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Performance and upgrade plans for the CMS detector

Marco Meschini for the CMS Collaboration

Abstract

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The CMS experiment at the CERN Large Hadron Collider has collected data during 2011 for an integrated luminosity exceeding $5\,\mathrm{fb}^{-1}$ at $7\,\mathrm{TeV}$ centre of mass energy. The detector has performed excellently, with very good data taking efficiency since the very beginning. The operational experience will be described, including the first part of 2012, focusing on some relevant technical aspects. New challenges dictated by the planned luminosity increase are ahead for CMS. A general overview of the upgrade plans to cope with increased luminosity scenarios will be given, including both medium and long term range.

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Performance and Upgrade Plans for the CMS Detector

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Abstract

The CMS experiment at the CERN Large Hadron Collider has collected data during 2011 for an integrated luminosity exceeding $5\,\mathrm{fb}^{-1}$ at 7 TeV centre of mass energy. The detector has performed excellently, with very good data taking efficiency since the very beginning. The operational experience will be described, including the first part of 2012, focusing on some relevant technical aspects. New challenges dictated by the planned luminosity increase are ahead for CMS. A general overview of the upgrade plans to cope with increased luminosity scenarios will be given, including both medium and long term range.

Key words: LHC, Tracking detectors, Silicon Detectors, Gas Detectors, Calorimetry, LHC Upgrades
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1. Introduction

The Compact Muon Solenoid (CMS) is one of two general purpose particle physics detectors in operation at the LHC (Geneva, Switzerland) since 2008. It has been collecting data from proton-proton colliding beams at centre of mass energies of 7 TeV in years 2010-2011 and 8 TeV in 2012. The detector has shown excellent performance, and the data taking efficiency has been above 90% on average. With increasing LHC luminosity, CMS has proved to be capable to trigger efficiently on physics events and to reconstruct them even in presence of many superimposed interactions in the same bunch crossing, the so-called high pileup conditions. In order to maintain optimal efficiency and to cope with the planned increases in luminosity, a detailed detector upgrade program has already started; first improvements will be put in place during the LHC machine shutdown in 2013, the rest following in steps until 2020 and beyond.

2. CMS Detector

CMS is a multipurpose detector designed to investigate a whole range of high energy physics phenomena. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead-tungstate scintillating-crystals electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. Three different type of detectors are used: Drift Tubes (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC). Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A more detailed description can be found in Ref. [1].

3. LHC Luminosity and CMS Data Collection Efficiency

The centre of mass energy of colliding beams in the LHC machine was 7 TeV in 2011 and was raised to 8 TeV for 2012, while the time between consecutive proton bunches remained unchanged at 50 ns. The machine parameter β^* was lowered from $\beta^* = 1$ m in 2011 to $\beta^* = 0.6$ m in 2012. This is the beta function at the collision point and is inversely proportional to the instantaneous luminosity, thus, its reduction resulted in a gain in luminosity. A set of comparisons testify to the huge progress achieved by the LHC in the last year. In 2011, the number of bunches injected in the machine was progressively increased until August when they finally reached 1380, the maximum allowed for present LHC configuration. By contrast, in 2012 the same number of bunches was achieved already by mid April, after less than two weeks of operation. The maximum peak instantaneous luminosity in 2011 was $4.0 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ while in May 2012 it has already exceeded $6.6 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In 2010, LHC delivered an integrated luminosity of $47\,\mathrm{pb}^{-1}$. In April to October 2011, $6.1\,\mathrm{fb}^{-1}$, and on 15 June 2012, after only two months of operation, the integrated luminosity in 2012 was already at $6.0\,\mathrm{fb}^{-1}$, the same amount as accumulated in the entire 2011 data collection period. LHC delivered and CMS integrated luminosities as a function of time are reported in Figures 1 and 2. The 9% inefficiency in data taking can be divided in a 3% deadtime and a 6% downtime. The largest downtime single source was a general cooling failure in Aug. 2012; other downtimes were more or less evenly shared among all subdetectors. The average fraction of operational channels has been greater than 98% in year 2011, and it was 98.6% at the beginning of 2012 data taking.

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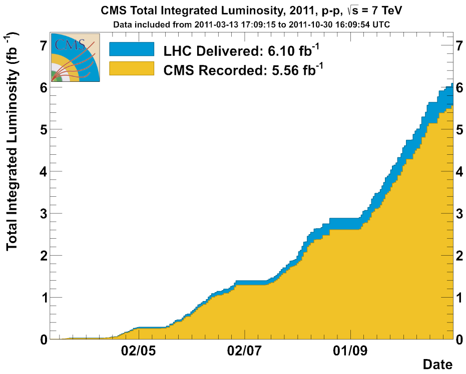

Figure 1: CMS delivered and recorded luminosities: Mar-Oct 2011.

