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Timing performance of the CMS ECAL and prospects for the future

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Timing performance of the CMS ECAL and prospects for the future

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Abstract. The CMS electromagnetic calorimeter (ECAL) is made of about 75000 scintillating lead tungstate crystals arranged in a barrel and two endcaps. The scintillation light is read out by avalanche photodiodes in the barrel and vacuum phototriodes in the endcaps, at which point the scintillation pulse is amplified and sampled at 40 MHz by the on-detector electronics. The fast signal from the crystal scintillation enables energy as well as time measurements from the data collected in proton-proton collisions with high energy electrons and photons. The stability of the time measurement required to maintain the energy resolution is on the order of 1 ns. The single-channel time resolution of ECAL measured at beam tests for high energy showers is better than 100 ps. The time resolution achieved with the data collected in proton-proton collisions at the LHC is presented. The time precision achieved is used in important physics measurements and also allows the study of subtle calorimetric effects, such as the time response of different crystals belonging to the same electromagnetic shower. In addition, we present prospects for the high luminosity phase of the LHC, where we expect an average of 140 concurrent interactions per bunch crossing (pile-up). It is currently being studied how precision time could be exploited for pileup mitigation and for the assignment of the collision vertex for photons. In this respect, a detailed understanding of the time performance and of the limiting factors in time resolution will be important.

1. Introduction

The primary goal of the Compact Muon Solenoid (CMS) experiment [1] is to explore particle physics at the TeV energy scale, exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) at CERN [2]. The electromagnetic calorimeter (ECAL), which measures the energy of electrons and photons produced in LHC collisions, is located inside a solenoid magnet. It is a hermetic homogeneous calorimeter made of 75848 lead tungstate ($PbWO_4$) scintillating crystals: 61200 in the barrel (EB) and 7324 in each endcap (EE). The scintillation decay time of the crystals is comparable to the LHC bunch crossing interval of 25 ns, and about 80% of the light is emitted in 25 ns. For the light detection, the crystals are equipped with avalanche photodiodes in the barrel and vacuum phototriodes in the endcaps. The main purpose of the ECAL is the precise energy measurement, needed for many physics analyses. The stability of the time measurement required to maintain the energy resolution is on the order of 1 ns. In addition to the energy measurement, the combination of the scintillation timescale of $PbWO_4$, the electronic pulse shaping, and the sampling rate allow excellent time resolution to be obtained with the ECAL. This is important in CMS in many respects. The better the precision of time measurement and synchronization, the larger the rejection of backgrounds with a broad time distribution. Such backgrounds are out-of-time proton-proton interactions, cosmic rays, beam halo muons, and electronic noise. Precise time measurement also makes it possible to put constraints on the presence of particles predicted by models beyond the Standard Model, identifying photons from the decay of long-lived new particles, which reach the calorimeter out-of-time with respect to particles travelling at the speed of light from the interaction point [3]. To achieve these goals the time measurement performance both at low energy (1 GeV or less) and high energy (several tens of GeV for showering photons) becomes relevant.

The performance of the calorimeter has been measured before the collisions using test beam electrons, cosmics and beam splash events [4]. The resolution for large energy deposits (E>50 GeV) was estimated to be better that 20 ps and the linearity of the time response has been also verified. During collisions, there are many additional effects which could worsen the performance, like run-by-run variations, inter-calibration effects, energy-dependent systematics, and crystal damage due to radiation. A first measurement of the timing performance and intercalibration of the CMS ECAL during collisions has been reported in [5], where the time resolution was about 190 ps in the barrel and 280 ps in the endcap.

The purpose of the studies described in this document is to re-evaluate the time performance and check if the calorimeter is stable over time.

Detailed studies on time resolution are also important for the upgrade of the detector foreseen in 2024, when the LHC is expected to reach to peak luminosities of $10^{35} cm^{-2} s^{-1}$ and it will be necessary to replace some components of the current detectors, especially in the forward region. The increased luminosity will introduce a multiplicity of simultaneous events (pile-up) of about 140 interactions per beam crossing. The pile-up of energy deposits coming from different interactions deteriorates the calorimeter performances in terms of energy measurement and particle identification, as individual particles are less isolated. A possible strategy to reduce pile-up effects consists in complementing the calorimeters with an extremely high time resolution, which would enable the energy deposits coming from different interaction vertices to be resolved in time.

