Mitigation of Anomalous APD signals in the CMS ECAL

W. Bialas, D.A. Petyt for the CMS Collaboration

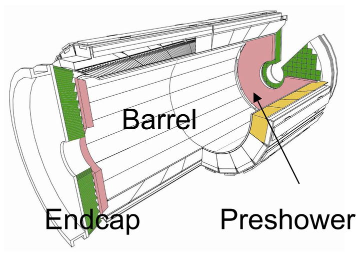
The CMS Electromagnetic Calorimeter (ECAL)

The Compact Muon Solenoid (CMS) is a large general-purpose detector operating at the Large Hadron Collider (LHC) at CERN. The main goal of CMS is to search for Physics beyond the Standard Model at the TeV energy scale.

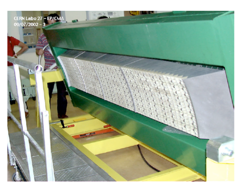
The main component of CMS to detect and measure the energies of electrons and photons is the Electromagnetic Calorimeter (ECAL). The CMS ECAL consists of 75848 lead tungstate ($PbWO_4$) crystals, organised into a barrel and two endcap detectors and providing coverage to |η|=3.0. Two silicon preshower detectors are placed in front of the endcaps, covering the pseudorapidity range 1.65< |η| < 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→γγ, and the target energy resolution is 0.5% for unconverted photons above 100 GeV.

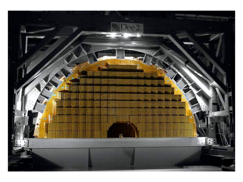
Scintillation light emitted by the Lead Tungstate crystals is converted to electrical signals by photodetectors glued to the rear face of the crystals. These photodetectors must be able to withstand the radiation environment of the LHC and be able to operate in the 3.8T magnetic field of CMS. Avalanche photodiodes (APDs) are used in the ECAL Barrel, and Vacuum Phototriodes (VPTs) are used in the ECAL Endcaps.



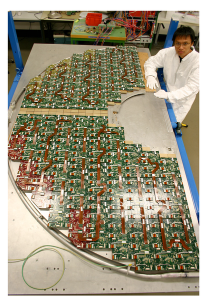
CMS Electromagnetic Calorimeter (ECAL)



Barrel (EB)
36 supermodules (1700 Crystals)
Total of 61200 PbWO4 crystals (34 types)
crystal mass 67.4 T
coverage: |η|<1.48



Endcap (EE)
4 half-disk Dees (3662 crystals)
Total of 14648 PbWO4 crystals (1 type)
crystal mass 22.9 T
coverage: 1.48<|η|<3.0

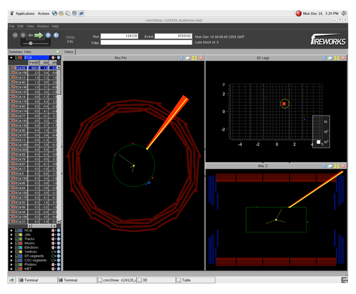


Preshower (ES)
4 half-disk Dees
Two Lead/Si planes
Total of 137216 Si strips (1.9x61mm2)
coverage: 1.65<|η|<2.6

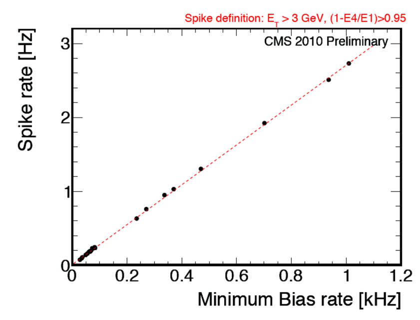
Anomalous signals - Characteristics

Anomalous signals, consisting of isolated large signals, have been observed in the ECAL Barrel during LHC proton-proton collisions data taking in CMS during 2009-11. 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 physics 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 pp collisions) striking the APDs and very occasionally interacting to produce secondaries that cause large anomalous signals through direct ionization of the silicon. This hypothesis has been checked by studying the APD response via laboratory [1] and test beam studies, and the development of Monte Carlo simulations where the APDs are treated as active volumes. Extensive studies of spike properties in data have been carried out, and algorithms to flag and remove them have been developed.



