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PERFORMANCE OF THE CMS DETECTOR DURING THE LHC RUN 2*

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Highlights of the performance of the CMS detector in the LHC Run 2.

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1. Introduction

With the restart of the LHC operations in April 2015, the Run 2 has started. For the CMS Collaboration [1], the second half of the year was driven by an intense activity mainly ongoing on three fronts: analyses based on Run 1 data, studies for the upgrade of the detector in view of the future phases of the LHC and, of course, collect and analyse proton–proton and heavy ions data. This paper focuses on the latter highlighting examples where the intervention completed during the LHC Long Shutdown 1 (LS1) concretised in an improvement of the performance for the CMS detector and its hardware and software infrastructure.

2. Operations of the CMS detector during the LHC Run 2

Sustained magnet operation has been difficult since the beginning of the data taking due an apparent build up of contaminant in the filters, adsorbs, turbines and heat exchangers of the cold box. Besides very intensive, diagnostic measurements, which are complicated by the very nature of cryogenic installations, an invasive programme of filter, absorber and turbine replacement has been undertaken using the pre-scheduled technical stops of the LHC where possible.

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The CMS Collaboration exploited the initial data to advance in the commissioning of the detector. Continuous changes in data-taking conditions made the first period quite demanding in terms of organization for on-line and off-line operation teams, with frequent changes of trigger menus, calibrations, *etc.*

Wednesday, November 4$^{\text{th}}$ marked the end of the high-energy 2015 proton run. During the full 2015 data-taking period, the LHC delivered 4.2 fb^{-1}, 3.8 fb^{-1} of which were recorded by the CMS. Out of these, 2.8 fb^{-1} have been taken at full field $B = 3.8$ T and are usable for analysis. The detector availability has been excellent with all the subsystems participating with a fraction of working channels above 97%.

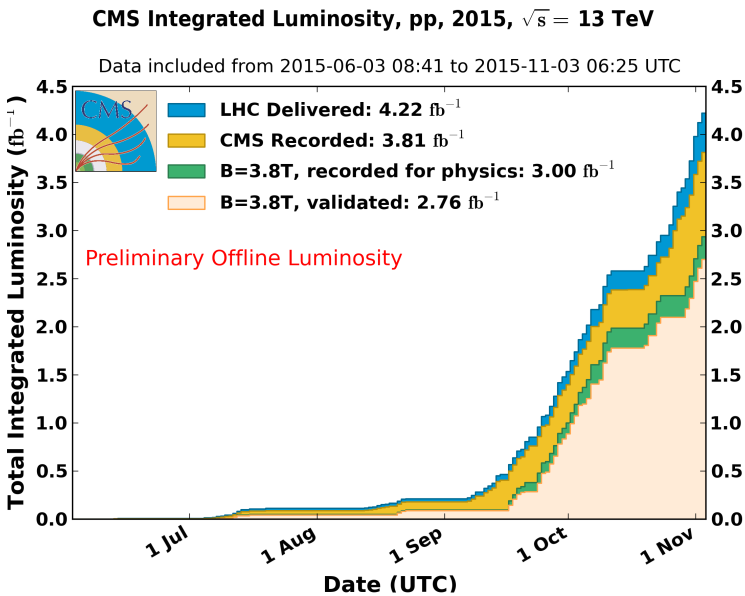

Fig. 1. (Colour on-line) Cumulative curves for the luminosity delivered by LHC (grey/azure), recorded by CMS (light grey/orange) and certified as good for physics analysis during stable beams (the lightest grey/light orange). The dark grey/green histogram shows the recorded luminosity, while CMS was taking data with full magnetic field (3.8 T).

3. Detector upgrade in preparation for the LHC Run 2

The LHC running conditions in the Run 2 differ from the Run 1 ones under two principal aspects: the center-of-mass energy has been increased from 8 TeV to 13 TeV and the bunch spacing went from 50 ns to 25 ns. The challenge for the detector is to provide an effective pile-up (PU) mitigation mechanism both for in-time and out-of-time pile-up while coping with higher event physics rate and an increased radiation level. With this in mind, during the LHC LS1, a number of upgrades was completed, both from the hardware and the software point of view in order to guarantee the excellent CMS performance achieved during Run 1. In the following sections, the improvements in the signal reconstruction of the electromagnetic calorimeter (ECAL) and the upgrade of the Trigger and Data Aquisition systems are described.

