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Run 3 performance of new hardware in CMS

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This report summarizes the upgrades of the CMS experiment at the LHC for the run 3 data taking, that started in 2022. Subdetectors, such as the silicon tracker, hadronic calorimeter, and muon system, are adapted to cope with increased particle rates and radiation damage. The performance of the detector is analyzed on the recently collected data. New methods for luminosity determination and trigger paths for beyond standard model processes were implemented. Machine-learning techniques were utilized in many cases, such as for particle identification.

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1. Introduction

At the end of 2018, the LHC at CERN ended its run 2 and the second long shutdown (LS2) started after almost four years of proton-proton (pp) collisions. During that time, maintenance and upgrades on the collider itself and the experiments it houses were conducted to retain and improve their performance for run 3, which began in 2022. This report summarizes the upgrades accomplished on the CMS experiment and outlines the detector performance based on recently acquired data [1].

2. Beam radiation, instrumentation, and luminosity (BRIL)

Since July 2022, the LHC has delivered pp collision data at $\sqrt{s} = 13.6\,\text{TeV}$ with an integrated luminosity of about $44\,\text{fb}^{-1}$, from which more than 92% are recorded and about 89% are certified as having good quality for data analysis. The CMS experiment features multiple methods to measure the luminosity in real-time (online) and after reprocessing the data (offline). Through redundant measurements, an uncertainty of $\delta\mathcal{L} = 2.1\%$ was achieved. One of the online devices that contributed significantly to this result is the fast beam condition monitor (BCM1F) that was rebuilt during LS2 and installed for the Run 3 data taking [2]. Four half-ring-shaped modules, two located on either side 1.9 m from the interaction point, are mounted around the beam pipe. Unlike its Run 2 prototype, which was testing two different technologies, the new detection mechanism is based on silicon diodes only, and equipped with cooling pads that provide a temperature of $-20\,^{\circ}C$ and mitigate radiation damage. With its fast response and readout, it is possible to measure the particle rate in short time intervals and study, among other things, the beam-induced background in detail. At the beginning of 2022, the device was read out four times between two collisions, i.e. every 6.25 ns. Later that year it was increased to six intervals, i.e. every 4.167 ns.

3. Silicon pixel tracker and tracking efficiency

The silicon pixels immediately around the beam pipe are the most stressed under radiation. After Run 2, they were extracted from the detector for maintenance and reinstalled in 2021. Additionally, a new identically constructed innermost pixel layer was replacing the previous one. As a result, the number of functional readout chips has increased from approximately 94% in 2018 to about 98.5% in 2022 [5, 6]. After re-installation, the exact positions of the detector modules are unknown, Thus, incremental detector alignment procedures are performed starting with cosmic ray tracks recorded before and after the solenoid is turned on. Subsequently, tracks from early pp collisions at 900 GeV and later 13.6 TeV are used to obtain a precise determination of the hit positions of particles [3, 6].

Apart from the hardware upgrade, software improvements have been implemented. For example, an algorithm was built that allows the tracks to be built in parallel, reducing the time consumption to cope with the increasing particle rate [8]. For the selection of good tracks, a DNN replaced a BDT, reducing the fake rate while keeping the efficiency at the same level [9].

The tracking efficiency was measured for $|\eta| < 1.6$ in pp collision data at 13.6 TeV collected until August 23, 2022, by selection events from Z bosons decaying into a pair of muons. The tag and probe procedure was used where one muon, the tag, is selected using tight requirements and the efficiency is calculated based on a second muon, the probe, selected with loser requirements. The tracking efficiency is then given as the fraction of muon pairs where the probe also produces a track. The tracking efficiency is measured for tracks reconstructed with and without the information of the muon chamber and found nearly 100% as a function of the muon p_{T} and η. The efficiency is also found to be very stable as a function of the number of primary vertices, which is an indication of the number of simultaneous collisions (pileup) [7].

4. Hadronic calorimeter and jet energy scale

Through the intense radiation during Run 1 and 2 data taking, the scintillators of the ECAL and HCAL systems became less transparent, lowering the detection efficiency. To mitigate the effect of radiation damage, and to maintain physics performance for jets and missing transverse energy (MET), an upgrade on the HCAL electronic was performed before 2018 for the barrel and in the LS2 for the endcaps. Old hybrid photodetectors were replaced with new silicon multipliers. These provide three times higher photon detection efficiency and 200 times higher gain. As part of the upgrades, the depth segmentation of the HCAL has been increased from 1–2 to 4 in the barrel and from 2–3 to up to 7 in the endcaps. The number of readout channels also has been increased by 350% and the time information on when a signal is measured is now stored with a 0.5 ns resolution. This opens new possibilities for physics analyses, for example in the search for long-lived particles (LLP) that decay in the HCAL. It can also help in deriving more dedicated jet energy corrections.