2. Measurement of time resolution at p-p collisions

The resolution is extracted by comparing the time measured in ECAL hits which are, or can be made, synchronous. Two methods are used:

- The first one is based on the comparisons of the time of the two electrons of a Z decay. The time of the electron corresponds to the one of the most energetic hit of the deposit (cluster). The time is corrected by the time-of-flight of the electrons, which is properly determined from the primary vertex position, obtained from the electron tracks. The two clusters are required to pass loose criteria on the shape of the deposit and the resulting invariant mass has to be consistent with the Z boson mass (60 GeV<m(ee)<150 GeV). The energy of each of the two hits must fall in the range 10 GeV<E<120 GeV. The resolution is extracted as the σ parameter of a gaussian fit to the core of the time difference distribution. The resulting resolution is plotted as a function of the effective amplitude, which depends on the amplitudes measured in the two crystals as $A_{eff} = A_1 A_2 \sqrt{A_1^2 + A_2^2}$. The amplitude is in units of ADC counts, with a dynamic range of 4000 and the electonic noise corresponds to about 1 count. This is shown in Fig. 1. The noise term is very similar to the one obtained prior to collisions [4] and the constant term turns out to be about 150 ps. The value obtained for the constant term is remarkable but it is still far from the test beam one, which was about 20 ps.
- the second method uses the two most energetic neighboring crystals of a photon cluster, with a similar amount of energy. The second requirement is to minimize the shower propagation effects. Additional selection criteria are applied, based on the shape of the ECAL cluster

and on the energy of the ECAL hit (E<120 GeV). The resulting resolution, as a function of the effective amplitude, is shown in Fig. 2. Here the constant term is smaller, about 70 ps, closer to the test beam results.

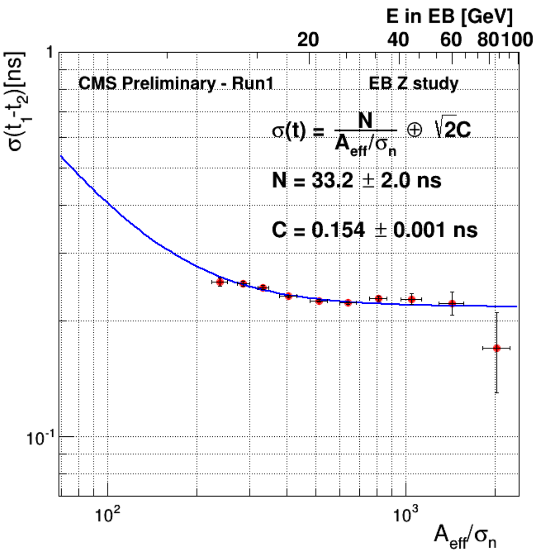

Figure 1. Barrel, electrons from Z decays: spread of the time difference as a function of the effective amplitude. A fit to the distribution, using the quadrature of a noise and a constant contribution, is superimposed.

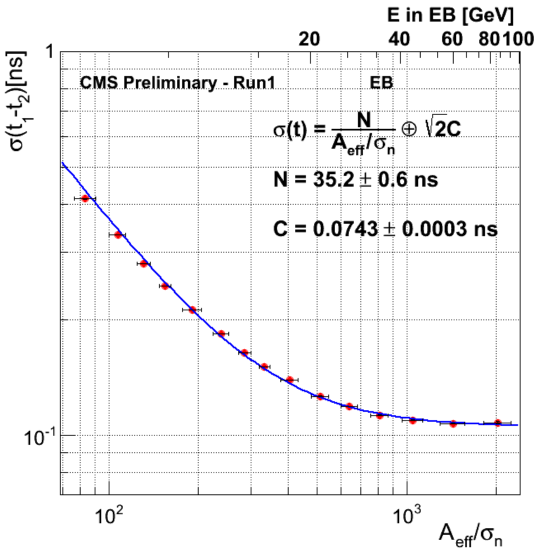

Figure 2. Study of neighboring crystals of a photon energy deposit: spread of the time difference as a function of the effective amplitude. A fit to the distribution, using the quadrature of a noise and a constant contribution, is superimposed.

