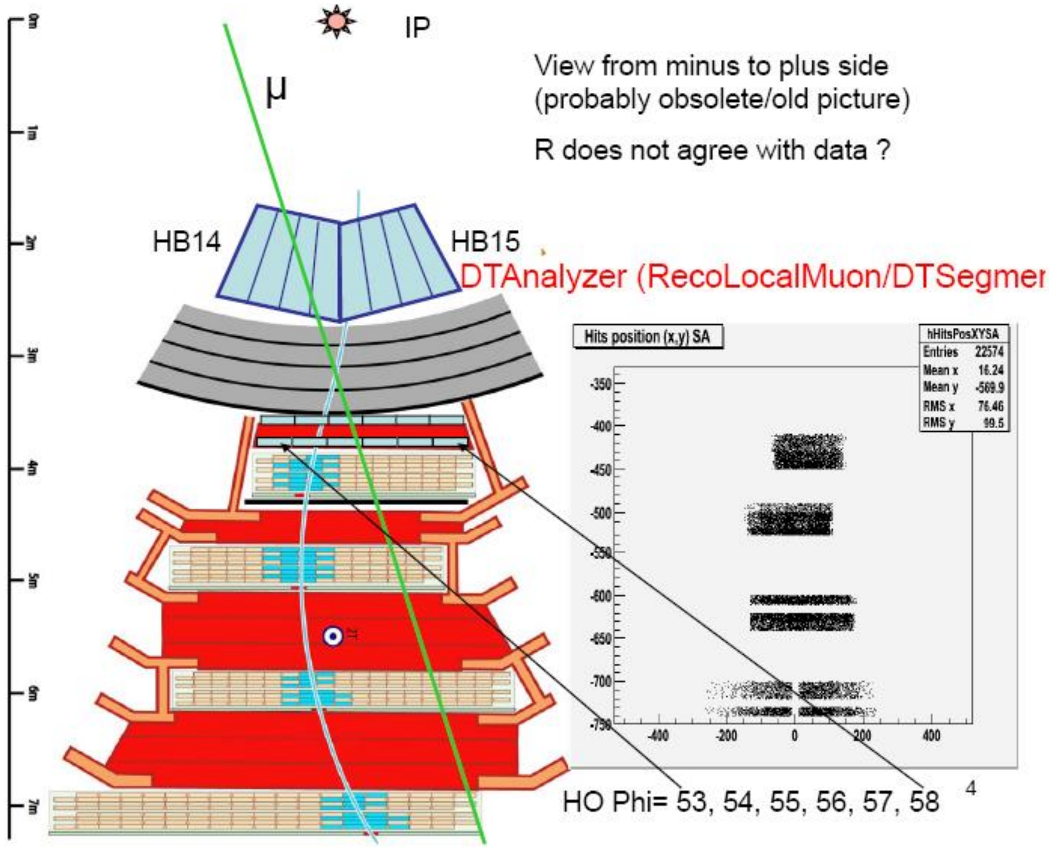

Figure 12: Diagram of DT sector S10 and HB and HO/YB0 Sector10 (S10) and two HB wedges (HB14 and HB15). HB14 covers phi=51, 52, 53, 54. HB covers phi= 55-58. HO/S10/YB0 covers phi= 53 thru 58. The scatter plot on the right shows the x-y distribution of hits in four S10 chambers (MB1, MB2, MB3 and MB4).

7. DT track distributions

Figure 13 shows an example of event display from r25179. This event was triggered by DriftTubeTrackFinder (DTTF). The track passed thru Sectors S10 (bottom) and S4 (top). Note that YB+2 wheel was displaced from its standard position by ~6.5 m (it is moved off the magnet).

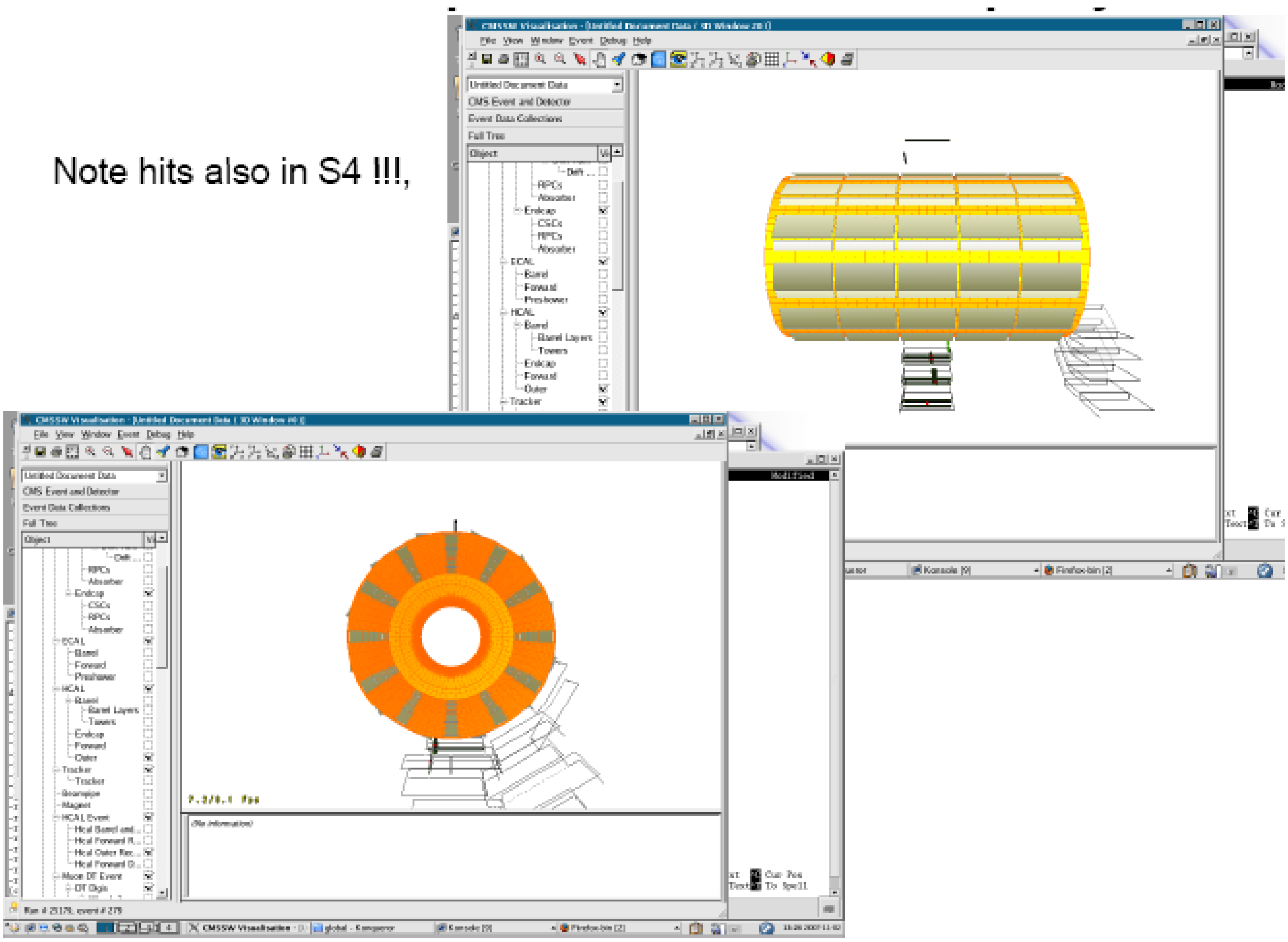

Figure 13: Example of event display from r25179.