CMS Event Display of a pp collision event, showing an isolated ECAL spike simulating a 600 GeV transverse energy deposit. (scintillation light in PbWO4 ~4.5 p.e./MeV)



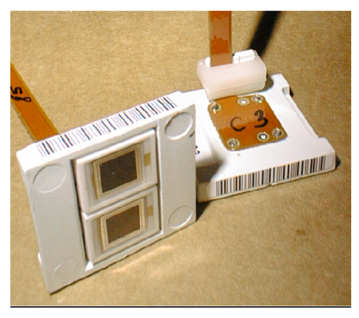
Rate of ECAL spikes in pp collisions at √s=7 TeV, as a function of the Minimum Bias collisions rate, measured using 2010 data. The spikes are defined as signals reconstructed with greater than 3 GeV transverse energy and more than 95% of the clustered energy in a single crystal. Using this definition, there is approximately one spike per 370 Minimum Bias triggered events in CMS.

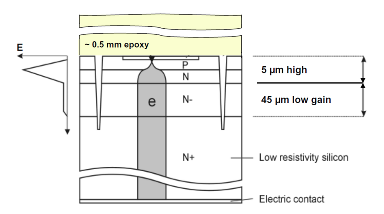
CMS Avalanche Photodiodes (APDs)

The 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. Each APD has an active area of 5×5 mm2 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 the table below.

The internal construction of the APD, illustrated below, consists of a 5μm thick "high-gain" silicon layer (gain=50) and a 45μm thick "low-gain" silicon layer (gain=1.4)





CMS Avalanche Photodiode (APD)

Sensitive area	5×5 mm^2
Operating voltage	340–430 V
Breakdown voltage - operating voltage	45 ± 5 V
Quantum efficiency (430 nm)	$75 \pm 2\%$
Capacitance	80 ± 2 pF
Excess noise factor	2.1 ± 0.2
Effective thickness	6 ± 0.5 μm
Series resistance	$< 10\ \Omega$
Voltage sensitivity of the gain $(1/M \cdot dM/dV)$	$3.1 \pm 0.1\%$/V
Temperature sensitivity of the gain $(1/M \cdot dM/dT)$	$-2.4 \pm 0.2\%$/°C
Rise time	< 2 ns
Dark current	< 50 nA
Typical dark current	3 nA
Dark current after 2×10^{13} n/cm^2	5 μA

