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Mitigation of anomalous APD signals in the CMS ECAL

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ABSTRACT: We describe the observation and mitigation of anomalous, large signals, observed in the barrel part of the CMS Electromagnetic Calorimeter during proton collisions at LHC. Laboratory and beam tests, as well as simulations, have been used to understand their origin. They are ascribed to direct energy deposition by particles in the avalanche photodiodes used for light readout. A reprogramming of the front-end electronics has allowed a majority of these anomalous signals to be identified and rejected at the first (hardware) trigger level with minimum impact on physics performance. Further rejection is performed in the high-level software trigger and offline analyses.

KEYWORDS: Performance of High Energy Physics Detectors; Calorimeters; Trigger algorithms; Solid state detectors

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1 The CMS Electromagnetic calorimeter

The Compact Muon Solenoid (CMS) [1] is a large general-purpose detector operating at the Large Hadron Collider (LHC) [2] at CERN. The main goal of CMS is to search for Physics beyond the Standard Model at the TeV energy scale. The main component of CMS to detect and measure the energies of electrons and photons is the Electromagnetic Calorimeter (ECAL) [3, 4]. The CMS ECAL consists of 75848 lead tungstate ($PbWO_4$) crystals, organised into a barrel and two endcap detectors and providing coverage to pseudorapidity $|\eta| = 3.0$. Two silicon preshower detectors are placed in front of the endcaps, covering the range $1.65 < |\eta| < 2.6$. The CMS ECAL is designed to provide excellent energy resolution in the harsh radiation environment of the LHC. The benchmark physics process is Higgs $\rightarrow \gamma\gamma$, and the target energy resolution is 0.5% for unconverted photons above 100 GeV. Scintillation light emitted by the lead tungstate crystals is converted to electrical signals by photodetectors glued to the rear face of the crystals. These photodetectors must be able to withstand the radiation environment of the LHC and be able to operate in the 3.8 T magnetic field of CMS. Avalanche photodiodes (APDs) are used in the ECAL Barrel, and Vacuum Phototriodes (VPTs) are used in the ECAL Endcaps.

2 Anomalous signals — characteristics

Anomalous signals, consisting of isolated large signals, have been observed in the ECAL Barrel during LHC proton-proton collisions data taking in CMS during 2009–12. These deposits, termed ECAL "spikes" are observed to occur at a rate that is proportional to the luminosity. As a consequence, they present issues for triggering CMS at high luminosity and must be eliminated from analyses in order to prevent large biases in the energies of reconstructed electrons, photons and jets. The spikes are understood to be associated with particles (produced in p-p collisions) striking the APDs and very occasionally interacting with material causing large anomalous signals through direct ionization of the silicon. This hypothesis has been checked by studying the APD response via laboratory and test beam studies, and the development of Monte Carlo simulations where the APDs are treated as active volumes [6]. Extensive studies of spike properties in data have been carried out, and algorithms to flag and remove them have been developed.

The APD CMS photodetectors are Hamamatsu type S8148 reverse structure (i.e., with the bulk n-type silicon behind the p-n junction) avalanche photodiodes (APDs) specially developed for the CMS ECAL [5]. Each APD has an active area of $5 \times 5\,\mathrm{mm}^2$ and a pair is mounted on each crystal. They are operated at gain 50 and read out in parallel. Each pair is mounted in a moulded capsule, which is then glued on the back of each crystal. The main properties of the APDs at gain 50 and 18°C are listed in [1]. The internal construction of the APD, consists of a $5\,\mu$m thick "high-gain" silicon layer (gain = 50) and a $45\,\mu$m thick "low-gain" silicon layer (gain = 1.4).

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3 Online rejection

Since the characteristics of ECAL spikes are localized high energy signals, they will often satisfy the conditions for triggering electrons and photons in CMS. If untreated, the rate of spikes would be a dominant component of the 100 kHz CMS Level-1 trigger rate bandwidth for luminosities above $L \sim 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Spike-like energy deposits are prevented from triggering CMS by exploiting additional functionality of the ECAL front-end electronics — the Strip Fine-grained Veto Bit (sFGVB). This bit, which is computed per trigger tower (5×5 crystal array, corresponding to a single readout unit of the ECAL front-end electronics) can be configured to flag spike-like energy deposits by comparing the energies recorded for each channel to a configurable threshold. If the sFGVB is set to zero, and the trigger tower transverse energy is greater than 8 GeV, the energy deposition is considered spike-like. The trigger tower energy is set to zero and the tower will not contribute to the triggering of CMS for the corresponding event.