Out of 30k triggers more than 14k events had track reconstructed using DTAnalyzer. Figure 14 (upper plot) shows phi distribution of reconstructed DT tracks (in degrees). The distribution is symmetric with respect to phi=0 axis (Near/Far side inside UX5 hall). The width (RMS) of the distribution is 14 degrees. However, as shown the lower plot; theta distribution of reconstructed DT tracks (in degrees) is asymmetric. Asymmetry with respect to theta=0 axis (larger number of events for negative z side) is caused by the fact that flux of the muons is higher on the –z side, which is closer to the ux5 shaft. Fake spike at theta=0 is caused by reconstruction failures in z. Events with reconstruction failures (z=0) were removed from further analysis.

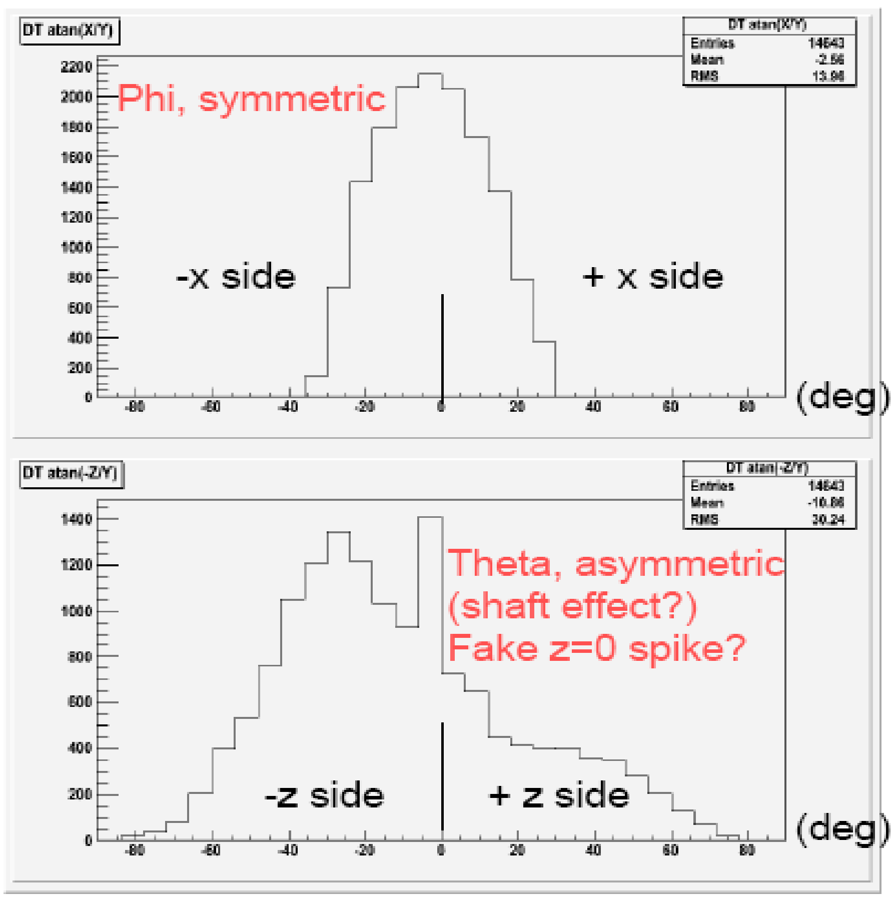

Figure 14:
Upper plot: Phi distribution of reconstructed DT tracks (in degrees).
Lower plot: Theta distribution of reconstructed DT tracks (in degrees).
Note: events with badly reconstructed track (z=0 events) were removed in further analysis.

8. DT track and HB energy correlations

Figures 15 and 16 show scatter-plots of x and z coordinates, DT track extrapolated to the HCAL and position of HCAL tower with energy above 5 fC. The plots demonstrate good correlation between muon track coordinates and signal in HCAL. On Figure 14, two bands of points correspond to HCAL signals in top phi sectors (phi index 51-58) and bottom phi sectors (phi index 15-22). The width of the band for bottom phi sectors (phi index 50-58) is narrower than for top phi sectors (phi index 25-22). This is most likely caused by a large DT track extrapolation error for upper sectors, as DT was providing triggers only from S10 sector, overlapping HCAL phi index 53-58.

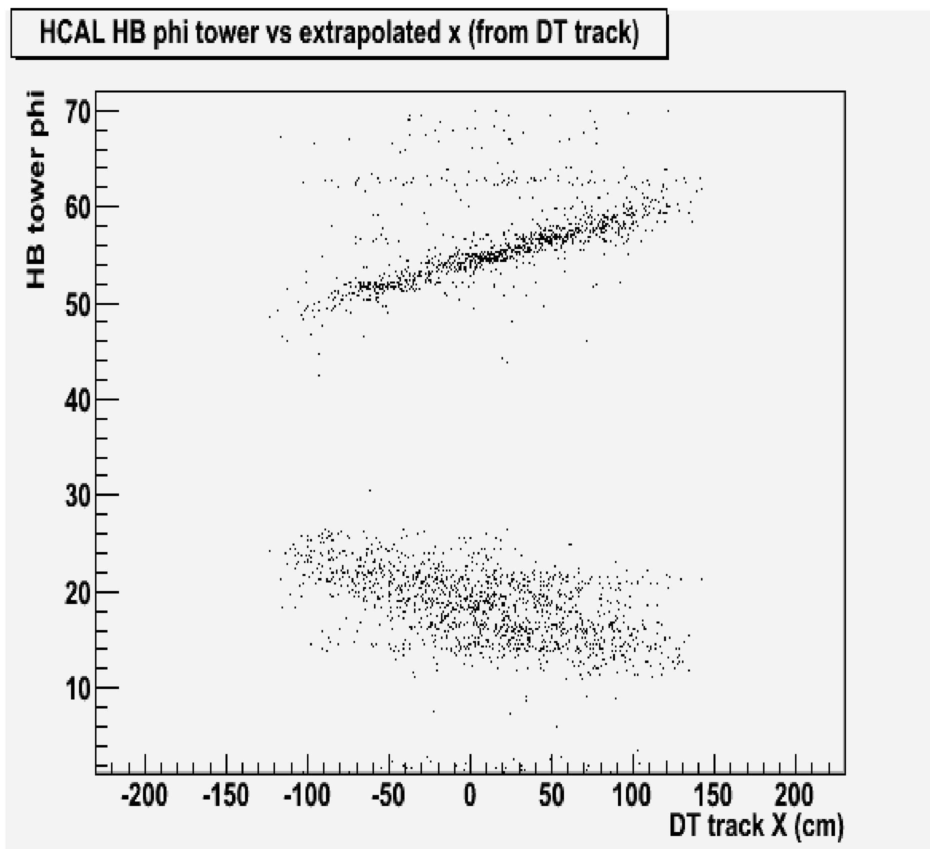

Figure 15: Position correlation between DT track and signal in HCAL. The coordinate where the muon intersected HB (y axis) was determined using phi index of HCAL tower with energy above 5 fC. The position of muon in DT (YB0/S10) was determined by extrapolating muon track to the radius approximately corresponding to the center of HB wedges (R_hcal=2.3m) in the detector x-y plane (x axis on the scatterplot).