Properties of the CMS APDs at gain 50 and 18 °C

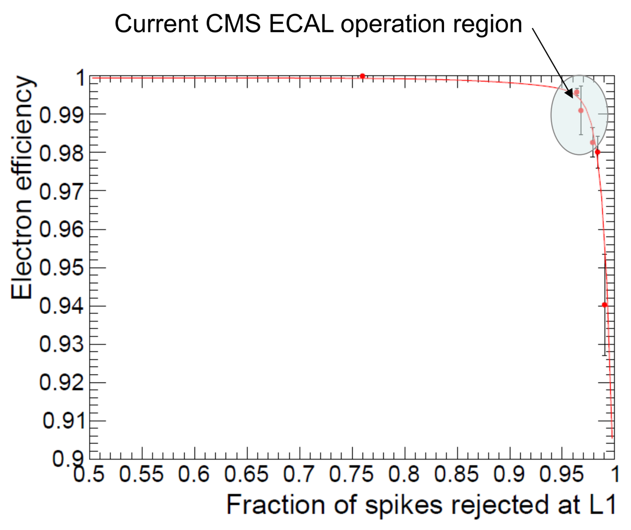
Online Rejection

Rejection results

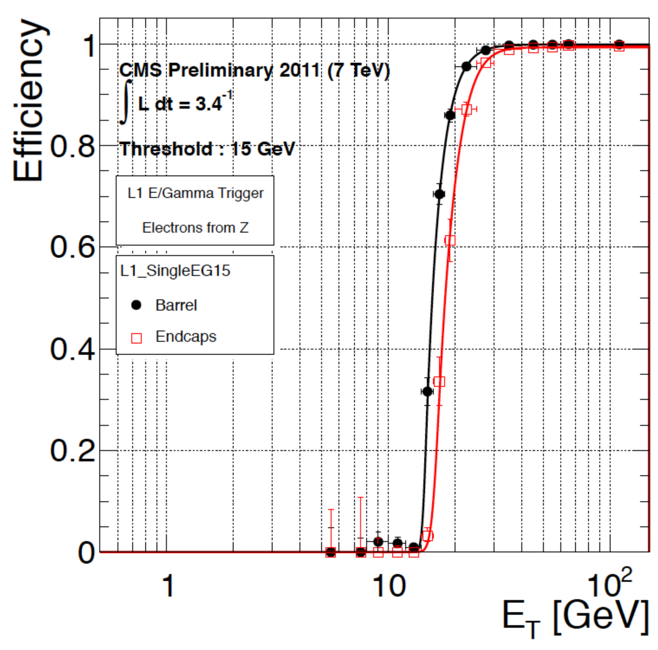
Since the characteristics of ECAL spikes are localized high energy signals, they will often satisfy the conditions for triggering electrons and photons in CMS. If untreated, the rate of spikes would be a dominant component of the 100 kHz CMS Level-1 trigger rate bandwidth for luminosities above L~10^{33}cm^{-2}s^{-1}.

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 (5x5 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. 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].



Electron efficiency as a function of the spike rejection at level 1 trigger



Electron trigger efficiency at L1 ("EG" threshold : 15 GeV ET), as a function of ET for electrons in the ECAL Barrel (black dots) and Endcaps (red dots).

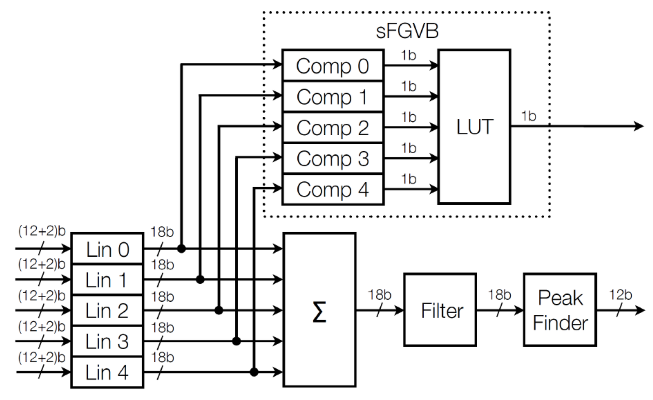
Online Rejection sFGVB algorithm

The sFGVB algorithm, used to reject "spike" signals in CMS, exploits additional hardware features of the FENIX chip of the ECAL Front End cards. Each 5x5 grouping of detector channels (denoted "Trigger Tower" or "TT") is segmented in 5 strips of 5 channels each. The signal amplitude for each channel is digitized by a 12 bit ADC, accompanied by 2 bits indicating the gain.

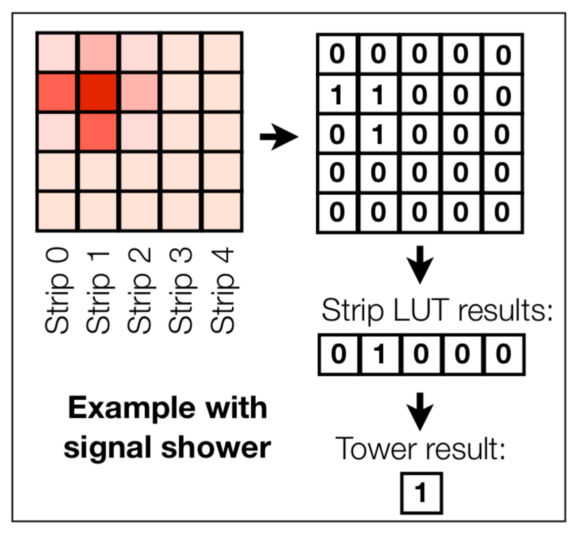
The amplitudes from all 25 channels in the TT are summed to provide the final 12 bit amplitude corresponding to the TT response.

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.

These resulting bits are then ORed together to produce the sFGVB flag. By careful choice of the channel threshold and patterns in the look-up table, one can eliminate with good efficiency the anomalous signals.