The sFGVB is now implemented in CMS and operational since April 2011. It has been measured to reject $> 95\%$ of spikes with transverse energy greater than 8 GeV, with only a small ($< 2\%$) effect on the efficiency for triggering real electrons.

3.1 Online rejection sFGVB algorithm

The sFGVB algorithm, used to reject "spike" signals in CMS, exploits additional hardware features of the FENIX chip of the ECAL Front End cards (figure 1). Each 5×5 grouping of detector channels (denoted "Trigger Tower" or "TT") is segmented in 5 strips of 5 channels each. Each channel input is in a compressed format, with a 12-bit ADC word and a 2-bit gain-range word. These (12+2)-bit words are expanded into a linear scale by the linearisers, whose function is to subtract any measured pedestal noise from each channel and to expand the compressed information from the FE boards.

The amplitudes from all 25 channels in the TT are summed to provide the final 12 bit amplitude corresponding to the TT response. To calculate the veto flag, a comparison is performed for each channel in the strip to a predefined threshold (configurable per strip).

The resulting 5 bit value (1 bit per channel) is used as an address to a look-up table, which produces 1 bit per strip (figure 2). These resulting bits are then ORed together to produce the sFGVB flag.

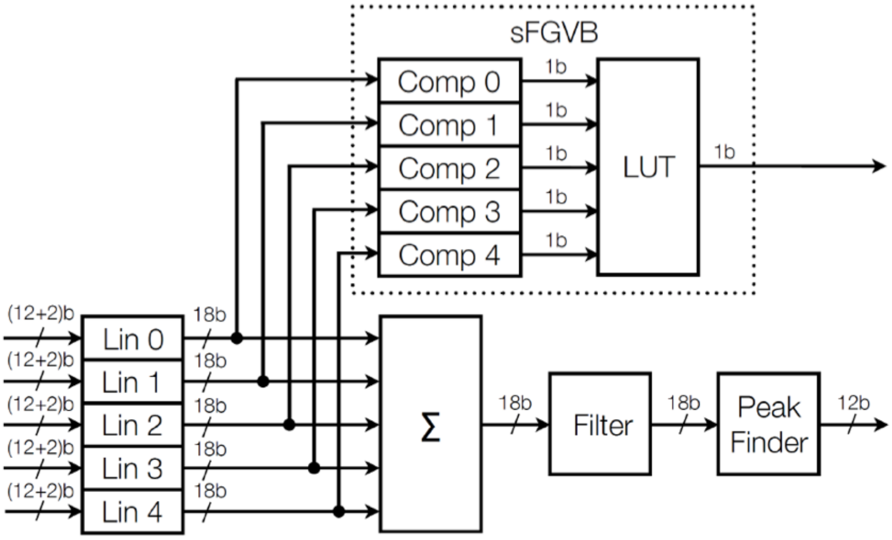
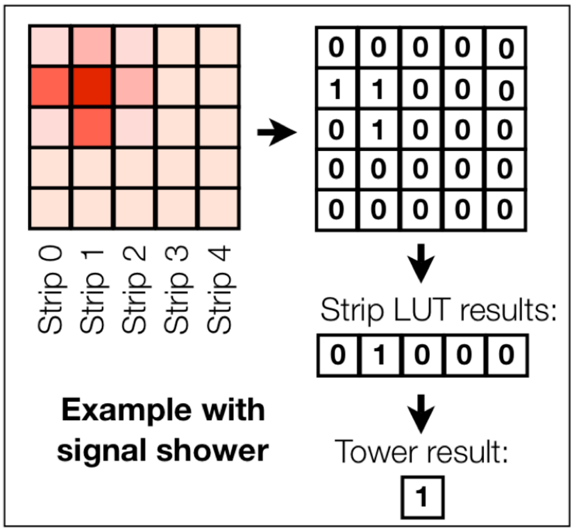


Figure 1. CMS ECAL front-end strip electronics overview.



0	0	0	0	0
1	1	0	0	0
0	1	0	0	0
0	0	0	0	0
0	0	0	0	0

Strip LUT results:

0	1	0	0	0

Tower result:

1

Figure 2. Operation of the Strip Fine-Grained Veto Bit (sFGVB) for a real electromagnetic shower deposit.

The optimal thresholds were determined by implementing a detailed emulation of the full Level-1 chain and computing the spike rejection efficiency (fraction of L1 candidates due to spikes that are eliminated by the algorithm) and the efficiency for triggering on real electrons/photons for a range of sFGVB thresholds.

