The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

05 November 2015 (v3, 17 November 2015)

Electromagnetic calorimetry at the highest energy and intensity proton-proton collider: CMS ECAL performance at LHC Run II and prospects for high luminosity LHC

Andrea Massironi for the CMS Collaboration

Abstract

The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) started operating at the Large Hadron Collider (LHC) in Spring 2015 with proton-proton collisions at 13 TeV center-of-mass energy and at a reduced bunch spacing of 25 ns. The instantaneous luminosity during LHC Run 2 is expected to exceed the levels achieved in LHC Run 1 significantly. In this talk we present new reconstruction algorithms and calibration strategies to maintain the superb performance of the CMS ECAL under these challenging conditions. We will show first performance results from the 2015 data taking period and give an outlook on the foreseen performance for Run 2. The current Run 2 of LHC is expected to accumulate a few hundred inverse femtobarn of proton-proton collisions before LHC will be upgraded to provide an even higher instantaneous luminosity, referred to as High-Luminosity LHC (HL-LHC). HL-LHC is expected to provide a few inverse attobarn of integrated luminosity. This will result in even higher rates of simultaneous proton-proton collisions, called pile-up (PU), up to and exceeding 140 PU collisions. Likewise the physics event rates will increase further which requires upgrades to the readout and trigger electronics of the existing ECAL. We will briefly discuss the upgrade plans and present in detail the plans to combat the PU under these conditions. One promising technique is based on the very good time resolution the CMS ECAL provides. We present the current status of timing performance of the CMS ECAL, plans to improve this for the future and examples of how this can be used for PU mitigation.

Presented at *IEEE-NSS-MIC-2015 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference*

Precision electromagnetic calorimetry at the highest energy and intensity proton-proton collider: CMS ECAL performance at LHC Run 2 and prospects for high luminosity LHC

Andrea Massironi,

Northeastern University, on behalf of the CMS collaboration.

Abstract—The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) started operating at the Large Hadron Collider (LHC) in Spring 2015 with proton-proton collisions at 13 TeV center-of-mass energy and at a reduced bunch spacing of 25 ns. The instantaneous luminosity during LHC Run 2 is expected to exceed the levels achieved in LHC Run 1 significantly. In this talk we present new reconstruction algorithms and calibration strategies to maintain the superb performance of the CMS ECAL under these challenging conditions. We will show first performance results from the 2015 data taking period and give an outlook on the foreseen performance for Run 2. The current Run 2 of LHC is expected to accumulate a few hundred inverse femtobarn of proton-proton collisions before LHC will be upgraded to provide an even higher instantaneous luminosity, referred to as High-Luminosity LHC (HL-LHC). HL-LHC is expected to provide a few inverse attobarn of integrated luminosity. This will result in even higher rates of simultaneous proton-proton collisions, called pile-up (PU), up to and exceeding 140 PU collisions. Likewise the physics event rates will increase further which requires upgrades to the readout and trigger electronics of the existing ECAL. We will briefly discuss the upgrade plans and present in detail the plans to combat the PU under these conditions. One promising technique is based on the very good time resolution the CMS ECAL provides. We present the current status of timing performance of the CMS ECAL, plans to improve this for the future and examples of how this can be used for PU mitigation.

Index Terms—ECAL, CMS, calorimetry

I. INTRODUCTION

THE CMS ECAL [1] is a high-resolution, hermetic, and homogeneous electromagnetic calorimeter made of 75,848 scintillating lead tungstate crystals. Its exceptional precision for energy measurement, as well as its timing performance, are invaluable tools for the discovery of new physics at LHC [2], [3]. The LHC started to operate at an increased center-of-mass energy of 13 TeV in spring 2015 after a two year shutdown. To increase the instantaneous luminosity the bunch spacing has been reduced by a factor 2 with respect to LHC Run 1. These operational conditions pose new challenges to maintain the excellent performance of the CMS ECAL. Among them is an increased rate of PU collisions (PU), almost a factor two larger than in LHC Run 1, an increased physics rate due to the increased center-of-mass energy and an increased radiation level. In the first part of this paper we present novel reconstruction

and calibration tools developed to cope with these challenges. Following the LHC Run 2 which just started, the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN [4] is expected to provide instantaneous luminosities of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The enhanced data rates will provide the datasets necessary to perform precision measurements of the Higgs couplings, probe rare Higgs production mechanisms and decays, study the scattering of longitudinally polarized W bosons, and search for physics beyond the Standard Model. Pile-up, physics event rates and radiation levels will increase and be even more challenging.

In the second part of this paper we discuss how these challenges can be addressed with upgrades to the readout and trigger electronics of the CMS ECAL barrel and with more far reaching upgrades of the forward part of the detector. We discuss in particular how the very good timing resolution of the CMS ECAL can be exploited to mitigate the effects of PU and the prospects to improve timing performance further.

II. CMS ECAL OPERATION AND PERFORMANCE AT LHC RUN 2

AN important challenge of the CMS ECAL operation at LHC Run 2 is the increased rate of PU collisions and the reduced LHC bunch spacing of 25 ns. This increases the probability of single calorimeter cells to be hit by a particle in successive bunch crossings and makes it more difficult to differentiate contributions from preceding and trailing bunches. The pulse from each crystal is sampled every 25 ns and a buffer of 10 digitized values is used to reconstruct the energy deposit. The very precise and reproducible pulse shaping of the ECAL electronics allows us to fit the 10 digitized samples with additional pulse hypotheses at different bunch crossings, in order to estimate the energy of the in-time energy deposit and remove the out-of-time contribution. The validation of this new method with the first data collected in 2015 is currently ongoing.