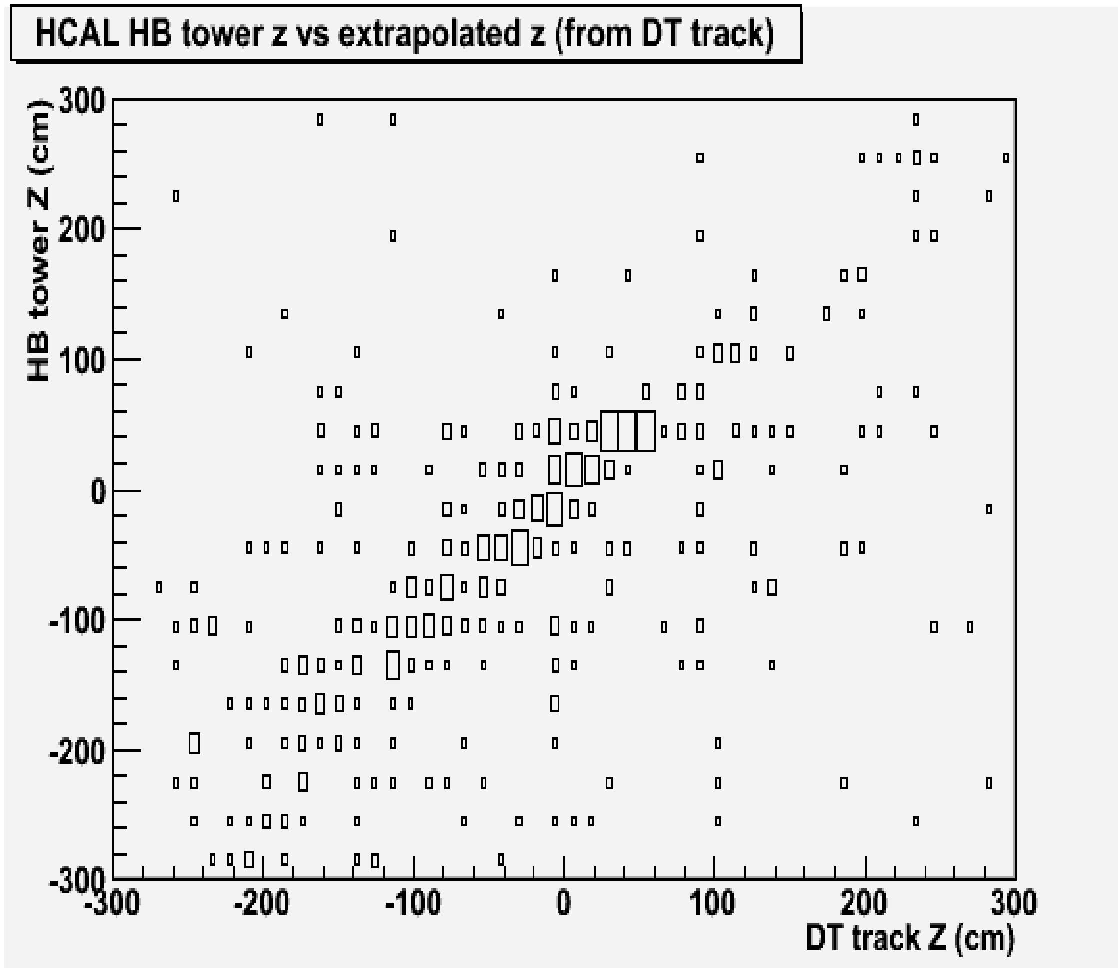

Figure 16: Correlation between DT track and HCAL towers. The position of muon in HB was determined using eta index of HCAL tower with energy above 5 fC (y axis). The position of muon in DT was determined by extrapolating muon track to the radius approximately corresponding to the center of HB wedges (R_hcal=2.3m) in the detector y-z plane (x axis on the scatterplot).

9. DT track and HO energy correlations

In addition, we have studied DT track and HCAL energy correlations in HO. We have used a subset of events with reconstructed DT tracks to check the correlation between x-z coordinates of DT track extrapolated to the surface of HO and coordinates of HO readout tower with energy deposit in HCAL. Out of an over 14k event with DT track, 4735 events passed E(HO)>5 fC cut. Note that HO tower size in phi is approximately 30cm at R=4m.

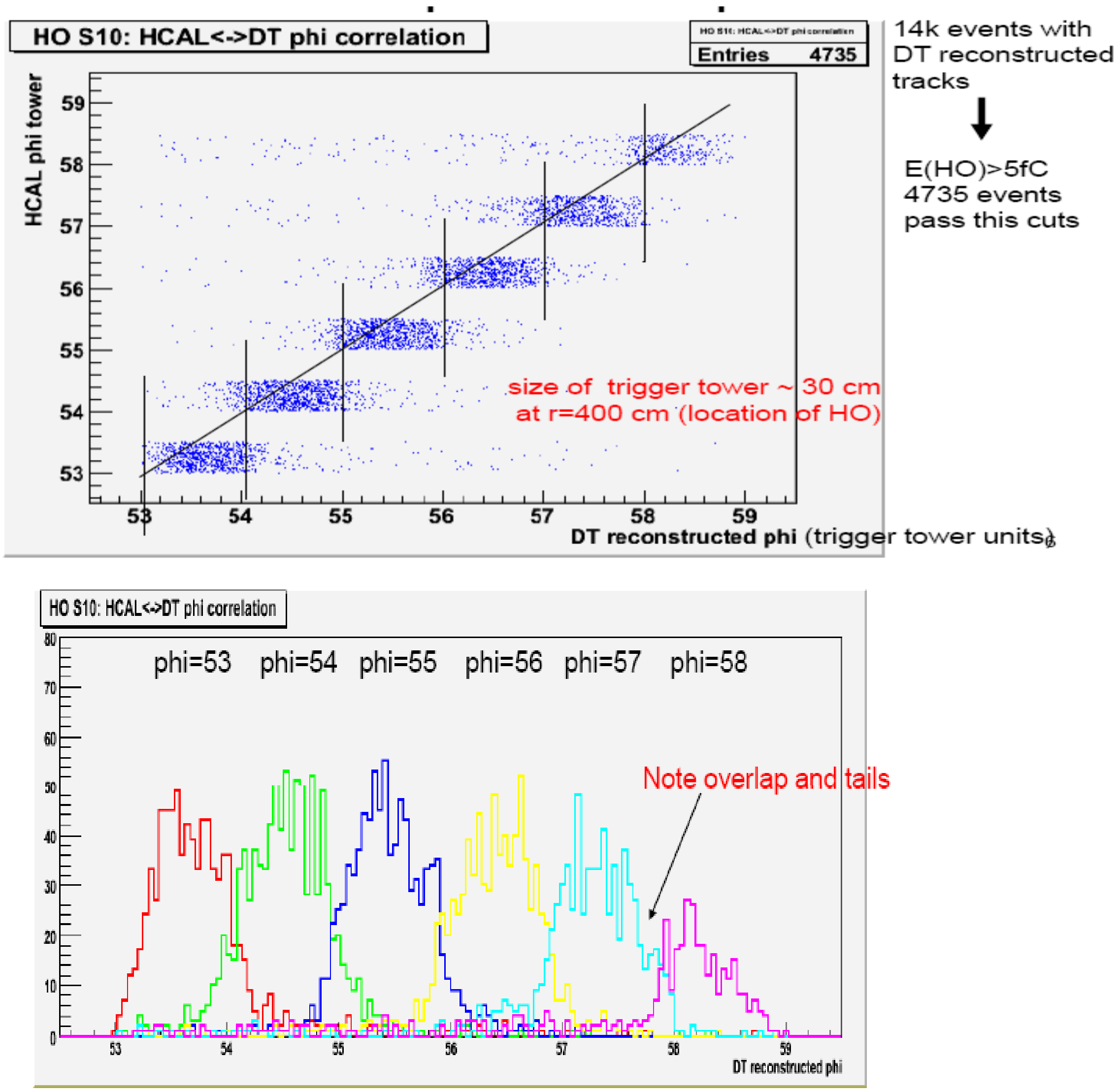

Figure 17:
Upper plot: Phi HCAL/HO tower with energy deposition above 5fC vs detector x position of the DT track extrapolated to the surface of HO scintillator (S10/YB0).
Lower plot: Projection of the same data on the x axis.