The optimum configuration for 2011 data was chosen to be an sFGVB threshold of 258 MeV for Level-1 electron/photon candidates with transverse energy greater than 8 GeV. This corresponds to a spike rejection of 96%, whilst maintaining a trigger efficiency for electrons with $E_T > 20\,\mathrm{GeV}$ of 99.6%.

The spike killing thresholds were optimised for the higher pile-up conditions experienced in 2012 data. A revised sFGVB threshold of 350 MeV, for electron/photon candidates with transverse

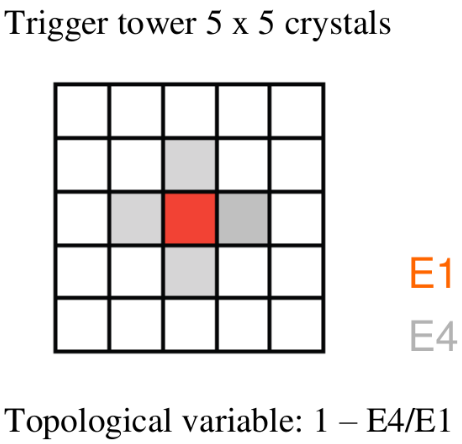


Figure 3. Definition of the “Swiss-Cross” topological variable (1-E4/E1).

energy greater than 12 GeV was used. This provides improved rejection of spikes for events with high event pileup, but preserves the same high trigger efficiency for real electrons and photons.

4 Offline rejection

The offline rejection of ECAL spikes in CMS relies on topological and timing characteristics. Spikes, which generally deposit energy in a single channel, have an anomalous pattern of energy sharing between crystals. An electromagnetic (EM) shower, well-centered on an ECAL crystal, will typically contain $\sim 80\%$ of its energy in the central crystal and $\sim 20\%$ of its energy in the neighbouring crystals. A cut on the “Swiss-cross” (figure 3) variable (1-E4/E1) of 0.95 rejects $>99\%$ of spikes with transverse energy greater than 10 GeV, with a negligible impact on the efficiency of selecting EM showers (figure 4) [7]. Figure 5 displays topological variable distribution with CMS real data and Monte-Carlo simulations, thus confirms efficiency of spike rejection.

Spikes and EM energy deposits have different signal pulse shapes. Since the spike is produced by a particle directly hitting the APD, the decay constant of scintillation light (~ 10 ns) is not present. When the pulse is fitted to extract the timing of the signal, the spike pulses generally appear early (figure 6). A cut on the signal timing (± 3 ns) is efficient at removing spike pulses ($> 90\%$ efficient), with negligible impact on EM energy deposits [8] (timing resolution < 1 ns for EM signals with energy > 1 GeV). Combining these two methods, topological and timing cuts, a spike rejection factor greater than 100 can be obtained.

5 Summary

The existence of large isolated signals in the CMS ECAL Barrel has been observed in pp collisions at the LHC. The origin of these signals due to direct ionization of the active silicon layers of the CMS APDs is supported by laboratory tests and Monte Carlo simulations.

The rate of anomalous signals in CMS is proportional to the minimum-bias collision rate, and to the number of charged tracks per event. Algorithms to efficiently remove these deposits in the online trigger and in the online reconstruction of physics data have been developed and deployed

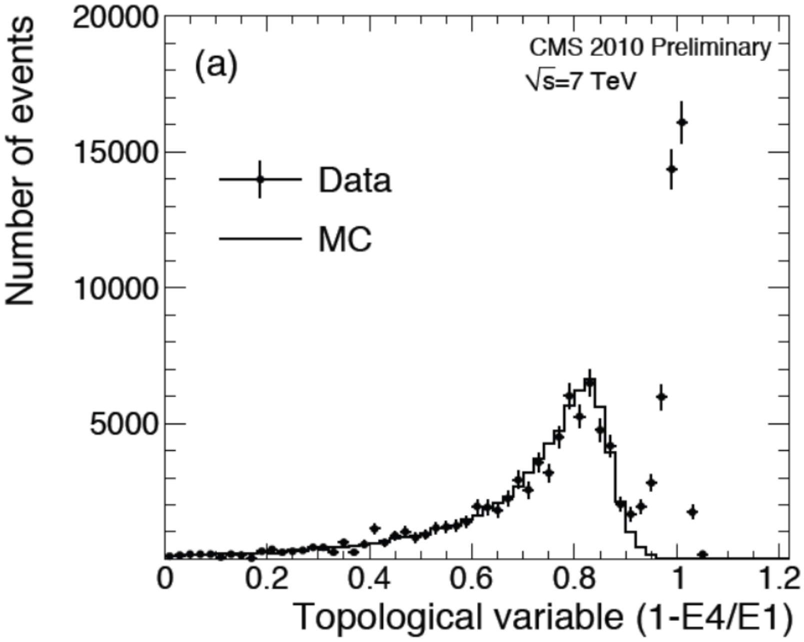


Figure 4. Distribution of the "Swiss-cross" variable for CMS data and Monte Carlo simulation. One can clearly see an extra component with (1-E4/E1) ∼ 1.0 in the CMS data. These correspond to spikes with almost all the clustered energy in a single crystal.

