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Identification and filtering of uncharacteristic noise in the CMS hadron calorimeter

CMS Collaboration

ABSTRACT: Commissioning studies of the CMS hadron calorimeter have identified sporadic uncharacteristic noise and a small number of malfunctioning calorimeter channels. Algorithms have been developed to identify and address these problems in the data. The methods have been tested on cosmic ray muon data, calorimeter noise data, and single beam data collected with CMS in 2008. The noise rejection algorithms can be applied to LHC collision data at the trigger level or in the offline analysis. The application of the algorithms at the trigger level is shown to remove 90% of noise events with fake missing transverse energy above 100 GeV, which is sufficient for the CMS physics trigger operation.

KEYWORDS: Calorimeters; Large detector systems for particle and astroparticle physics

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1 Introduction

The primary goal of the Compact Muon Solenoid (CMS) experiment [1] is to explore physics at the TeV energy scale, exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) [2]. The CMS hadron calorimeter (HCAL), together with the electromagnetic calorimeter, form a complete calorimetry system for the measurements of jets and missing transverse energy (MET). The measurement of jets and MET is essential for identifying many Standard Model processes (e.g., QCD multi-jets, top, W+jets, and Z+jets) as well as new physics signatures.

Early commissioning studies have identified a small number of non-responsive readout channels within the hadron calorimeter [3]. Low rates of sporadic noise, in which the hadron calorimeter reports spurious energy deposition, have also been observed. Although the overall rate is low, such noise can result in large values of measured MET. Triggers that rely on MET can thus be particularly affected by this noise. Rejection algorithms have been developed to remove events identified as noisy at the trigger level.

The results presented here are based on data collected from detector commissioning tests without the solenoidal field and with the solenoidal magnet operating at its nominal axial field strength of 3.8 T, and from initial LHC tests circulating single beams of protons. A collection of 300 million cosmic ray muon events was recorded from the Cosmic RUn at ZEro Tesla (CRUZET), a set of commissioning runs taken between May and September 2008 with the magnetic field off. A month-long detector-commissioning exercise undertaken from October to November 2008, referred to as the Cosmic Run At Four Tesla (CRAFT), was used to collect 270 million cosmic ray-triggered events with the CMS solenoidal magnet ramped to 3.8 T. Data from single beams of 450 GeV/c

protons were collected in September 2008, with the solenoid off. Single beam data included "halo" events, in which muons produced from interactions of off-axis beam protons with beamline elements traversed the detector, and "splash" events, in which the beam was intentionally directed into closed collimators 150 m upstream of CMS, resulting in high muon fluxes and large energy signatures in the calorimeter.

An overview of the CMS hadron calorimeter hardware and readout electronics chain is provided in section 2. The construction of physics objects from the hardware output is also addressed. Observed problems in the hadron calorimeter output discovered during detector commissioning are described in section 3. Section 4.1 details the algorithms used to detect and flag such problems, as well as methods for filtering events identified as noise. Section 4.2 summarizes the performance of noise identification and filtering algorithms on commissioning data and Monte Carlo (MC) simulated events.

2 CMS calorimeter description

The CMS detector is composed of an inner silicon tracking system surrounded by a scintillating crystal electromagnetic calorimeter, a brass/steel sampling hadron calorimeter, and muon detectors. The tracker and the majority of the calorimeters lie within the cryostat of the solenoidal magnet. The muon detectors and portions of HCAL lie outside the cryostat. Data from all these systems are filtered through a two-level trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events with a latency of two microseconds. The High Level Trigger (HLT) processor farm further decreases the event rate from 100 kHz to 100 Hz before data storage [1]. HLT paths based on missing transverse energy are particularly sensitive to HCAL noise, as discussed in section 4.1.

2.1 HCAL design

The HCAL detector is divided into four subdetectors (figure 1), comprising a total of 9072 channels. The HCAL barrel (HB) and endcap (HE) detectors surround the electromagnetic calorimeter, and are contained completely within the high magnetic field region of the solenoid. HB provides coverage in the pseudorapidity (η) range $|\eta| < 1.4$, while HE provides overlapping coverage in the region $1.3 < |\eta| < 3.0$. The HCAL forward calorimeters (HF) provide measurements of energetic forward jets and increase the hermeticity of the missing transverse energy measurement. The HF subdetectors extend the HCAL pseudorapidity coverage into the $|\eta|$ region 2.9–5.0. The effective HCAL thickness in the region $|\eta| < 1.3$ is extended by the addition of an array of "outer barrel" (HO) scintillators outside the magnet cryostat. Each subdetector spans the full range of the azimuthal angle ϕ.

The HB and HE subdetectors consist of layers of plastic scintillator within a brass/stainless steel absorber. These subdetectors are segmented into readout channels that cover an area of 0.087×0.087 in $\eta - \phi$ space. In the regions where $|\eta|$ is greater than 1.74, the ϕ segmentation is more coarsely granulated. Scintillation light is detected by hybrid photodiodes (HPDs), with each HPD collecting signals from 18 different HCAL channels.

