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Run2 performance of the CMS detector

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Abstract

Short description of the Run2 performance of the CMS detector.

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Performance of the CMS detector in Run 2*

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

1. Introduction

With the beams circulating in the LHC in April 2015, the Run 2 has started. For the CMS [1] collaboration 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

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.

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 online and offline operation teams, with frequent changes of trigger menus, calibrations, etc.

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Wednesday November 4th marked the end of the high-energy 2015 proton run. During the full 2015 data taking period, LHC delivered 4.1 fb^{-1} , 3.7 fb^{-1} of which were recorded by CMS. Out of these, 2.7 fb^{-1} have been taken at full field, $B=3.8 \text{ T}$ 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. Cumulative curves for the luminosity delivered by LHC (azure), recorded by CMS (orange) and certified as good for physics analysis during stable beams (light orange). The green histogram shows the recorded luminosity while CMS was taking data with full magnetic field (3.8 T).

3. Detector updates since LHC Run 1 and the LHC Run 2 challenge

Run 2 data taking differs from Run 1 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 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 Acquisition 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. ECAL barrel pulse shape: dots represent the 10 digitized samples, the red distributions (other light colors) represent the fitted in-time (out-of time) pulses with positive amplitude. The dark 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 1% in the central barrel is at reach, as shown in Fig. 3.

Fig. 3. Relative electron (ECAL) energy resolution unfolded in bins of pseudorapidity η for the barrel and the endcaps. Electrons from $Z \rightarrow e^+e^-$ decays are used. The resolution is shown for low bremsstrahlung electrons ($R_9 > 0.94$, with $R_9 = E_{3 \times 3}/E_{\text{Supercluster}}$). The resolution σ_E/E is extracted from an unbinned likelihood fit to $Z \rightarrow e^+e^-$ 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, so that physics data collection will not be compromised. 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 2x1 region object instead of a 3x3 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 Monitorin (DQM) teams re-designed and improved their systems. The new DAQ system includes a major replacement and upgrade of:

- the cluster 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 achieved a much better separation of responsibilities between the DAQ and DQM team, yet this required a deep re-thinking of the processing logic of the online 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 $\sim 150\text{k}$ jobs running in parallel. On the software side, in Run 2, CMS has capitalised on the major improvements achieved by the massive amount of work performed during LS1: CMS has successfully transitioned to a 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 performance of CMS simulation, which has been sped up by a factor 2, primarily from the introduction of the Russian Roulette [6] method inside CMS calorimeters, and from optimizations of CMS simulation sub-libraries. All these achievements were crucial in facing the Run II challenges within the computing resource constraints.

4. Summary

The first few months of data taking at 13 TeV were mainly devoted to 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 analyzed not without surprises: even if not significant enough to claim a discovery an excess in the di-photon mass spectrum around 750 GeV was revealed. The first few months of data taking in 2016 will possibly give some confirmation of the 2015 results.

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