Figure 17 (upper plot) shows a scatterplot of phi HCAL/HO tower (y axis) with energy deposition above 5 fC vs detector x position of the DT track extrapolated to the surface of the HO scintillator (x axis). Good correlation indicates that energy deposited in HO is indeed coming from muons. Lower plot shows projection of the same data on the x axis. Extrapolated DT track x distributions are shown in a different color for events with detected energy in HO>5fC, using a different color for each phi in S10. Note some overlap (+/- 5cm) and tails in extrapolated x distributions, which could be caused by poor track extrapolation or noise in HO.

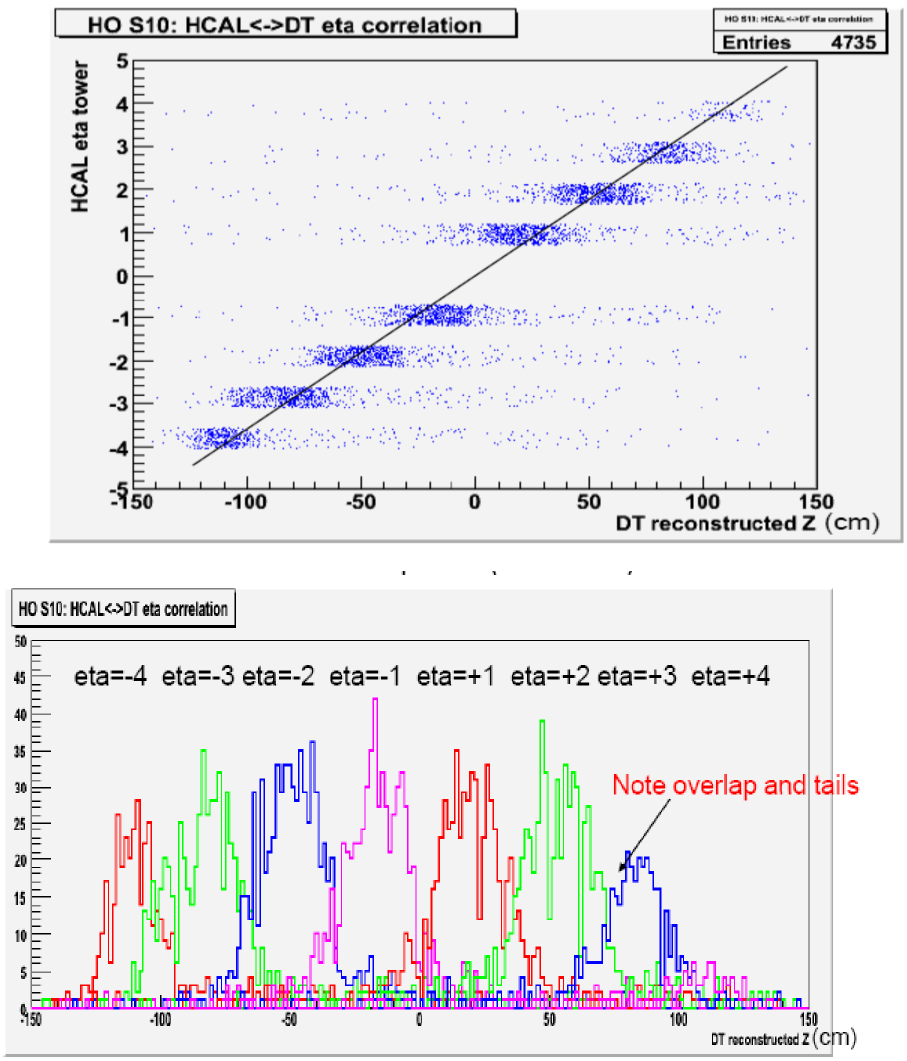

Figure 18:
Upper plot: Eta of HCAL/HO tower with energy deposition above 5fC vs detector z position of the DT track extrapolated to the surface of HO scintillator (S10/YB0).
Lower plot: Projection of the same data on the x axis.

A similar check of the correlation of energy observed in HO and position of DT extrapolated track was done in eta (detector z) direction. The following two plots (Figure 18) demonstrate that there is good correlation between the index of eta tower in HO and the value of detector z (in cm) from DT track to the position extrapolated to the surface of HO scintillator. HO/YB0/S10 spans from eta index =-4, corresponding to z=-110cm to eta index = 4, corresponding to z =+110cm.

10. Study of HO muon energy spectrum

In order to make an unbiased comparison of the energy spectrum of cosmic ray muons observed in HO, events were selected with the following criteria:

1. The DT track passes through same eta/phi tower in both layers of HO/YB0
2. The track is extrapolated to HO plane and used as a pointer to select HO seed tower
3. A 3x3 block of HO towers is searched and a tower is selected with the highest energy deposition

Note that this is fully unbiased selection, as no explicit energy cut is applied on the HO energy spectrum. However, the algorithm by design shifted the energy spectrum up from zero, as it selected the tower with highest energy. The magnitude of the shift was estimated by running the same algorithm on a sample of random trigger events (pedestals).

Figure 19 shows the HO energy spectrum extracted using the algorithm described above. The red (solid line) histogram corresponds to muon spectrum (DT triggers, r25179). The mean (average) value of the spectrum is 4.8fC. The blue (dashed line) histogram corresponds to the spectrum obtained by analyzing random trigger HO data (pedestal events). The mean energy for shift is 1.4fC.

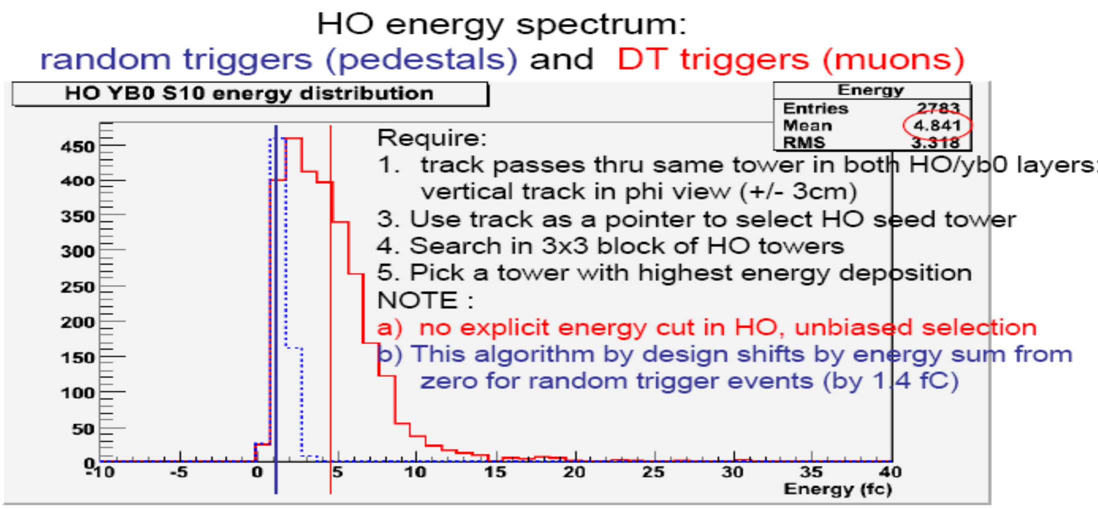

Figure 19: Energy spectrum in HO showing random triggers (pedestal events, blue-dashed curve) and DT triggers (muon events, red-solid curve).