The HF subdetector is a Cerenkov light detector made of quartz fibers embedded within a 165 cm long steel absorber. There are two types of fibers within HF: "long" fibers that span the

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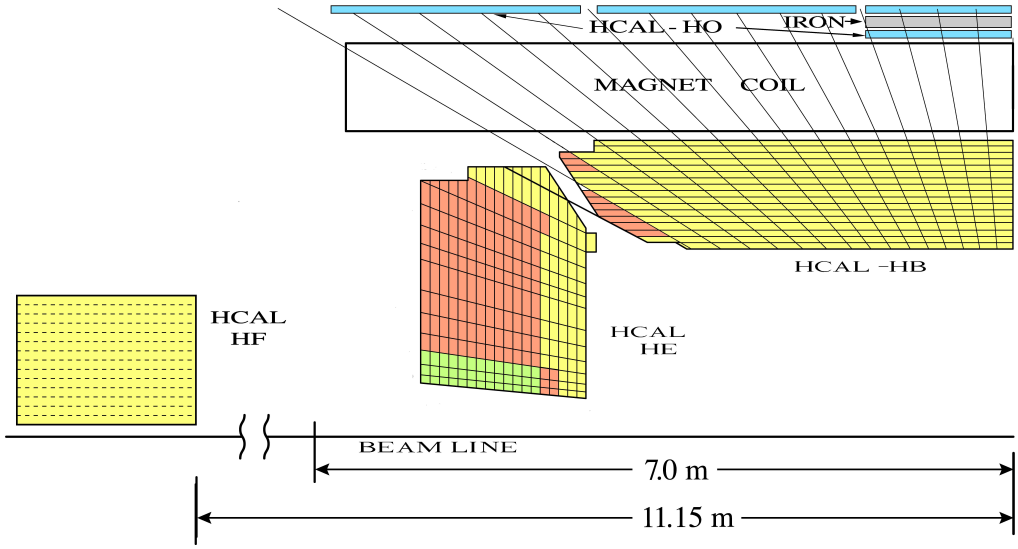

Figure 1. Quarter view of the CMS hadron calorimeter. The shading indicates the optical grouping of scintillator layers into different longitudinal readouts.

length of the subdetector, and "short" fibers that begin 22 cm into the detector. Differences between signals read out from the long and short fibers are used to distinguish between electromagnetic and hadronic showers. Long and short fibers are separately grouped to span 0.174 radians in ϕ, and intervals in η ranging between 0.111 and 0.178. Each group is read out separately as a single HF channel. (In the region $|\eta| > 4.7$, each HF channel covers 0.348 rad in ϕ.) Photomultiplier tubes (PMTs) connected to the fibers via light guides convert detected light to electrical signals.

Seven-bit analog-to-digital converters (ADCs) digitize the signals from the calorimeter for readout. Signals from 4 HPDs or 72 PMTs are digitized within a single 72-channel readout box (RBX). Further discussions of the design and performance of the HB, HE, and HF subdetectors can be found in refs. [4, 5].

2.2 Reconstruction of HCAL objects

The ADC output of each calorimeter channel is computed every 25 ns, once per LHC clock cycle. The size and shape of the ADC output over a period of up to ten consecutive 25 ns intervals ("time slices"), along with the appropriate conversion constants, allow the measurement of the energy deposited and the time when the energy deposition occurred. Calibration with LED and laser sources, as well as with radioactive sources of known energy, ensures that the conversion constants provide the correct output energy values [1].

The CMS reconstruction software stores the reported energy and time information for all HCAL channels with energy greater than 0.3–0.8 GeV in an event, with the exact threshold varying by subdetector and geometric location of the channel. A "quality flag" is also stored for each channel. Quality flags are used to identify specific occurrences in which otherwise well-behaving channels display anomalous responses, as described in section 4.1. The quality flags also indicate whether additional corrections were applied when reconstructing a channel's energy and time infor-

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mation. Channels that show persistent problems are tracked within a separate status database [6]. Information from both the quality flags and the status database is used in constructing physics objects from the HCAL channels.

Reconstructed HCAL energies are combined with information from the electromagnetic calorimeter to form projective calorimeter towers. These towers contain the sums of energies from their constituent electromagnetic calorimeter and HCAL channels. A channel that is identified as problematic, either by its quality flag or by information in the status database, may be excluded from the formation of the calorimeter tower, or used to mark the tower as problematic. Information about rejected or problematic channels within a calorimeter tower is in turn used to reject or flag jet and particle objects reconstructed from the towers.

A user-controlled set of parameters defines how the quality flag and status database information are used during event reconstruction. Channel quality flags are used to flag or reject problematic towers within individual events, while the channel database information is used to mark all towers containing persistent problematic channels.

3 Classification of HCAL readout problems

A number of channels with intermittent and persistent problems have been observed in the CRAFT and CRUZET commissioning data. The classification schemes for defining each type of problem are given below.