A further study, comparing crystals belonging to either the same or different readout units, is also performed. The redaout unit corresponds to a trigger tower which is a 5x5 matrix of crystals. This is to see if the origin of this residual 70 ps constant term is due to residual timing jitter in the electronics or the clock distribution to the individual readout units. In Figures 3 and 4 the result for crystals in the same and different readout units are shown, respectively. The different constant term (67 ps vs 130 ps) does not explain the difference with respect to the test beam results but indicates that there are effects related to the electronics which need to be further investigated.

The stability of the time measurement as a function of time and pseudorapidity has been also checked. Both can reveal a dependence of the time measurement performance on the luminosity and radiation. The analysis of neighboring crystals in the same readout unit has been repeated in different run number ranges, Fig. 5 (this is equivalent to a study as a function of time), and in bins of pseudorapidity, Fig. 6. The spread of the time difference is extracted in an energy range where the constant term contribution is expected to dominate, i.e. for A_{eff}>30 GeV. The time resolution resulted to be very stable.

3. Physics potential of precise timing at HL-LHC

The high luminosity phase of LHC (HL-LHC) is complicated by the increased multiplicity of simultaneous events (pile-up): about 140 interactions per beam crossing, with a spread of approximately 6 cm and 300 ps along the beam axis, are anticipated. The pile-up of energy deposits coming from different interactions deteriorates the calorimeter performances in terms of

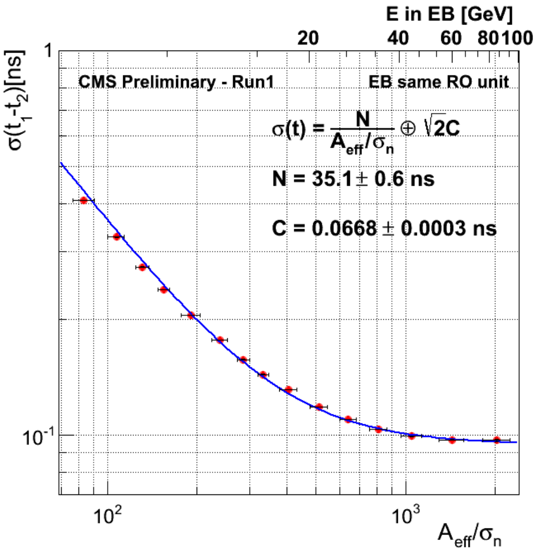

Figure 3. Study of neighboring crystals in the same readout unit of a photon energy deposit: spread of the time difference as a function of the effective amplitude. A fit to the distribution, using the quadrature of a noise and a constant contribution, is superimposed.

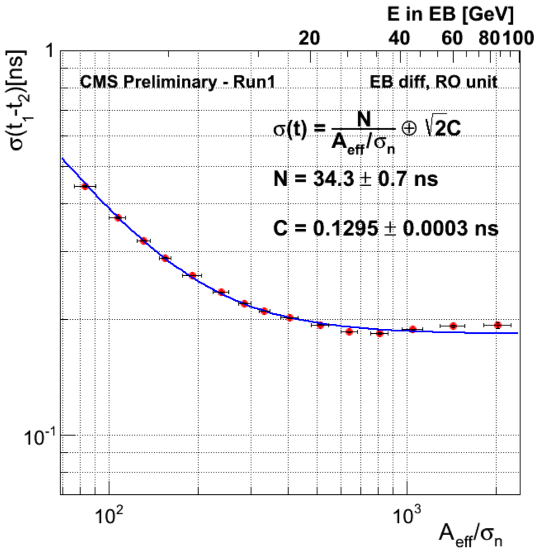

Figure 4. Study of neighboring crystals in different readout units of a photon energy deposit: spread of the time difference as a function of the effective amplitude. A fit to the distribution, using the quadrature of a noise and a constant contribution, is superimposed.