3.1. The ECAL performance

The CMS ECAL [2] is a high-resolution, hermetic, and homogeneous electromagnetic calorimeter made of 75,848 scintillating lead tungstate crystals. 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 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 described method proved to be very effective in measuring the amplitude of the in-time pulse shape. An example of fitted pulse for simulated events with 20 average pileup interactions and 25 ns bunch spacing is reported in Fig. 2.

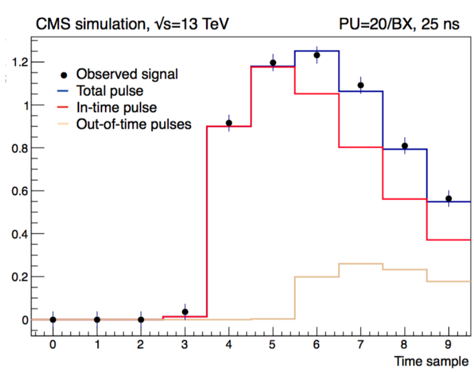

Fig. 2. (Colour on-line) ECAL barrel pulse shape: dots represent the 10 digitized samples, the grey/red distributions (light grey/orange) represent the fitted in-time (out-of-time) pulses with positive amplitude. The black/blue histograms represent the sum of all the fitted contributions.

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 in minimum bias events. All these different methods are needed to obtain the excellent energy resolution that had been exploited during LHC Run 1 for new physics searches. The triggers, data flow and calibration procedures for all methods have been optimized for operation at LHC Run 2, and the analysis of the data collected in 2015 confirmed that an energy resolution close to 1% in the central barrel is at reach, as shown in Fig. 3.

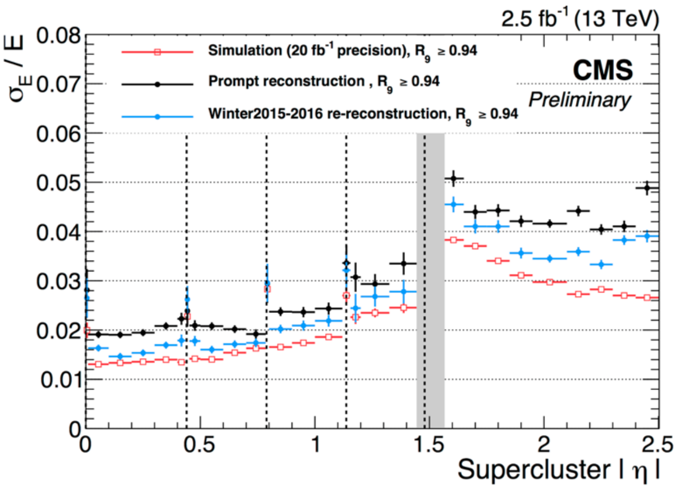

Fig. 3. Relative electron (ECAL) energy resolution unfolded in bins of pseudo-rapidity η for the barrel and the endcaps. Electrons from $Z \to e^+e^-$ decays are used. The resolution is shown for low bremsstrahlung electrons ($R_9 > 0.94$, with $R_9 = E_{3\times3}/E_{\text{supercluster}}$). The resolution $\sigma_{E/E}$ is extracted from an unbinned likelihood fit to $Z \to e^+e^-$ events, using a Breit–Wigner function convoluted with a Gaussian as the signal model. The resolution is plotted separately for data and MC events. The MC is generated assuming the calibration precision that was achieved with the amount of data collected in Run 1.

3.2. DAQ, trigger, monitoring and computing

An intensive program of upgrade and consolidation touching the CMS trigger, the data acquisition (DAQ), the data quality monitoring (DQM) and the computing systems has been carried out during the LS1 with the general goal of improving the performance of the overall infrastructure: from doubling the High Level Trigger (HLT) bandwidth to improving the CMS software making it more efficient from the memory and the performance point of view.

3.2.1. Trigger

The CMS experiment has installed a two-stage upgrade to their calorimeter trigger to ensure that the trigger rates can be controlled and the thresholds can stay low to ensure that the physics reach is not affected by the higher luminosity. The first 6 months of data taking have been an intense period to complete the phase-1 upgrade of the Level-1 trigger. The Stage-1 calorimeter trigger upgrade went into physics production at the beginning of the 50 ns proton–proton operations. As shown in Fig. 4, the electron/photon trigger efficiency is remaining high even when isolation is imposed to reduce the trigger rate and the new tau trigger, using a 2×1 region object instead of a 3×3 regions, has improved its performance significantly.