The following types of intermittent signals have been observed thus far:

- **Ion Feedback**. HCAL HPDs occasionally generate appreciable signals even when no light is incident on their photo-cathodes. Such signals are predominantly caused by a thermally emitted electron ionizing a gas or surface molecule in the acceleration gap of the HPD. That ion is accelerated back to the cathode and liberates further electrons, causing a signal equivalent to many photo-electrons. This behavior typically manifests itself as a significant energy deposit in a single channel of an HPD within an event. Ionization near an edge or corner between the hexagonal HPD pixels may lead to deposits in two or three channels.

- **Other HPD Noise**. It is known that the presence of an external magnetic field can alter the flashover voltage of dielectric materials [7]. Misalignments between the electric field within an HPD and the external solenoid field can lower the flashover voltage of the HPD. This can lead to an avalanche of secondary electrons, producing significant energy deposition in a large number of channels within an HPD. In addition, large energy deposits in multiple HPD channels have been observed even with the solenoidal field off. Signals appearing in a large number of channels within a single HPD, regardless of the state of the magnetic field, are categorized as "HPD noise".

- **RBX Noise**. Events have been observed in which nearly all of the 72 channels within a single HB or HE RBX report large observed energies. Though the cause of this is not yet understood, its distinctive signature allows it to be identified within an event.

- **PMT Window Hits**. Occasionally an energetic charged particle directly impinges upon the window of an HF PMT rather than striking a HF quartz fiber. This results in an abnormally

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large apparent energy signal for a signal channel within the HF. Such a signal may be identified by comparing the reported energies between associated long and short fibers at a given (η, ϕ) position.

- **ADC Saturation**. The ADC output of each channel was designed to cover a large dynamic range, allowing for energies up to 1.4–2.4 TeV in each HB channel, 1.7–2.4 TeV in HE, 2.0–4.4 TeV in HF, and 3.0 TeV in HO. Although these limits are not expected to be exceeded during collision data collection, energies beyond these thresholds have been observed in "beam splash" data.

Examples of persistent problems include channels that fail to report correctly formatted data and channels that continuously report higher-than-expected energies. These are referred to as "dead" and "hot" channels, respectively. Dead or hot channels can likewise result in incorrectly measured jets and biased MET measurements. Algorithms for identifying both intermittent and persistent problems are described in section 4.1.

Noise rates were determined from a set of 13 000 CRAFT events triggered on calorimeter jets with at least 6 GeV of transverse energy. Although attempts were made to remove events with cosmic ray muons, a small number of air shower or muon bremsstrahlung events may remain within the sample. Figure 2 shows the rates of intermittent noise in HB and HE versus RBX energy and MET. The MET is calculated from energy deposits in HB, HE, and the electromagnetic calorimeter. Only RBXs that recorded at least 20 GeV of total deposited energy were considered in computing the noise rates. Rates were determined from the approximately 280 (out of 288) HPDs within HB and HE that were ramped to their nominal high voltage during CRAFT.

For the purposes of these rate calculations, an RBX is considered to exhibit "RBX noise" in an event if at least 19 channels report energies of 1 GeV or more. Since each HPD contains 18 channels, this requirement ensures that the noisy behavior is not contained within a single HPD. An RBX containing between 10 and 18 channels with energy greater than 1 GeV is considered to exhibit "HPD noise", while an RBX with one to nine such channels is classified as exhibiting "ion feedback". This last classification encompasses both true ion feedback and signals from cosmic ray muons. These definitions allow for the presence of multiple noise types within an event in the case that more than one RBX exhibits noise. Two of the 13 000 examined events were found to contain more than one noisy RBX.

The distribution of the number of channels above the 1 GeV threshold is shown in figure 3 for RBXs with total energy greater than 20 GeV. Clear peaks are visible at 18 and 72 channels. These are the expected signatures for HPD noise and RBX noise, respectively.

The set of triggers to be used for collecting initial collision data at CMS is expected to include two triggers based on the MET calculated at the HLT. These two triggers will use MET thresholds of 45 GeV and 100 GeV, respectively. The rates of these triggers due to physics events have been estimated from a sample of simulated minimum bias events at a collision energy of 10 TeV. The respective rates of the 45 GeV and 100 GeV triggers at a luminosity of 8×10^{29} cm^{-2} s^{-1} have been estimated to be 0.3 Hz and less than 0.1 Hz. As shown in figure 2, the rate of noise events passing each MET trigger is more than an order of magnitude larger than the rate of physics events.