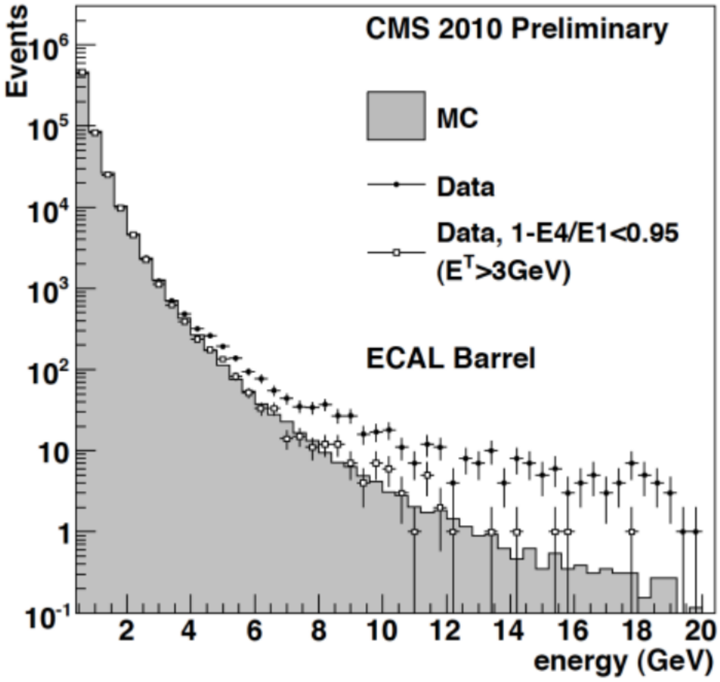


Figure 5. ECAL crystal energy spectra recorded during 7 TeV collisions data taking, compared to Monte Carlo simulation (without spike simulation). The excess of high energy signals (due to spikes) in the data is effectively removed by the Swiss-cross cut.

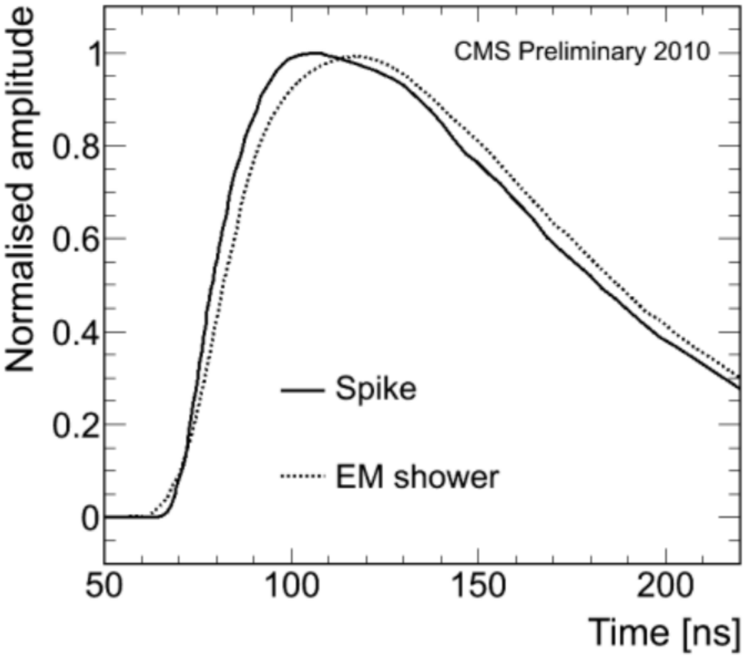


Figure 6. Difference in signal pulse shape between a spike (solid line), which directly ionizes the APD and a typical electromagnetic energy deposit (dashed line), which induces light in the $PbWO_4$ crystals.

in CMS. These algorithms have proved effective in rejecting spikes for LHC instantaneous luminosity above $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, and remain efficient for the high event pile-up conditions experienced in 2012.

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