Since the ECAL and HCAL responses are nonlinear, sequential corrections on the measured signal are applied to obtain a precise measurement of the jet energy and MET [10]. An offset correction that was applied in Run 2 because of contributions from pileup particles has been found to be negligible in Run 3. This has been made possible by the new approach for jets, the pileup-per-particle identification (PUPPI), where every particle is weighted with a probability that it comes from the main interaction. Preliminary corrections on the detector response from simulation and residual differences observed in data have been derived and show a good detector performance [11].

5. The CMS muon system

The muon detectors in CMS have so far withstood the radiation very well and are expected to be further operated. The original readout electrons for the CSC system, however, would have resulted in significant data loss from the higher particle flux and increased trigger rates obtained in run 3, and would have even more so for the HL-LHC [17]. For this reason, new electronic boards have been deployed during LS2 for the chambers closest to the beam pipe. Optical fibre are installed to transport the trigger data. The power supply was also upgraded to meet the requirements of the new devices.

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6. Z boson counting

The measurement of Z bosons decaying into a pair of muons is a process with a high production rate and very clean signature, making it the perfect process to calibrate and test the detector. A new method has been developed to measure $Z \rightarrow \mu\mu$ events as a handle for luminosity determination. The two muons in the final state are used to measure identification, reconstruction, and trigger efficiencies in situ, i.e. using the same data and their invariant mass spectrum is fit to subtract nonresonant backgrounds. The measurement is performed in short time intervals, about 20 minutes, to account for changing detector conditions [19]. Since almost all corrections are derived directly from the data, this represents a full end-to-end analysis, that is executed in a quasi-online routine, which is further completely complementary to traditional luminosity measurements. Early 2022 data has thus been used to validate the luminosity determination [18],

7. The CMS trigger system

The first step, level 1 (LV1) of the trigger system reduces the the 40 MHz incoming pp collision event rate down to 100 kHz using custom electronics such as FPGAs. During LS2, new trigger paths were developed to select signatures expected from beyond standard model (BSM) processes exploring previously unknown regimes. Such trigger focus on LLP that produce displaced tracks, or decay within the HCAL or muon station [12]. For the second step, the high level trigger (HLT), a more streamlined version of the CMS reconstruction is performed, reducing the event rate down to 1 kHz. The main improvements for Run 3 are the use of heterogeneous architectures, i.e. parallel processing based on multicore CPU and GPUs, that allow to reduce the reconstruction time spent per event. Currently, about 40% of the event processing is offloaded, including steps in the calorimeter and pixel reconstruction, pixel tracking, and vertex reconstruction [13]. An essential milestone with respect to the high luminosity LHC (HL-LHC) is reached, where homogeneous architectures will become inevitable. For Run 3, new HLT selections were implemented for example based on recent progress in machine learning [14]. A graph neural network based algorithm aims to identify jets with small or large cone size radia, improving the signal efficiency at the background fake rate, enriching the data with for example with $H \rightarrow bb$ events to further study less tested processes [15].

8. Summary and outlook

In three years of shutdown, the CMS detector was successfully upgraded and well prepared for Run 3, the next period of data taking from 2022 to 2025. So far, data with good quality has been taken in 2022 and the beginning of 2023, and the performance of the various subdetectors has been widely characterized. The hardware was further adapted to study previously unexplored physics processes which have obtained more attention in recent years. Besides the many hardware upgrades, improvements on the software side, mainly coming from the rapid development in machine learning and parallel processing, also have their contribution. From these improvements, and the expected increase in total luminosity, new physics results will enhance our understanding of fundamental science.

Many updates are only an intermediate step in the grand challenge for the high luminosity LHC, which is scheduled for 2029 and where up to 200 simultaneous proton-proton collisions are targeted, allowing to access an unprecedented amount of data. The CMS Collaboration is also well prepared for this and many successful years of data taking can be expected. Results from this data will push the boundaries of our knowledge in particle physics further ahead for many years to come.

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