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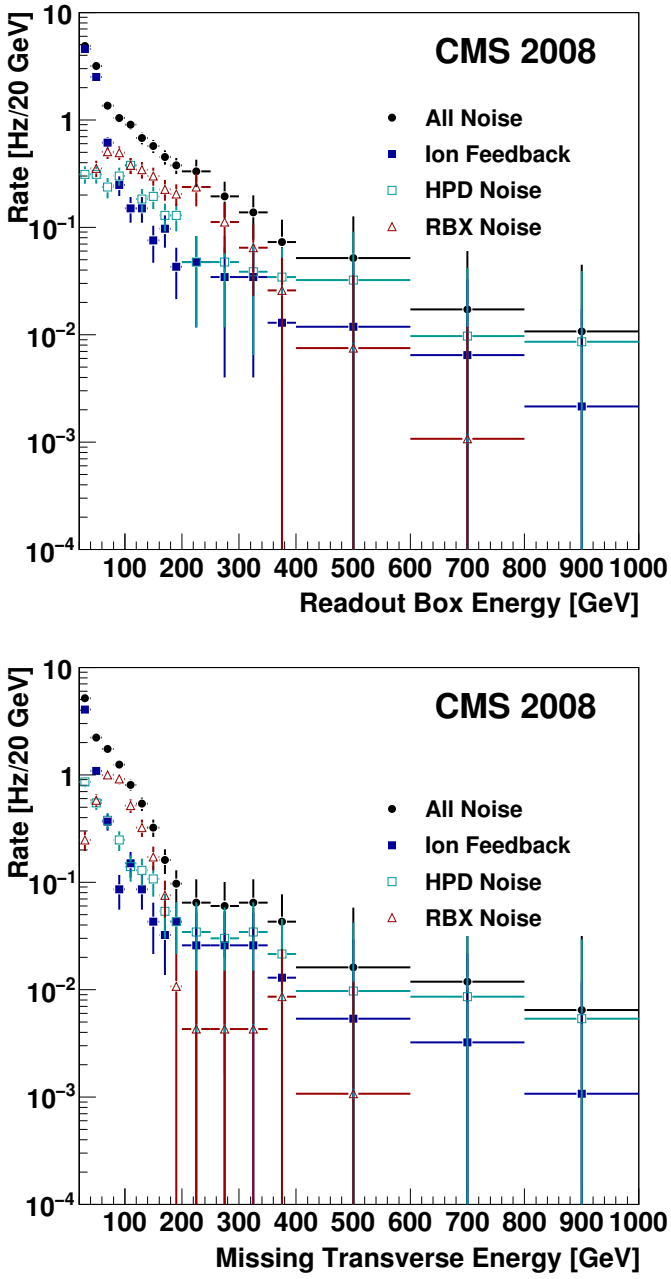

Figure 2. HCAL noise rates from CRAFT data passing a 6 GeV jet trigger. Rates are plotted vs. (top) readout box energy and (bottom) missing transverse energy for all events with at least one HB/HE readout box containing more than 20 GeV of energy. Only channels with energy greater than 1 GeV are considered when calculating contributions to the readout box energy.

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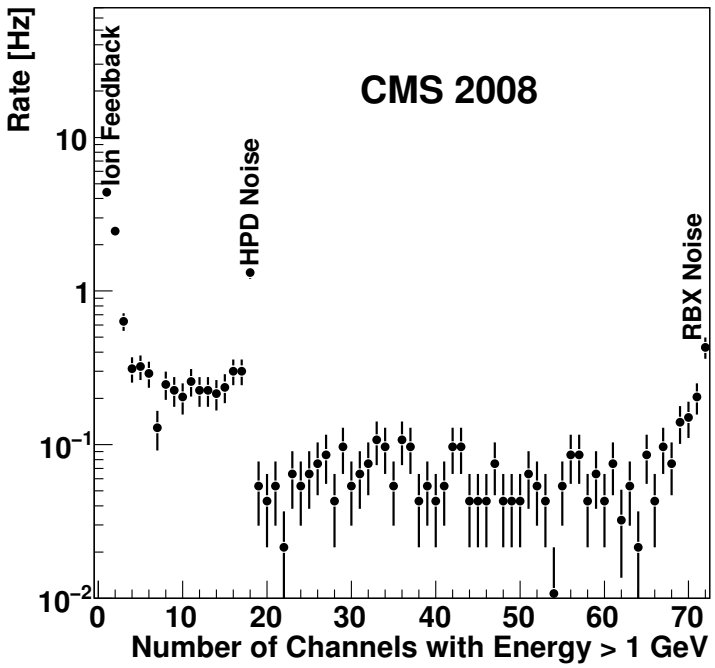

Figure 3. Number of HCAL channels within a single RBX with energy greater than 1 GeV, for readout boxes with a total energy greater than 20 GeV. Data were collected from CRAFT events triggered on calorimeter jets with at least 6 GeV of transverse energy.

4 Identification algorithms and performance

4.1 Identification

Algorithms within the CMS reconstruction software have been devised for identifying intermittent HCAL problems due to HPD noise, RBX noise, PMT window hits, and ADC saturation. Because ion feedback typically occurs within a single channel, and on a timescale smaller than the 25 ns clock pulse of the accelerator, it is not explicitly flagged as HCAL noise. It is instead treated as a contribution to the uncertainty in jet energy resolution [3]. Separate algorithms have been developed to identify persistently hot and dead channels.

If at least 17 of the 18 channels within an HPD report at least 1 GeV of energy, all channels within that HPD are flagged as noisy for that event. This requirement flags channels that contribute to the peaks labeled as "HPD Noise" and "RBX Noise" in figure 3. A second check on barrel and endcap noise is performed by evaluating the pulse shape in HB/HE signals. A typical HB/HE signal contains a sharp peak followed by a "tail" that extends for several time slices. The tail is defined as the summed charge in the three time intervals following the three intervals contributing to the bulk of the charge distribution, as illustrated in figure 4. A channel is flagged as noisy if the charge contained in the tail of the distribution is outside an expected range when compared to the total integrated charge, as shown in figure 5 and detailed in section 4.2. Similar effects appear in both magnet-on and magnet-off data.