energy measurement and particle identification, as individual particles are less isolated. In order not to compromise the sensitivity to exclusive channels and the reconstruction of the missing transverse energy (MET), a crucial observable in searches for processes beyond the standard model, innovative solutions should be identified to mitigate pile-up effects. A possible strategy consists in complementing the transversal segmentation of the calorimeters with an extremely high time resolution, which would enable the energy deposits coming from different interaction vertices to be resolved in time. To set the scale, a time resolution of 30 ps corresponds to about 1 cm in flight length. This has to be compared with the size of the beam spot, which corresponds to about 6 cm. A TOF-based selection could then be able to achieve a pile-up rejection factor of about 6.

There are several possible uses of this time information: 1) It can be used to determine the primary vertex when there is a small track activity in the event. This is particularly important for the Higgs to two photons analysis, where there is a limited number of extra jets in the event and the vertex determination is crucial for the Higgs mass resolution; 2) The time information can be included in the pile-up jet rejection algorithms. Presently, they are based on tracks and on the jet shape but they are not very effective outside the acceptance of the tracking detector. The time would make these algorithms more performant in the forward region. 3) ECAL hits not consistent with the primary p-p collision can be filtered out with the timing. This reduces the ECAL occupancy, which is particularly relevant for reconstruction and trigger issues at 140 pile-up conditions. 4) The time information can be integrated with the CMS Particle Flow algorithm. Particle Flow is a reconstruction algorithm that combines all inputs from the different CMS detectors to improve the resolution of the physics objects, in particular jets and missing transverse energy. The Particle Flow algorithm currently applies timing cuts on the ECAL hits consistent with the resolution measured in the data. The gain in performance with an improved

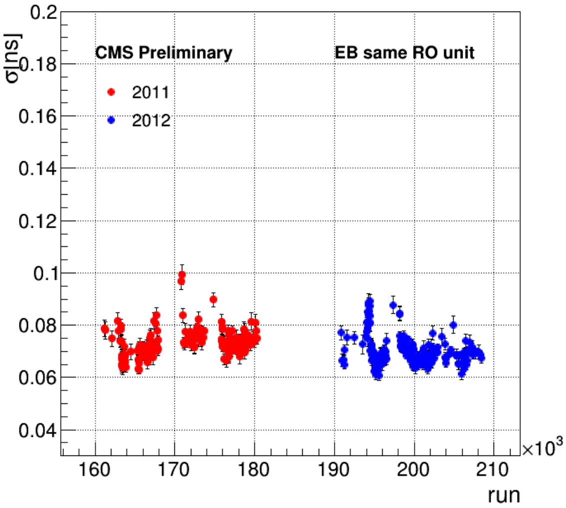

Figure 5. Stability of the time resolution as a function of the run number, estimated with the neighboring crystals method (same readout unit). The resolution corresponds to the σ of a gaussian fit to the core of the time difference distribution for A_{eff}>30 GeV.

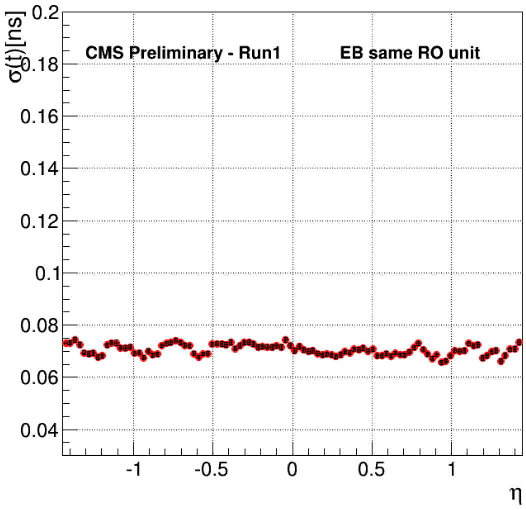

Figure 6. Stability of the time resolution as a function of the pseudorapidity, estimated with the neighboring crystals method (same readout unit). The resolution corresponds to the σ of a gaussian fit to the core of the time difference distribution for A_{eff}>30 GeV.

time resolution is currently being investigated in detail.