CMS ECAL front end strip electronics overview



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

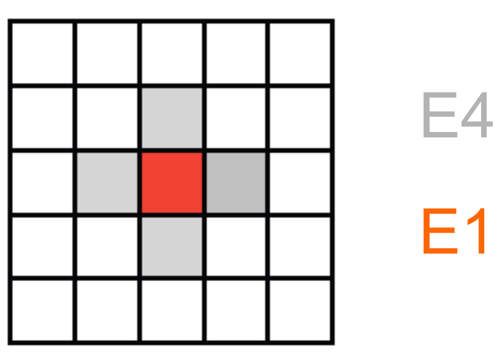
Offline Rejection

Rejection of ECAL spikes in CMS relies on topological and timing characteristics

1) 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 ~80% of its energy in the central crystal and ~20% of its energy in the neighboring crystals. A cut on the "Swiss-cross" 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 [2].

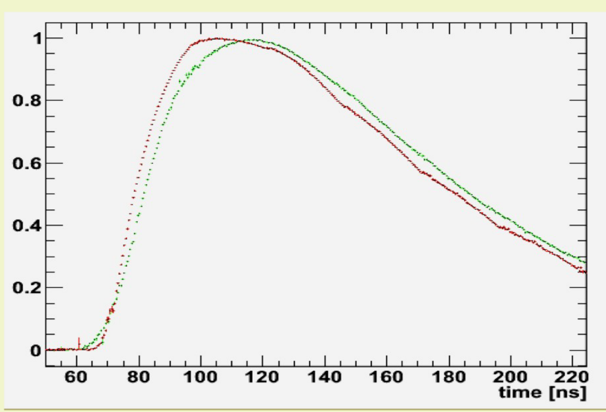
2) Spikes and EM energy deposits have different signal pulse shapes. Since the spike is produced by a particle directly hitting the APD, the decay constant of scintillation light (~10 ns) is not present. When the pulse is fitted to extract the timing of the signal, the spike pulses generally appear early. A cut on the signal timing (±3ns) is efficient at removing spike pulses (>90% efficient), with negligible impact on EM energy deposits (timing resolution <1ns for EM signals with energy > 1 GeV)

"Swiss-cross Variable"
(1 –E4/E1)

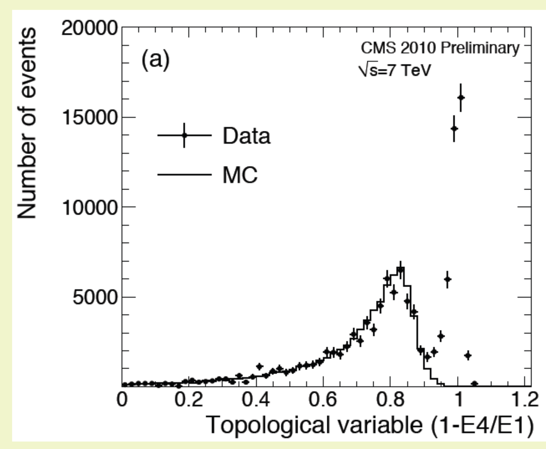


Measures the isolation of an energy deposit in the ECAL

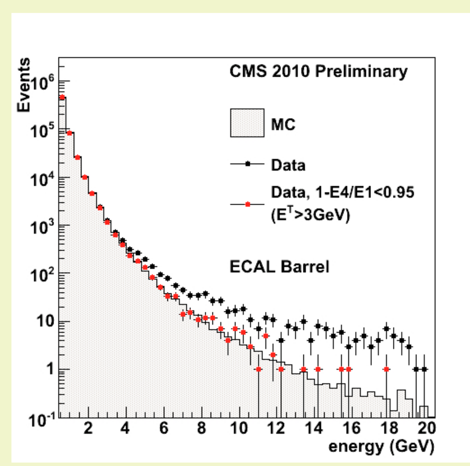
Spikes:
Swiss-cross ~1
EM shower:
Swiss-cross < 0.9



Difference in signal pulse shape between a spike (red), which directly ionises the APD and a typical electromagnetic energy deposit (green), which induces light in the PbWO4 crystals.



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.



ECAL crystal energy spectra recorded during 7 TeV collisions data taking, comparred 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.

References:
[1] Q. Ingram, "Response of APDs to low energy neutrons", NDIP11: International Conference on New Developments In Photodetection, 4-8 Jul 2011, Lyon (France)
[2] CMS Collaboration, "Electromagnetic calorimeter commissioning and first results with 7 TeV data", CMS-Note-2010-012
[3] CMS Collaboration, "Triggering on electrons and photons with CMS", CMS CR -2012/028