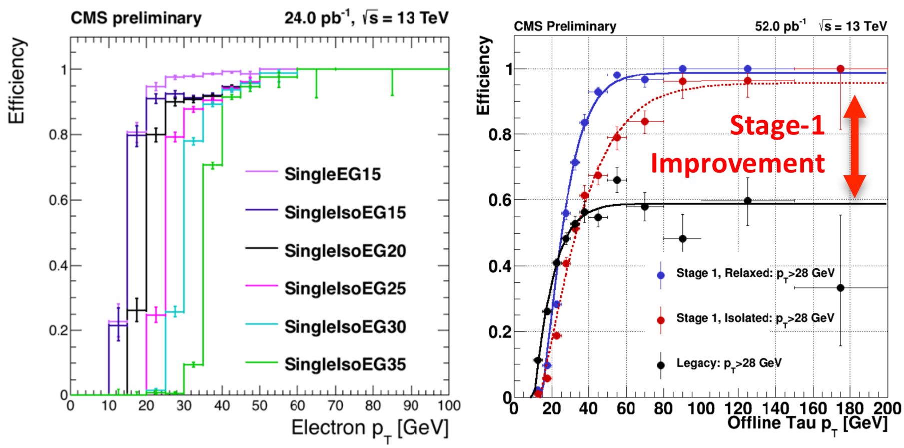

Fig. 4. Left: Stage-1 electron/photon trigger efficiency *versus* reconstructed p_{T} for different e/γ trigger and thresholds. Isolation reduces the rate significantly with only a small drop in efficiency. Right: Tau trigger efficiency for 2 Stage-1 upgrade triggers and the legacy system. A tremendous improvement in the tau trigger was realized with the Stage-1 hardware.

3.2.2. Data Acquisition System and Data Quality Monitoring System

During the LS1, the Data Acquisition (DAQ) and Data Quality Monitoring (DQM) teams re-designed and improved their systems. The new DAQ system includes a major replacement and upgrade of:

— the computer infrastructure;

— the core DAQ system (called DAQ2), based on 10/40 Gbps Ethernet for data concentration and event distribution and Infiniband [3] for event building providing a bandwidth of 200 GB/s;

— the High Level Trigger (HLT) system. The full HLT farm, comprising three generations of processing nodes, now provides a processing capacity of about 200 ms per event at an input rate of 100 kHz. The software and hardware infrastructure to provide input, execute the HLT algorithms and deal with output data transport and storage is entirely file-based;

— the Storage and Transfer System (STS) based on the Lustre file system [4] distributed file system storage system. This storage system is currently sized with a capacity of 350 TB and provides a raw bandwidth of 10 GB/s.

Following the DAQ upgrade, the DQM framework has been redesigned as well. The new design profited from the DAQ upgrade to improve the maintainability and ease the operations for both the DAQ and DQM team, yet this required a deep re-thinking of the processing logic of the on-line DQM data in order to provide a short latency monitoring. Since the first recommissioning phases after the LS1, the newly deployed DQM performed in a stable and reliable way and proved to be extremely useful in spotting problems at all levels.

3.2.3. Computing infrastructure and software

During the first months of collisions, the CMS computing infrastructure demonstrated the ability to sustain a load as high as ~ 150 k jobs running in parallel. On the software side, in Run 2, CMS has capitalised on the major improvements achieved by the massive amount of development performed during LS1: CMS has successfully transitioned to multi-threaded reconstruction application capable of processing multiple events concurrently, with good CPU efficiency and significant memory savings [5]. Intensive developments were carried out to improve the performance of the Geant4 [6] based simulation, which has been sped up by a factor 2, primarily from the introduction of the Russian Roulette [7] method inside CMS calorimeters, and from optimizations of CMS simulation sub-libraries. All these achievements were crucial in facing the Run 2 challenges within the computing resource constraints.

4. Summary

The first few months of data taking at 13 TeV were crucial for the recommissioning of the CMS detector after the LS1. All the systems proved to be able to cope with the new and challenging beam conditions: higher energy and reduced bunch spacing. An integrated luminosity of 2.7 fb^{-1} has been analysed and the CMS Collaboration looks forward to analysing additional data from 2016 in order to capitalize the effort made in 2015.

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