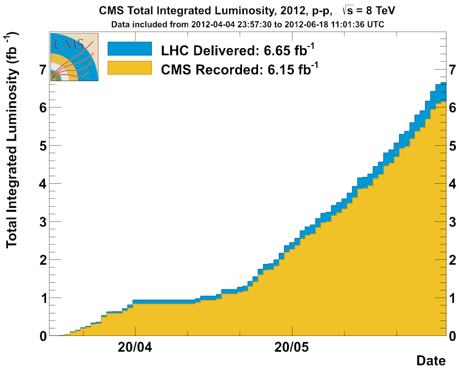

Figure 2: CMS delivered and recorded luminosities: Apr-Jun 2012.

4. CMS Performance

A lot of progress has been made to understand the CMS detector, with the aim of continuously improving the overall performance. We give here just a few representative cases. The luminosity increase together with the 50 ns bunch spacing has brought the pileup to a considerable level already in 2011, earlier than expected, due to the outstanding LHC performance. In these conditions, the Level-1 Trigger (L1) ran at about 80 kHz (Fig. 3); this rate was then reduced by the High Level Trigger (HLT) to a few hundred Hz of events written on disk. The typical pileup is of the order of 30 interactions per bunch crossing at the beginning of a standard LHC fill; an example of the pileup versus time taken from the CMS online monitor is shown in Fig. 3. One of the challenges CMS has to face is to keep

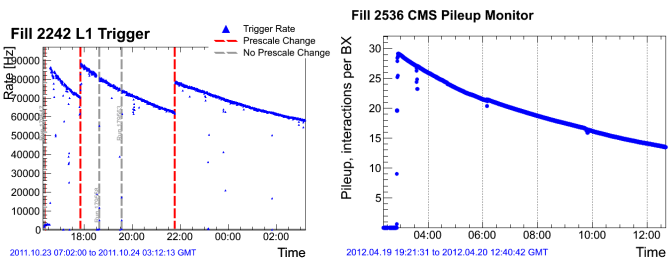

Figure 3: L1 trigger rate (left) and interactions per bunch crossing (right) vs. time.

the trigger thresholds low as pileup increases. This has been achieved by integrating the progress made in the offline software into the HLT, and exploiting all the features of CMS, like the high magnetic field and the resolution of the Tracker. Indeed, tracking particles in presence of pileup is a difficult task, but it has been overcome reconstructing events even with 40 interaction vertices. The excellent spatial resolution of the

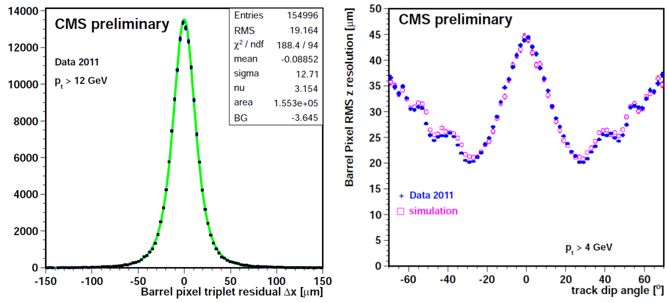

Figure 4: Pixel barrel hit resolution in rϕ (left) and z projections (right).

pixel and the microstrip silicon tracker, seen in Fig. 4 and 5, has been the key to this achievement. Pixel data are used by

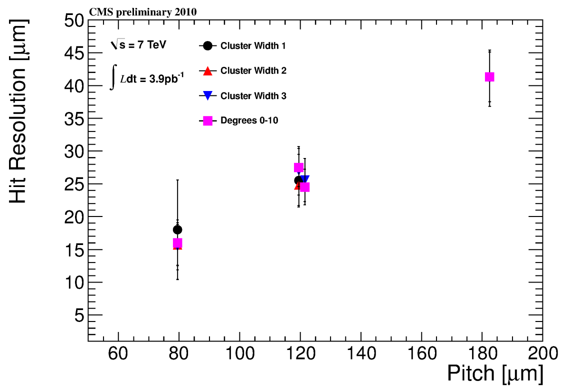

Figure 5: Silicon microstrip hit resolution as a function of strip pitch for different cluster widths and tracking angle.

the HLT for fast seeding, vertex reconstruction along the beam axis and pileup combinatorial reduction. The pileup impacts heavily on the CPU time and RAM needed to fully reconstruct collision events. In 2011, CMS setup a dedicated group to work on both technical software aspects and tracking algorithms, and has managed to reduce the memory footprint by 40% and the reconstruction time per event by 60%. These changes were incorporated into a new CMS SW release, version 5_2_0. At present the time needed to reconstruct 100 events is 50 minutes, and the required RAM is 1.1 GB. Concerning the muon detection system, a key component in the trigger, an automated system has been put in place to adjust the HV of the RPCs depending on temperature and atmospheric pressure. This has led to a more stable efficiency and cluster size in the RPC, as shown in Figures 6 and 7. The Electromagnetic Calorimeter is a crucial component in many physics analyses, particularly in the search for the Higgs boson. For optimal performance, it is extremely important to have a stable energy scale and very good resolution. The stability of the energy scale was achieved in 2011 by applying corrections from the Laser Monitoring (LM) system.