The calibration of the CMS ECAL relies on physics references such as the di-photon invariant mass of neutral meson decays (π^0 and η into $\gamma\gamma$), the ratio between the tracker based momentum and the ECAL reconstructed energy for electrons from Z and W decays, di-electron invariant mass of Z decays, as well as azimuthal symmetry of the energy flow

Fig. 1. Relative response to laser light (440 nm in 2011 and 447 nm from 2012 onwards) injected in the ECAL crystals, measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity, for the 2011, 2012 and 2015 data taking periods.

in minimum bias events [5]. All these different methods are needed to obtain the excellent energy resolution that had been exploited during LHC Run 1 for new physics searches [6], [7]. The triggers, data flow and calibration procedures for all methods have been optimized for operation at LHC Run 2. The crystal transparency change and VPT response changes due to conditioning under irradiation are measured (Fig. 1) and corrected for by the laser monitoring system.

The analysis of the first 2015 data shows a good agreement between the energy spectrum in the crystals, shower shape variables, di-electron invariant mass, and their simulation with update conditions for the start of Run 2. A good energy scale and resolution has been established in the prompt reconstruction, where the calibration constants have been propagated from Run 1 to Run 2 values by means of the laser monitoring system.

III. PRECISION CALORIMETRY AT THE HIGHEST ENERGY: CMS ECAL AT HL-LHC

BOTH the PU rate and the physics event rate will increase further for the HL-LHC. Upgrades to the calorimeter hardware are necessary to cope with these conditions. The goal is to maintain the detector performance and trigger efficiency achieved during LHC Run 1. The upgrade plans include the replacement of the front-end electronics of the CMS ECAL barrel detector and a complete replacement of the endcap portion of the detector [8]. An increased granularity of the forward calorimeter will help maintain good performance and efficiency.

Although the crystals in the ECAL barrel do not need to be replaced, the electronics will need to be upgraded, to cope with the new challenging environment. The new CMS trigger will require longer latency time for the front-end electronics (from 6.4 μ s to 12.5 μ s), thus requiring a redesign of the front-end electronics of ECAL. In addition, the front-end electronics replacement will enable the use of single crystal information at the very first stage of the trigger selections. This will allow to cope with higher PU and irradiation effects, such as the increased number of anomalous events in the APD (spike

events), characterized by direct interaction of particles in the readout unit of a single crystal. An optimized shortening of the pre-amplifier pulse shaping time is currently ongoing and will improve spike rejection, and help to reduce noise and out-of-time PU contribution. In addition, the barrel operating temperature will be decreased from 18° C to 8° C in order to mitigate the increase in APD dark current noise due to irradiation (by a factor of 2).

A crucial handle on the mitigation of PU is the very good timing performance of the CMS ECAL. A resolution of around 150 ps for high energy electromagnetic clusters was achieved during LHC Run 1. The good timing resolution allows the removal of hits based on the time-of-arrival at the calorimeter. Timing information can also be used to subtract neutral energy from PU in electromagnetic clusters and to help in the identification of jets from PU. This technique can be used also to improve the performance of physics analyses, such as vertex assignment in Higgs searches in two photons final state: a time resolution of about 20-30 ps correspond to a spatial resolution of about 1 cm, within which the vertex assignment has a negligible effect on the invariant mass resolution. A test beam campaign is currently ongoing to estimate the best achievable time resolution with the best possible electronics. For precise timing the clock distribution system needs a deep revision, as this has been the limiting factor for the time resolution during Run 1.

IV. CONCLUSION

THE CMS ECAL has demonstrated excellent performance at LHC Run 1. The ongoing LHC Run 2 and even more so the future HL-LHC run will push the challenge to maintain this performance and improve it. In this paper we have discussed various aspects of the energy measurement of the calorimeter and its calibration procedures, which are important ingredients for meeting these ambitious goals. Data from the ongoing LHC Run 2 and studies for the HL-LHC upgrade have been presented.

REFERENCES

- [1] [CMS Collaboration], “CMS: The electromagnetic calorimeter. Technical design report,” CERN-LHCC-97-33, CMS-TDR-4.
- [2] [CMS Collaboration], “Observation of the diphoton decay of the Higgs boson and measurement of its properties,” *Eur. Phys. J. C* **74**, no. 10, 3076 (2014)
- [3] [CMS Collaboration], “Measurement of the properties of a Higgs boson in the four-lepton final state,” *Phys. Rev. D* **89**, 092007 (2014)
- [4] L. Rossi, and O. Bruning, “High Luminosity Large Hadron Collider A description for the European Strategy Preparatory Group”, Tech. Rep. CERN-ATS-2012-236, CERN, Geneva, Aug 2012.
- [5] [CMS Collaboration], “Energy Calibration and Resolution of the CMS Electromagnetic Calorimeter in pp Collisions at $\sqrt{s} = 7$ TeV,” *JINST* **8**, P09009 (2013)
- [6] [CMS Collaboration], “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV” *JINST* **10**, P06005 (2015)
- [7] [CMS Collaboration], “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV” *JINST* **10**, P08010 (2015)
- [8] [CMS Collaboration], “Technical Proposal for the Phase-II Upgrade of the CMS Detector”, CERN-LHCC-2015-010. LHCC-P-008