In HO/YB0, two consecutive phi slices are read out be a single HybridPhotoDetector (HPD). HPD gain is one of the factors that determines the amplitude of muon signal. For HO, variation of HPD gain is at the level of 10%. The data shown in Figure 20 is separated by phi sections which are read out by the same HPD. Note that distributions shown here correspond to 1.5 hours of data taking using a single DT sector (S10/YB0), with trigger rate of ~ 7Hz. The average of energy depositions of muons in the three groups (corrected for 1.4fC shift) are 3.7fC, 3.3fC and 3.4fC.

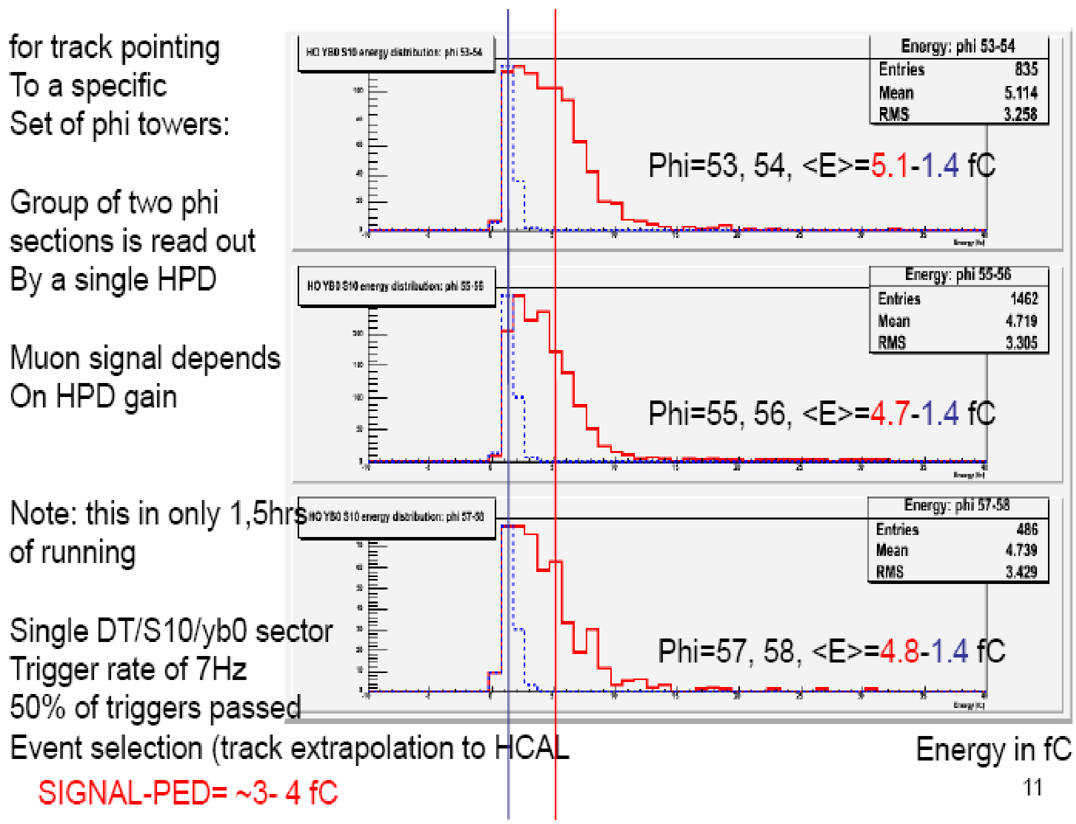

Figure 20: Spectra for HO, separated into three groups; Phi=53 and 54, Phi=55 and 56, Phi=57 and 58.

Figure 21 shows reference muon spectrum observed in H2 setup TestBeam 2003. Here muons were directed into the center of a single eta/phi tower, aligned with the tower axis. The upper plot shows single tower spectrum for muons. The lower plot shows spectrum for random trigger (pedestal) events. Here, energy is in ADC counts (w/o pedestal subtraction). Results are consistent with spectra measured with UX5 DT triggered data.

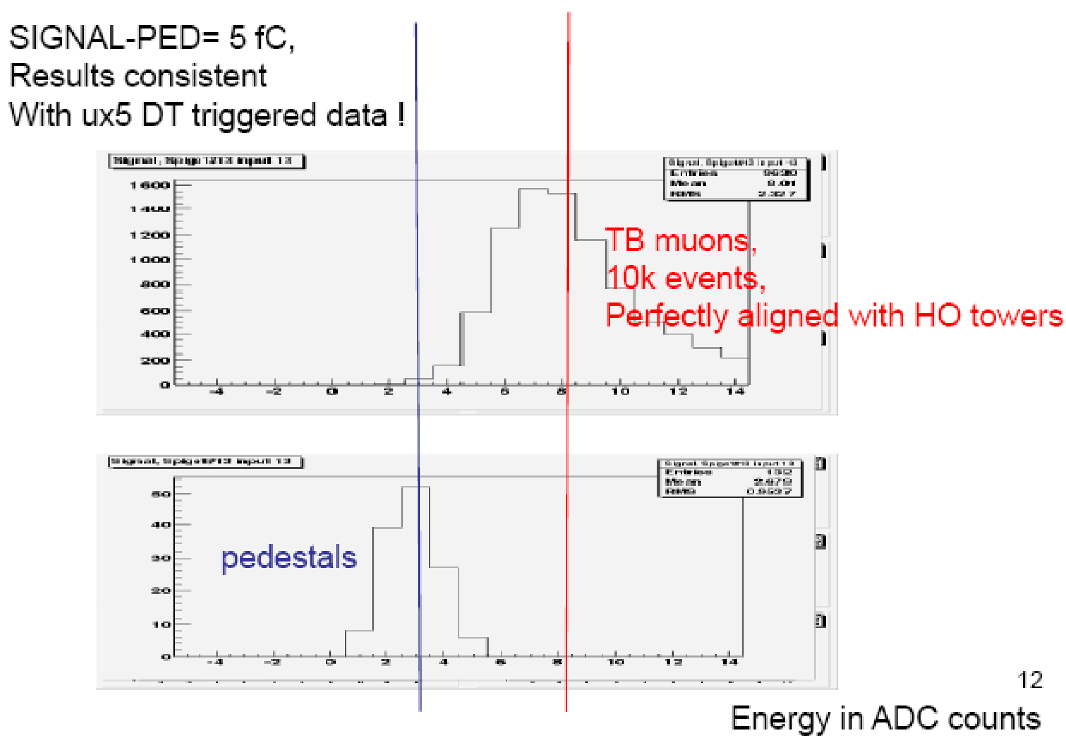

Figure 21: Muon spectrum recorded in H2 testbeam facility in 2003.

11. Study of choice of threshold for HCAL muon trigger

In Appendix A we have described estimates of noise rates for HCAL muon trigger. The conclusions from the study of noise rates for HCAL muon trigger are the following:

a) The singles noise rates are too high (in kHz) with respect to expected muon rates (in Hz), even for relatively high thresholds.
b) Coincidence noise rates for detector configuration with 8 HB wedges on top and 8 HB wedges on bottom, but without back-to-back requirement are at the level of 200 Hz for threshold of 4 ADC counts
c) The rate is a factor of 32 lower (6 Hz) if one requires back-to-back trigger with two towers, such that pedestal subtracted energy of two consecutive time slices (TS) is above 4 ADC counts: (2TS-ped)>4

In order to determine the optimal value of the threshold for the HCAL muon trigger, we have studied the efficiency of muons to pass HCAL muon trigger as a function of trigger threshold. We have used a subset of muon events from run 25179. Muon events were selected using reconstructd DT tracks. Only muons passing through HBminus eta towers -1 through -12 were included. We required muon passes through top wedges 4-7 (phi=11 – 26), and through bottom wedgs 13-16 (phi= 47-62). At least one tower in the top wedges and at least one tower in the bottom wedges had to have energy in a same bunch crossing of (2TS-ped)> 4. Figure 22 shows the efficiency curve for a muon to pass the HCAL trigger requirement in top and bottom sections. For threshold of 4, the probability of a muon to pass the trigger requirement is above 20%. However, for a threshold of 5, probability falls to the level of 6%.

