The Compact Muon Solenoid Experiment
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Mitigation of Anomalous APD Signals in the CMS Electromagnetic Calorimeter

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Abstract

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Fig. 1. Anomalous event recorded in December 2009, with $E \approx 1$ TeV reconstructed energy in a single ECAL channel. All the neighboring channels recorded energy deposits compatible with the RMS noise fluctuation.

Abstract—Anomalous, large signals are observed in the barrel region of the CMS electromagnetic calorimeter during pp collisions at the LHC. Laboratory and beam-test studies, as well as Monte Carlo simulations, have been used to understand their origin. They are ascribed to direct energy depositions by particles in the Avalanche Photo-Diodes used for the scintillation light readout. Their properties and rates are summarized. The methods employed to reject these signals in the online trigger selection and in the offline event reconstruction are presented.

THE Compact Muon Solenoid (CMS) [1] is a particle detector operating at the Large Hadron Collider (LHC) at CERN. Its mission is the exploration of the TeV energy scale and the study of fundamental interactions. The electromagnetic calorimeter (ECAL) is a homogeneous calorimeter built from 75,848 lead tungstate (PbWO_4) crystals. The calorimeter is contained within the 3.8 T CMS magnet. In the central region, $|\eta| < 1.48$ (EB), the scintillation light is detected with avalanche photodiodes (APDs) while in the forward region, $1.48 < |\eta| < 3.0$ (EE), vacuum phototriodes (VPTs) are used. Two silicon strips preshower detectors are placed in front of the endcaps, covering the pseudorapidity range $1.65 < |\eta| < 2.6$. A detailed description of the ECAL can be found in [1], [2].

Following the start of pp collisions at the LHC in 2009, the CMS detector has recorded anomalous signals in the central region of the ECAL detector (Fig. 1). Their energy spectrum ranged up to the TeV scale and in some cases saturated the single crystal readout. These signals, known as “ECAL

Fig. 2. “Swiss cross” distribution, defined as $1 - E_4/E_1$, in data and MC simulation (not including simulated anomalous signals).

spikes”, have the following characteristics:

- They are isolated in most cases, having all energy reconstructed in a single channel;
- Spikes have a faster rise time compared to the scintillation signal;
- The spikes are uniformly distributed in EB. They do not occur in EE, where VPTs are used for the detection of scintillation light.

Studies based on Monte Carlo (MC) simulations indicate that anomalous signals originate from direct ionization of the silicon in the APDs from heavily ionizing particles produced in pp collisions. The most frequent spike progenitors are neutrons produced within the crystal volume giving an np reaction either in the (hydrogen rich) protective epoxy coating of the APDs or directly in the APD amplification region. Laboratory measurements using neutron sources irradiating the APDs showed that neutrons can induce signals of equivalent energies of several hundred GeV[3].

In $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC, the rate of anomalous signals is about 1 per 370 minimum bias events. A linear dependence of the rate with respect to the event charged particle multiplicity was observed. Information from the energy distribution of the shower and the pulse shape is used to suppress the anomalous signals.

Fig. 3. Energy spectrum of EB signal candidates, all events (black points) and after spike suppression (red points).

The lateral size of the EB crystals is comparable to the Molière radius of PbWO_4 ($R \approx 2.4$ cm). An electromagnetic (EM) shower is contained in several crystals, while spikes are usually isolated in a single channel. The “Swiss cross” variable, defined as $1 - E_4/E_1$, measures the energy ratio of the four adjacent crystals (E_4) around the channel with the maximum reconstructed energy (E_1). For spikes, the “Swiss cross” is ≈ 1 , while EM showers mostly take values < 0.95 (Fig. 2). A large suppression of the rate of spikes ($> 99\%$) is achieved by requiring that the “Swiss cross” variable be < 0.95 for energy deposits with $E_T > 3$ GeV (Fig. 3).