Although channels within a noisy HPD or RBX typically report large energies, some channels

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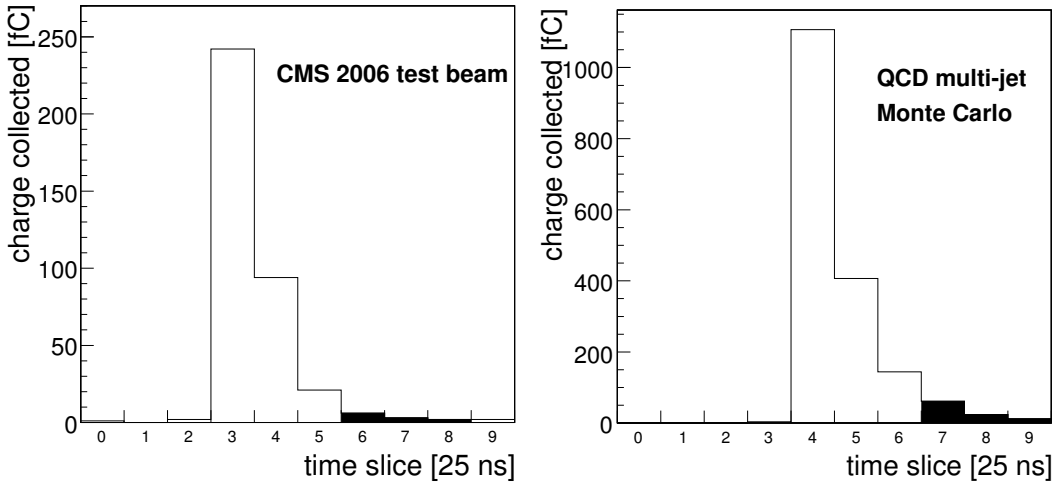

Figure 4. Expected HCAL signal pulse shape, from (left) pion test beam data [4] and (right) a simulated QCD multi-jet sample . The tails of each pulse are shaded in black.

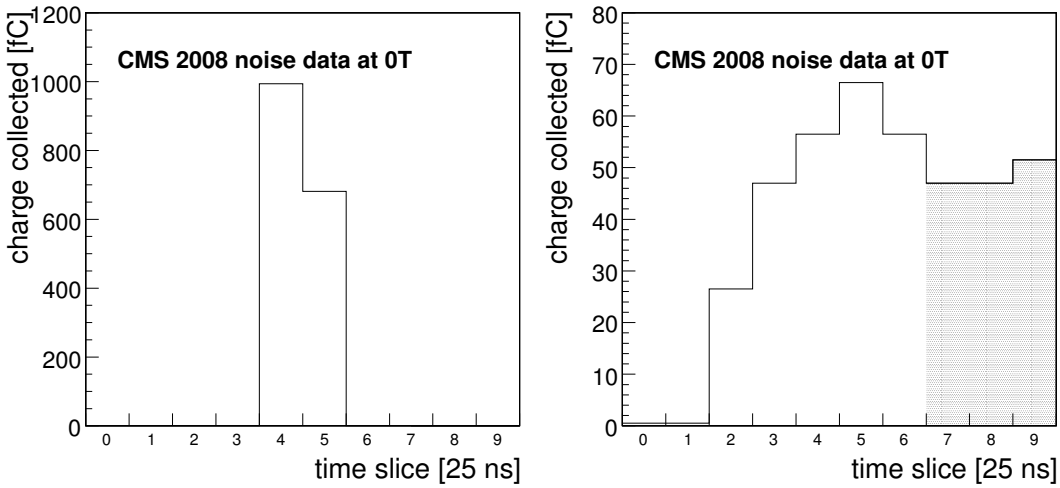

Figure 5. Each figure shows a charge distribution from a single HB channel in a CRUZET event. Events were collected from a trigger that required a minimum energy of 10 GeV from any two neighboring HCAL towers. The channel on the left has no tail, while the (shaded) tail of the channel on the right is abnormally large. Both channels are flagged as noisy.

may fall well *below* the expected energy scale associated with electronics noise during the 250 ns readout period. These channels report zero ADC counts during the noise event. A large multiplicity (≥ 8) of such channels within an RBX is an indicator of RBX or HPD noise.

The timing of energy deposits in a channel relative to the trigger can also indicate HPD or RBX noise. The unusual pulse shape associated with the noise can result in a reconstructed time that is substantially offset from the trigger decision time. The relative timing of a high energy deposit ($\gtrsim 25$ GeV) can be reconstructed typically within ± 5 ns, so a reconstructed time outside this window is characteristic of HCAL noise [8].

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PMT window hits within the HF are flagged by comparing the energies reconstructed from long and short fibers with the same (η, ϕ) values. Given a pair of adjacent long and short fibers, with energies E_L, E_S, respectively, the fiber channels are flagged as noisy if (a) the maximum transverse energy reported by the two channels is at least 2 GeV, and (b) if the energy ratio R, defined as

$$R \equiv \left| \frac{E_L - E_S}{E_L + E_S} \right| \quad , \tag{4.1}$$

is greater than 0.99.