Here we present studies based on simulations, assuming that a detector capable of very precise time measurement can be integrated in the electromagnetic calorimeter in the forward region. We used samples of H $\rightarrow \gamma\gamma$ events with an average number of pile-up interactions of about 20. In Fig. 7 the performance in terms of vertex determination is shown as a function of the time resolution of the detector. The vertex of the two photons from the Higgs decay is reconstructed via a χ^2 fit which uses the measured time of the two photons and their expected time-of-flight, under the assumption they come from the same interaction point. The time fo the photon corresponds to the time of the most energetic crystal of the cluster. As shown, it is possible to reach a resolution in the vertexing better than 1 cm if the time resolution is about 30 ps. In Fig. 8 the impact of a precise time detector on the total energy reconstructed in the electromagnetic calorimeter is illustrated. Here ΣE_T^{ECAL} corresponds to the sum of the transverse energy of all ECAL cells above the electronic noise threshold. It can be noticed that the original distribution without pile-up can be restored by imposing a requirement on timing of $\pm$ 30 ps.

4. Conclusions

The resolution of the time measurement of the CMS electromagnetic calorimeter has been investigated with samples of electrons and photons taken during p-p collisions. In the barrel, the relative time resolution of adjacent channels in an electromagnetic cluster was found to be 70 ps for large energies if the channels belong to the same electronic readout unit. This resolution is 130 ps for channels belonging to different readout units. The timing performance is stable over time and at different pseudorapidities.

A possible use of a precise timing detector for the LHC Phase II upgrade is currently being studied. We show that, in events with two photons, the time information can be used to determine the primary vertex position with a resolution smaller than 1 cm, even without any

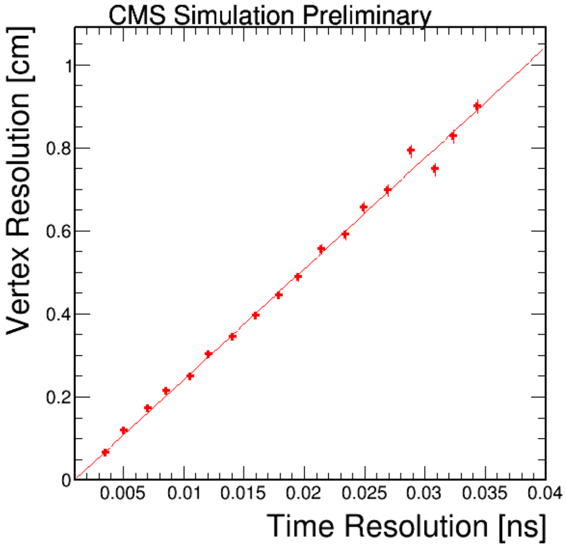

Figure 7. Resolution of the primary vertex determination using the time of two photons coming from the Higgs decay, as a function of the resolution of the timing detector.

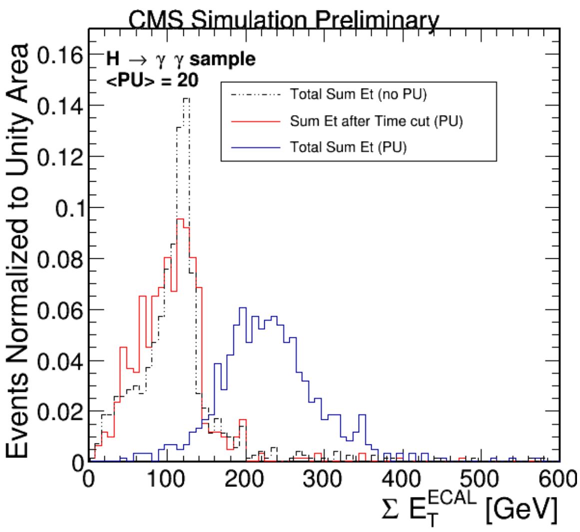

Figure 8. Impact of a selection based on time on the calorimeter-based ΣE_T variable.

tracking information and assuming a better than 30 ps resolution in time. A selection based on time also allows for a large reduction of the electromagnetic hit multiplicity, thus improving the energy measurements, resolution and trigger occupancy.

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