The peak of the scintillation light spectrum from PbWO_4 is at 430 nm with 80% being emitted within 25 ns. The reconstructed time of EM showers from pp collisions is calibrated such that the mean value is zero, with a precision of $O(100)$ ps for $E > 1$ GeV. The measured ECAL time is extracted on an event-by-event basis for each channel. This variable is used to discriminate between spikes and EM energy deposits. For spikes, the absence of an EM shower in the crystals implies a faster rise time in the pulse shape (Fig. 4). The different pulse shape of the spikes with respect to the EM signal biases the time reconstruction, which assumes the EM signal pulse shape. Spikes peak at ≈ -11 ns and have a long tail attributed to slow neutrons (Fig. 5). A window of 3 ns in the selection of the signal candidates is $> 90\%$ efficient in removing the spikes [6].

The “Swiss cross” variable and the time variables are, to a good approximation, uncorrelated (Fig. 6). The former depends on the energy sharing in the neighboring crystals while the latter depends solely on the generated pulse of the candidate signal. This permits the estimation of the residual spike background in physics analysis using data control regions. Typically, the level of the background is measured to

Fig. 4. Normalized pulse shapes for an electromagnetic shower (dashed line) and a spike (solid line) measured in data.

Fig. 5. Reconstructed time in data and MC simulation. The out-of-time signals peaking at ≈ -11 ns are attributed to anomalous signals while the long tail is believed to be due to slow neutrons. The secondary maxima in the positive time region are caused by the quantisation of the time samples used in the readout (25 ns spacing).

be significantly less than $< 1\%$. A further discussion of the effect on spikes on CMS physics analyses can be found in [4].

Since the characteristics of ECAL spikes are localized high energy signals, they will often satisfy the conditions for triggering electrons and photons in CMS. A detailed description of the trigger algorithm can be found elsewhere [5]. If untreated, 60% of the electron/photon trigger candidates above a threshold of 12 GeV would be caused by spikes. At high luminosity these would be the dominant component of the 100 kHz CMS L1 trigger rate bandwidth. The basic building block for forming electron/photon triggers is the “trigger tower” which, in EB is a 5×5 crystal matrix. The energies of the 25 channels are summed and used as input in the trigger decision. The strip fine-grained veto bit (sFGVB) is used for the online spike rejection. The number of crystals above a programmable threshold are counted in strips of 5×1

Fig. 6. Scatter plot showing the “Swiss cross” against the reconstructed time for EB channels with $E_T > 3$ GeV. EM signals are located in the region $1 - E_4/E_1 < 0.95$ and $|T| < 3$ ns.

Fig. 7. Pattern of an EM shower compared to an anomalous signal used as input to the strip fine-grained veto bit for the online spike rejection.

crystals. The resulting 5-bit word, which records how many channels in the strip are above threshold, is used as the index in a lookup table, which outputs one bit per strip. It is configured to return zero if only one channel in the strip is above threshold (spike-like) and one if more than one channel is above threshold (corresponding to a typical electromagnetic (EM) shower). If the tower transverse energy is greater than 8 GeV (12 GeV in 2012) and the sFGVB is set to zero, the trigger tower with the spike-like candidate will not contribute to the triggering of the event [5]. A significant rate reduction is observed which ranges from 20%-80% depending on the trigger path thresholds. The online spike rejection efficiency has been measured to be 96% with respect to the offline rejection while being $< 1\%$ inefficient for EM showers [7].

In summary, anomalous signals in the CMS electromagnetic calorimeter have been observed and understood to be due to direct ionization of the amplification region of the APDs from heavily ionizing particles produced in pp collisions. Their rate is proportional to the event particle multiplicity and their energy spectrum extends up to the single channel saturation level of $E \approx 1.8$ TeV. Flexibility in the programmable detector front-end electronics made it possible to reject the anomalous signals with an efficiency $> 96\%$. Anomalous signals are suppressed offline with $> 99\%$ efficiency using shower shape and pulse shape information. The deployment of the online

and the offline rejection algorithms minimize the impact of the anomalous signals on physics analyses.

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