The bulk of the signal charge from an HF hit is expected to be collected within a single 25 ns time slice [5]. An HF channel is flagged as noisy if (a) a significant ADC signal peak (> 10 counts) is found, and (b) the ratio of that peak value to the counts in the window immediately before (after) the peak is less than 2.5 (1.0). These constraints will be tightened as the HF timing is refined.

Another set of HCAL quality flags is used to determine the reliability of the energy and time information reported by each channel. Any channel reporting a saturated ADC level is flagged as problematic, since the correspondence between measured and true energy is lost. Channels whose readouts are out of synchronization with the rest of the detector are also flagged as problematic.

At present, persistently problematic channels are defined as those channels exhibiting abnormal behavior in at least 5% of the events collected in a given data period. A channel is considered hot if it reports at least 5 GeV of energy in at least 5% of collected events. A channel is also considered hot if it remains above a threshold energy of 3 GeV for at least 1 000 consecutive events, and if this condition persists for at least 5% of the collected events. These two definitions serve complementary purposes, with the first aiding in the identification of hot channels energetic enough to affect trigger rates, and the second serving as a scan for channels that are consistently "warm" but not energetic enough to disrupt triggering. The energy thresholds used in these definitions were determined from simulated QCD multi-jet samples and CRAFT data, and were chosen so that physics signals do not cause the channels to be mis-tagged as problematic. The thresholds will be re-tuned and adjusted to appropriate values for each subdetector (HB, HE, HO and HF) on the basis of LHC collision data.

An HCAL channel is considered dead if no correctly-formatted data are found from that channel in a sample of at least 10 000 events, and if this condition persists for at least 5% of the events collected in a given data-taking period. A channel is also considered dead if it consistently fails to exceed a given threshold energy. The first test provides a check that data are being received from each channel, and the second provides an *in situ* check of the energy reconstruction for that data. As with the hot channel algorithm, the dead channel thresholds are user-controlled, and will be re-tuned on collision data.

Noise flags may be used to identify problematic channels or as a means to reject entire events as noisy. Two additional algorithms for providing rejection of noise events have been developed. These algorithms, after optimization and performance studies with first collision data, can be applied at the HLT to either flag events as potential noise or to reject them completely. The algorithms are:

- Rejection Algorithm I: rejects any event containing a channel with a hit multiplicity or charge ratio flag, as described above;

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- Rejection Algorithm II: rejects events in which at least one RBX contains more than 8 channels with 0 ADC counts, and also rejects events in which any channel with energy greater than 25 GeV has less than 70% of its total charge contained within the signal pulse peak or falls outside a 13 ns window around the trigger;

- Rejection Algorithm III: a more stringent version of Rejection Algorithm II, requiring any channel with energy greater than 25 GeV to have 80% of its total charge within its signal peak, and to lie within a 9 ns window around the trigger. Additionally, no HPDs may contain more than 16 channels with energy above 1.5 GeV.

4.2 Algorithm performance

The channel-flagging algorithms described in the previous section were tested on CRAFT and single beam data taken in the fall of 2008. They were also applied to samples of simulated QCD multi-jets, $t\bar{t}$, and 1 TeV Z' events at a collision energy of 10 TeV. The tests on simulated samples serve as a cross-check of the algorithms, to ensure that expected physics signals are not falsely tagged as noise.

The channel-flagging algorithms that detect problematic HPD output were applied to data from special CRUZET noise data triggered on events where two neighboring HCAL towers contained at least 10 GeV of energy. The algorithms were also applied to QCD multi-jet, $t\bar{t}$, and $Z' \rightarrow t\bar{t}$ simulations to evaluate their effects on real physics signals. The distribution of HPD hit multiplicities is shown in figure 6. HPD noise, in which all 18 channels within an HPD report energy deposits greater than 1 GeV, is evident in the noise data, while simulated events and data triggered on cosmic ray muons show lower multiplicities. Figure 7 shows the distribution of ADC pulse tails vs. total collected charge, and illustrates the difference in tail distributions between muon-triggered and noise-triggered data.

The noise requirements as defined in figure 7 are loose enough not to falsely tag any physics signal as noise. These loose cuts allow for minor differences in ADC pulse shape between real and simulated data. In tests over a few thousand simulated events, no channels were flagged as noisy by the algorithms. The algorithm was also applied to a subset of CRUZET events that passed a special noise trigger requiring at least 40 GeV of energy deposited within a single RBX. In these HCAL-triggered noise data, 94% of all events contained at least one channel flagged as noisy.

The rate of fake MET signals in CRAFT data before and after the application of HB/HE noise reduction algorithm is shown in figure 8. The application of Rejection Algorithm I can reduce fake noise signals by a factor of 6.5 (10) for events with MET greater than 45 (100) GeV. Rejection Algorithms II and III are substantially more efficient than Algorithm I at removing noise, but they also reject a small fraction of physics signal. Algorithm II falsely rejects $\sim 0.4\%$ of all simulated $t\bar{t}$ events, while Algorithm III rejects $\sim 3\%$ of such events.