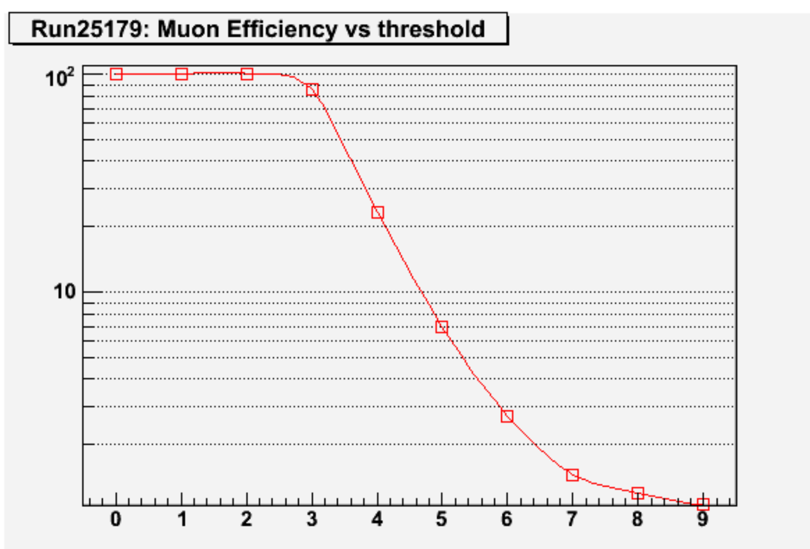

Figure 22: Efficiency of Muons to pass ‘HCAL muon trigger’ vs threshold, in ADC counts. Muons to pass the trigger require coincidence of at least two towers.

Figure 23 shows geometrical (eta vs phi) distribution of HCAL towers passing two different HCAL muon trigger criteria. The upper plot corresponds to events passing HCAL muon trigger: (2TS-ped> 5 ADC counts). Using this threshold, we observe that muons pass this trigger requirement: there is increased density of points in the region of eta index=0 and phi index=54 (bottom wedges) and eta index=-7 and phi index =18 (top wedges). The lower plot corresponds to events that pass HCAL muon trigger criteria with threshold=10 ADC counts. In this particular case, only noise events pass the trigger requirement. For some phi values (for example phi index=64 on the –z side) increase density implies large noise from HPD reading out this particular 5 degree section of HCAL.

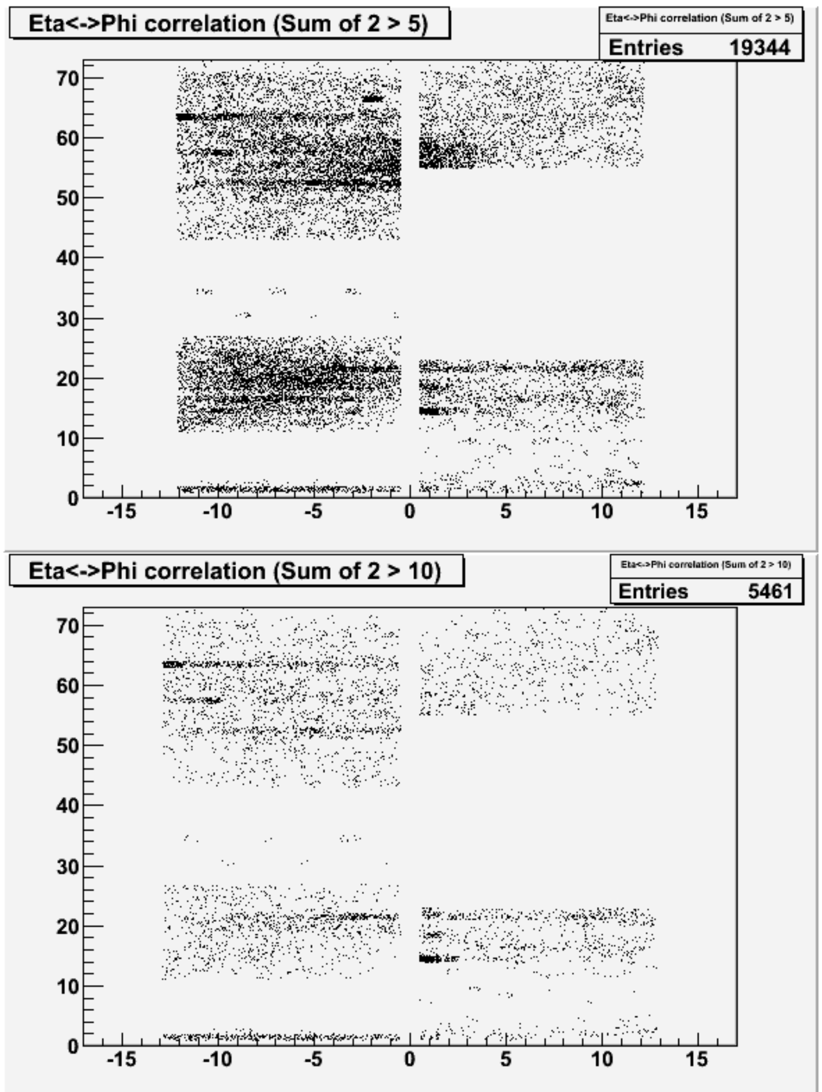

Figure 23: Geometrical (phi v eta) distribution of muon events from run 25179.
Upper plot : Events that pass HCAL muon trigger criteria (2TS-ped> 5).
Lower plot: Events that pass HCAL muon trigger criteria (2TS-ped)>10.

12. Summary

HCAL participation in Global Run at the End of September (GRES) was very successful. The readout of HCAL has been timed in wrt to DT and RPC triggers. Clear muon signal in HCAL was observed when looking at events triggered by DT (~5.5% of triggers).

We have also observed events with energy deposition (E> 6 fC) in two hcal towers, one in the upper and the other in the lower section of HCAL half-barrel. These events were consistent with a muon (muons) passing thru the top and bottom wedges. Top-to-Bottom time difference (0.5 bx) is consistent with the speed-of-light.

On October 22, we took an integration run to address the problems noticed during GRES, in particular the apparent mismatch between DT and HCAL event fragments noticed in R20734. Analysis of October 22nd run (R25179) provided proof of good matching between DT track position extrapolated to HCAL (HB and HO) and muon signal observed in HCAL. It also provided a chance to take a first look at the analysis of cosmic muon energy spectra. The muon energy spectra observed in this run are consistent with muon energy spectra observed in the TestBeam H2 setup in 2003.

Approximate trigger rate of a single YB0 sector varies from 7Hz (S10. or vertical axis) to few Hz (S1, or horizontal axis). In roughly 5% of DT/YB0/S10 triggers, one observes energy deposit above 7.5fC in an HB single tower. In roughly 1% of such triggers, two HB towers, one in the top and one in the bottom section, have energy deposits above 6fC.

Approximately 10% of DT triggers have tracks which intersect HO/YB0 counters crossing both layers of HO within same 10 degree phi sector. Thus, in an hour of running (at 7Hz), one can collect statistics of 1k DT events which can be used to validate HO calibration. Muon energy spectrum in HO/YB0 has RMS/mean of 100%. This implies that a few days of running would provide enough events to obtain a few percent statistical accuracy in measurement of HO muon energy spectrum.