Testing of the HF noise-tagging algorithm was performed on CRAFT data and LHC beam halo data. The CRAFT results were collected from events passing a muon trigger, while beam halo events were required to pass either an HF calorimeter trigger or a muon system halo trigger. High muon rates in the beam halo data resulted in large numbers of PMT window hits, as shown in figure 9. Tests of the saturation algorithm showed no saturated HCAL channels in either CRAFT cosmics data or simulated $t\bar{t}$ samples. Beam halo events also resulted in no saturated channels,

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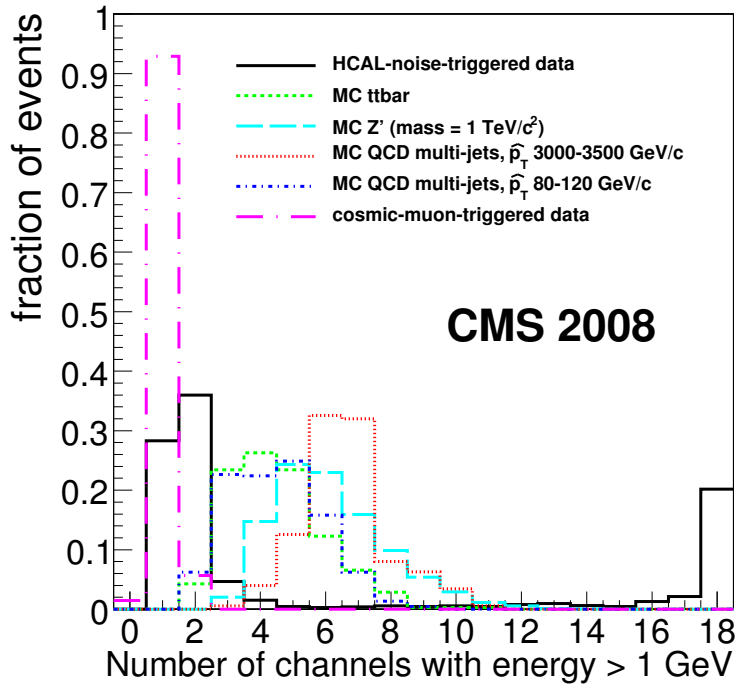

Figure 6. Number of HPD channels with energy > 1 GeV for the highest-multiplicity HPD in an event, for CRUZET noise and cosmic ray data, as well as simulated (MC) events.

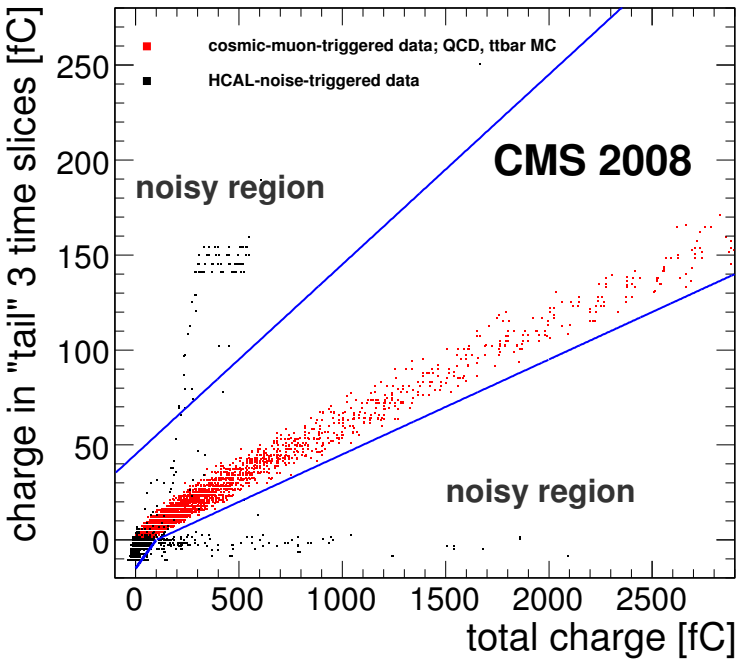

Figure 7. Sum of charges in the tail of the ADC pulse vs. sum of charges over the entire pulse. The lines indicate the noisy regions; channels falling within these regions are flagged as noisy.

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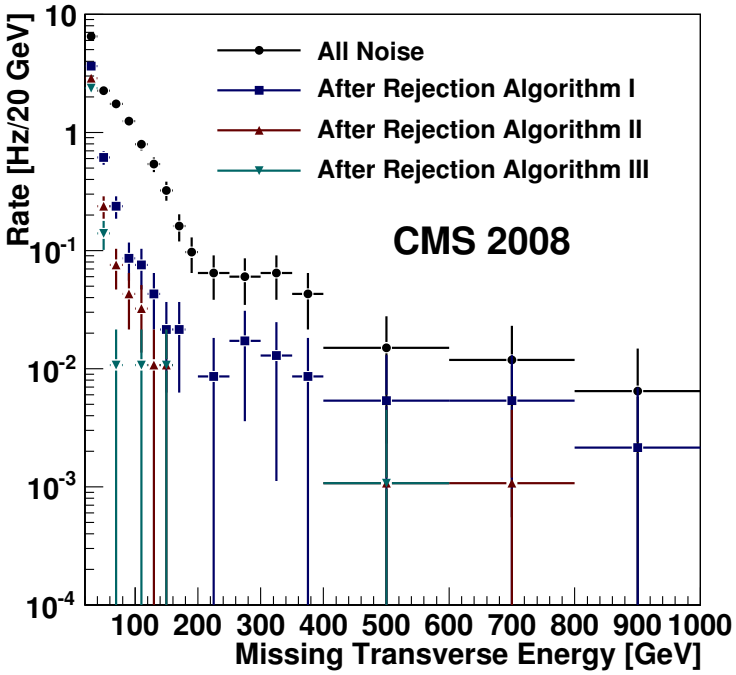

Figure 8. HCAL noise rates vs. MET in CRAFT data, before and after the application of noise rejection algorithms. Rates were determined from events passing a 6 GeV jet trigger, and with at least 40 GeV of measured MET.

while splash events produced an average of 20 saturated HF channels. The HCAL timing synchronization algorithm was also used to identify synchronization errors in CRAFT data. The resultant post-CRAFT upgrades to the HCAL timing have lowered the rate of such synchronization errors to less than 0.1%.

Searches for persistent problems during CRAFT identified a single hot channel in HF. This channel was repaired, and there are currently no hot channels within HCAL. No dead channels were observed in HB, HE, or HF. A total of five dead channels was found in the region of HO that is being used in event reconstruction. These channels are not accessible for repair, and have been recorded as dead in the status database. The total fraction of dead channels within the HCAL is less than 0.25%.

5 Summary

Sporadic uncharacteristic noise has been observed within the CMS hadron calorimeter during *in-situ* commissioning. A number of algorithms to identify the channels in which such noise occurs have been designed and implemented. These algorithms address noise and readout issues seen in cosmic ray muon and single beam data from 2008.

The observed noise rate is less than 8 (3) Hz in events containing at least 45 (100) GeV of measured MET. This rate is reduced by an order of magnitude by excluding events flagged by the noise algorithms as containing problematic channels. The algorithms have already been useful for

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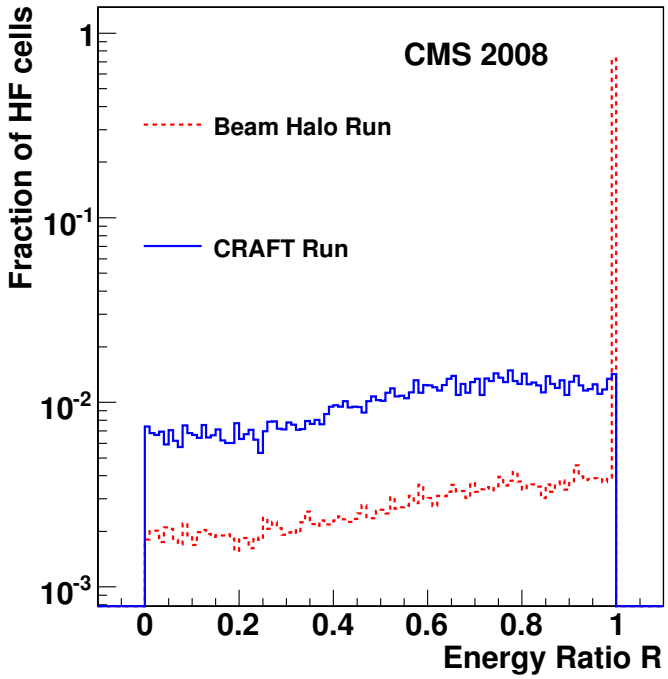

Figure 9. Ratios of energy differences to energy sums of adjacent long and short HF fiber channels in CRAFT and LHC beam halo data. Long and short channels with ratios greater than 0.99 are flagged as noisy.

identifying problematic channels during CRAFT, leading to a reduction in the rate of events with large measured MET in 2009 commissioning studies.

Further suppression may be gained by the application of more stringent noise rejection algorithms. Such algorithms reduce the noise rate to less than 0.1 Hz for events with MET greater than 100 GeV, comparable to the expected rate from 10 TeV collisions at a luminosity of 8×10^{29} cm^{-2} s^{-1}, while reducing the detection efficiency for various physics signals by a few percent. These algorithms may be applied at the trigger level to reduce noise rates, or within the offline reconstruction to separate potential noise events for further study. Additional information for identifying noise is available from other detectors during offline reconstruction. This information allows for more refined noise rejection algorithms that incur a smaller reduction in signal efficiency.

Channels identified as problematic may be corrected during event reconstruction or excluded from the reconstruction entirely. Initial tests on data show that the algorithms for identifying problematic channels correctly mark both persistent and sporadic known problems with high efficiency. Further tests on simulated events indicate a low mis-tag rate for properly behaving channels.

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