Clearly, to establish HO absolute and relative energy calibration, one will need large amount of statistics data taken with the magnetic field on. The data taken so far, and any data taken with magnet off, should be considered as a practice run for future, magnet-on, high statistics data.

Study of HCAL noise rates indicate that requirement of back-to-back coincidence in four top and four bottom wedges for a pedestal subtracted sum of two consecutive time slices and threshold of 4 ADC counts (2TS-ped>4) should result in a trigger rate of ~ 6 Hz. Applying these trigger criteria to a subset of muons selected with DT tracks yielded efficiency for selecting muons at level of 20% (2TS-ped>4) and 5% (2TS-ped>5).

13. Acknowledgements

We would like to acknowledge help and support we have received in preparation for and during the integration run on Monday, October 22nd from the entire HCAL group. We also would like to thank other CMS groups which made that run possible: DT group (Marina Passaseo, Luigi Guiducci, Marina Giunta, Marco Zanetti, Ugo Gasparini, Marco Dallavalle, Alberto Benvenuti, Stefano Lacaprara), GT group (Ivan Mikulec, Christian Hartl), DTTF group (Jorge Fernandez De Troconiz, Janos Ero, Emmanuelle Perez), CDAQ group (Gerry Bauer) and EventDisplay group (Ianna Osborne). We are grateful to Tina Vernon to proof-reading this note.

Appendix A. Estimate of noise rates for HCAL muon trigger

We have made an estimate of noise rates for various schemes of HCAL muon trigger. For this purpose, we have analyzed pedestal runs recorded in local mode with random triggers. Figure A1 shows raw ADC distributions (one time slice) for 864 channels for HB, partition a (six HBplus and six HBminus wedges). Pedestals for HB have been flattened. DAC (norm) settings were chosen independently for each of the qie channel, so that mean pedestal is approximately 3 ADC counts. The upper plot shows data in linear y scale, the lower plot shows same data in logy scale.

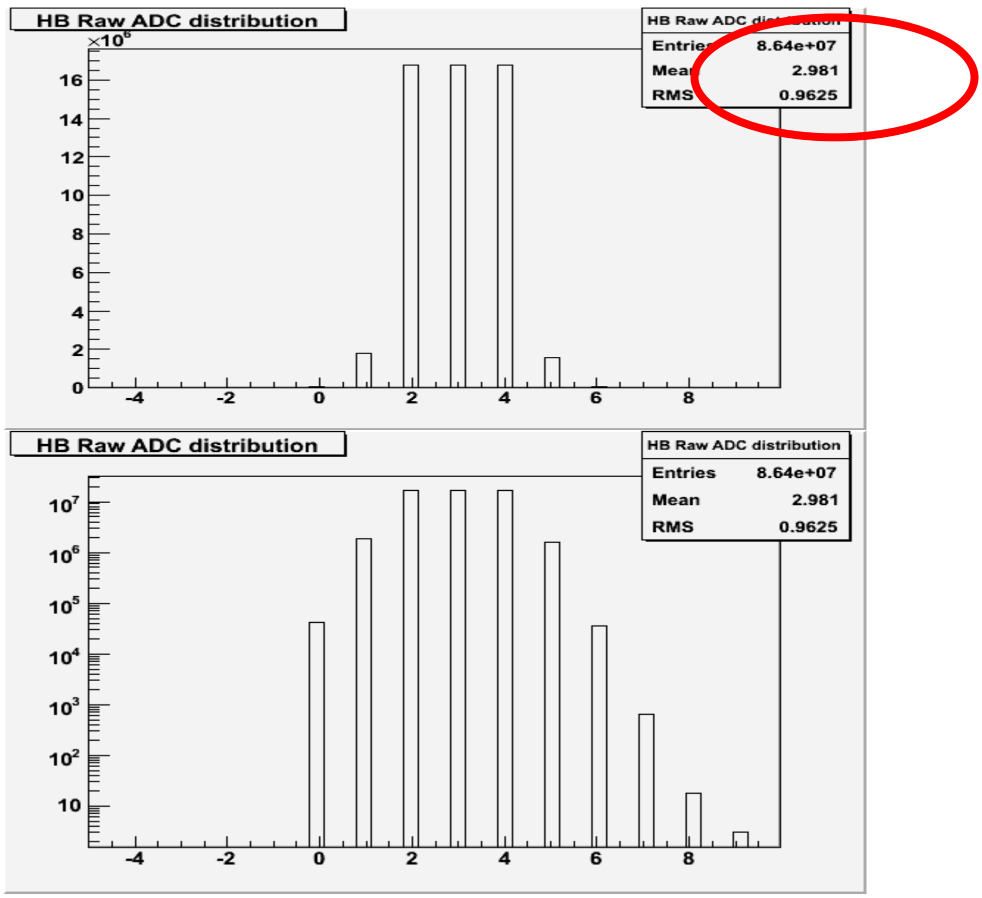

Figure A.1: R29413, partition Ha, 864 channels active, 10k events. Raw ADC value distributions, one time slice (1TS). Upper plot: Linear scale. Lower plot shows same data in log scale. For this setting, assuming symmetric pedestal distribution, less than 10**(-5) events would fluctuate below zero.

Next, we simulate trigger firmware in the HTR, i.e. we look at the distribution of the sum of two consecutive time slices and subtract average pedestal (in this particular case =3 ADC counts/time slice). Figure A.2 shows these distributions for HB, partition_a. Figure A.3 shows an integrated distribution of (2TS-ped) for HCAL vs threshold. Using this distribution, we would like to determine at which rate pedestal subtracted two time-slice sums (2TS-ped) are above the given threshold.

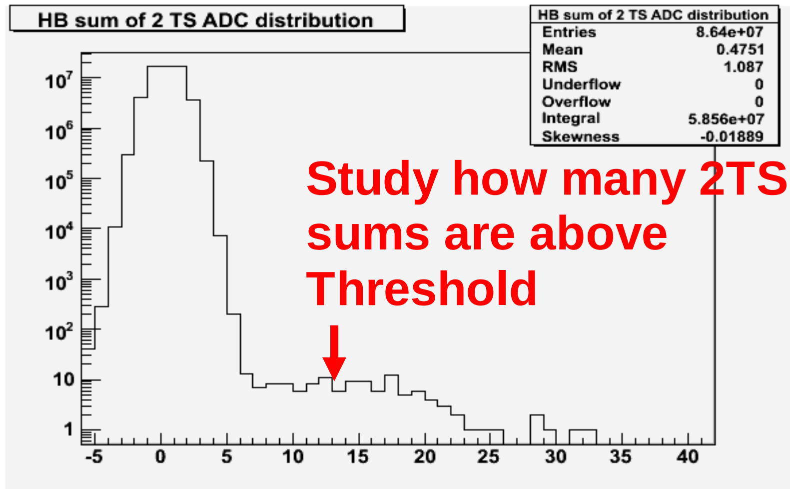

Figure A.2: Sum of two consecutive time slices with pedestal subtraction of 6 (assume Ped=3 per TimeSlice). HCAL trigger check 2TS is running sum against threshold. Here, Signal is defined as: Signal = 2TS(raw, in adc) – 6. The data shown here is for 10k run for Ha partition (864 channels/event, 10k events, 10 entries/event = 8.64*10**7).

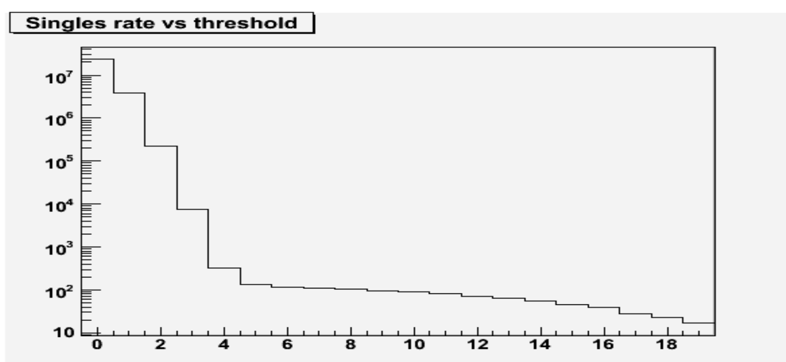

Figure A.3: Integrated number of HCAL towers with (2TS sum – ped)> Th vs threshold. Data corresponds to 10k pedestal run, taken for partition HBHEa. Front-end (LV) was powered only for a total of 12 wedges (six on HBplus and six on HBminus).

Since each event contains 10 bunch crossings, 10k triggers correspond to 100k bunch crossings. In one second there are 40M bunch crossings (400 times more that in 10k triggers). Thus, in order to convert the number of observed events (for 10k triggers, HB, partition_a) to the expected rate (in Hz), one should multiply the number of observed events by 400.

To obtain noise rates for different detector configurations, one needs to scale the event rate for HB only, partition_a by the ratio of number of towers for a given detector configuration. Detector configuration for HB only, partition_a, consists of 12 wedges. Full HB consists of three times more wedges (36). A detector subset considered to be active for HB muon trigger test included a total of 16 wedges: 8 wedges on the top, (HBplus and HBminus wedges 13, 14, 15, 16) and eight wedges on the bottom (HBplus and HBminus wedges 4, 5, 6 and 7).

Sum	Events for (100 k bunch crossings) HB only (12 wedges) partition_a (N_th)	Singles rate, For full HB, 36 wedges (expected)	Singles rate, 8 TOP x 8 BOT, 16 wedges (expected)
2TS-ped>3	7523	7523*400*3=9.0 MHz	7523*400*(16/12)= 4.0 MHz
2TS-ped>4	328	328*400*3=393 kHz	328*400*(16/12)= 174 kHz
2TS-ped>5	131	131*400*3=157 kHz	131*400*(16/12)= 70 kHz

The table above summarizes the observed number of events passing a given cut and extrapolated singles rates, expected for the given threshold and particular detector configuration. Clearly the singles noise rates are too high (in kHz) with respect to expected muon rates (in Hz), even for relatively high thresholds.

Given these singles HCAL noise rates, it is clear that the only practical way for HCAL to trigger on muons is to require coincidence between muon signal in top and bottom wedges. Using the above table, one can predict the number of random coincidences, when noise in two towers (one from the top and one from the bottom) crosses the threshold in same bunch crossing.

In this calculation, we assume that one of the towers is within a particular half of the detector (top wedges) and the other tower is in the other half of the detector (bottom wedges):

P1= (1/2*N_th/100k) (probability of a single tower above threshold in a single bucket)
P2= P1*P1 (probability of two towers above threshold in a single bucket)
R2 = P2*100k*400 (number of coincidences per second, equiv. to rate in Hz)

The table below summarizes the coincidence noise rate estimates for three different detector configurations. Note that HCAL trigger sector consists of 4x4 HCAL towers, thus there are 4 trigger sectors per one 20degree HB wedge. Third column corresponds to the rate estimate when one half of the HB partition_a was used as ‘top’ detector and the other half as ‘bottom detector. This leads to a total of 24x24 possible trigger tower combinations. The fourth column corresponds to the rate for detector configuration, with 8 HB wedges on top and 8 HB wedges on the bottom. Here we assume that signal from any trigger section can match signal from any trigger section on the bottom. This leads to a total of 32x32 possible combinations. In the fifth column, we consider the case of back-to-back trigger, which reduces number of possible noise combinations by factor of 32.

Sum	P1= 1/2*N_th/100k	Coincidence rate, 6 x 6 wedges 24 x 24 trigger sector combinations	Coincidence rate, 8 TOP x 8 BOT Any combination of 32 x 32 trigger sector combinations	Coincidence rate, 8 TOP x 8 BOT (back-to-back only, Total of 32 combinations
2TS-ped>3	0.037	139 *400 = 56 kHz	96 kHz	3 kHz
2TS-ped>4	0.002	0.3* 400 = 106 Hz	192 Hz	6 Hz

The conclusions from study of noise rates for HCAL muon trigger are the following:

d) The singles noise rates are too high (in kHz) with respect to expected muon rates (in Hz), even for relatively high thresholds.
e) Coincidence noise rates for detector configuration with 8 HB wedges on top and 8 HB wedges on the bottom, but without back-to-back requirement are at the level of 200 Hz for the threshold of 4 ADC counts
f) The rate is factor of 32 lower (6 Hz) if one requires back-to-back trigger with two towers, such that : (2TS-ped)>4 ADC counts

As a verification of the above HCAL coincidence noise rate estimates, we have counted the number coincidence events we observed in the pedestal run (r24913). We have subdivided HB (partition_a) into two halves. Then we have counted how many events pass the condition that there is a tower in each of the halves with (2TS-ped> Th) in same bunch crossing (see Figure A.4). We have observed 437 coincidence events for Th=3 ADC counts. This is a factor of three higher than the number of events predicted using extrapolation from singles rates.

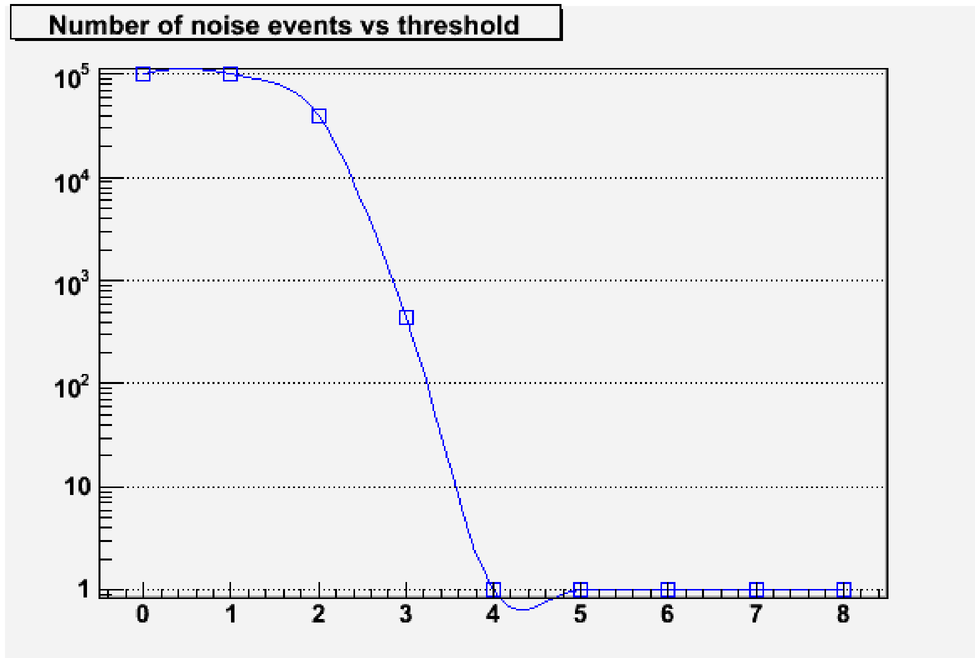

Figure A.4: The number of events with two different towers with pedestal subtracted energy in two consecutive time slices above given threshold (in ADC counts), 2TS-ped> Th. Data corresponds to r24913, 10k random (pedestal) triggers, HB only, partition_a. This is equivalent to 100k bunch crossings.