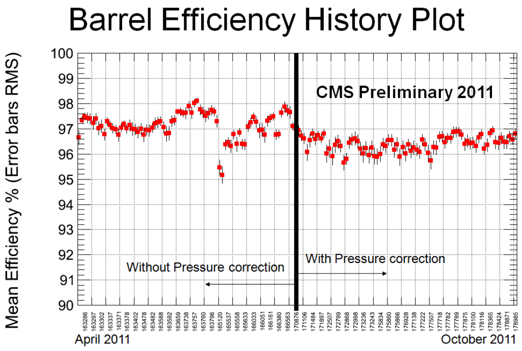

Figure 6: RPC Barrel efficiency in 2011 before and after T and P compensation

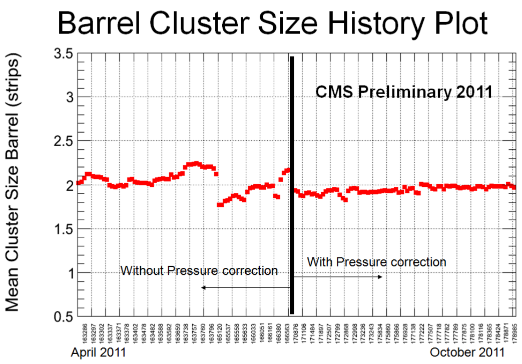

Figure 7: RPC cluster size in 2011 before and after T and P compensation

After these corrections, a comparison of electron energy measured in ECAL with the momentum measured in the tracker for a selected sample $W \rightarrow e\nu$ decays results in an RMS of 0.12% in the barrel and 0.45% in the endcap. The results for barrel can be seen in Fig. 8. The instrumental resolution, with preliminary

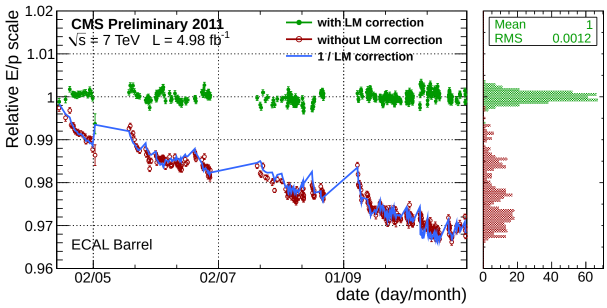

Figure 8: ECAL barrel energy scale stability in 2011

energy calibration for 2011, obtained from $Z \rightarrow e^+e^-$ invariant mass, is 1.0 GeV in ECAL barrel, as can be seen in Fig. 9. As an example of the precision results which can be obtained by CMS we mention here the discovery, in 2011 data, of an excited Ξ_b baryon, described in Ref. [2]. A typical expected signal from the baryon decay as recorded in CMS is shown in Fig. 10, where all the particles in the decay chain, described in the figure insert, have been identified. The mass of the new b baryon is measured to be 5945.0±2.8 MeV, and the signal significance was evaluated to be 6.9σ.

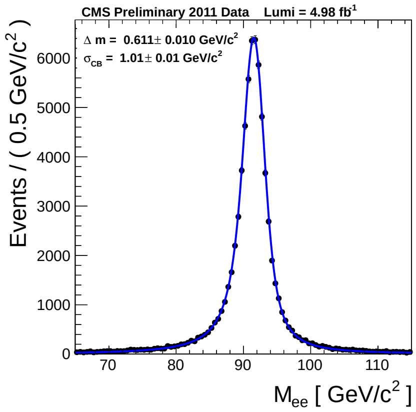

Figure 9: ECAL barrel energy scale resolution

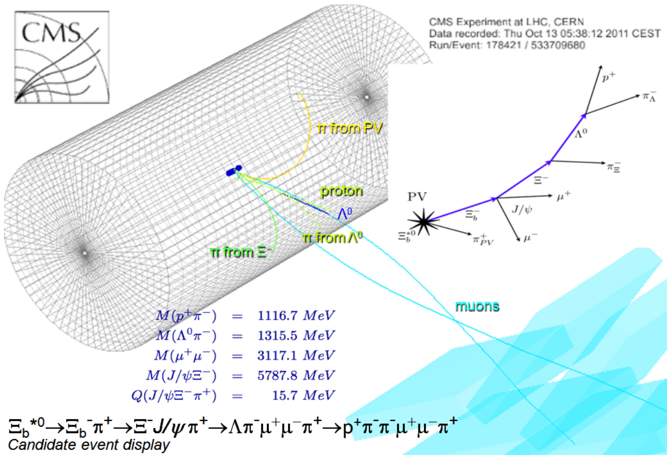

Figure 10: A reconstructed event from an expected Ξ_b^* baryon decay

5. CMS Upgrades

Over the next decade the peak luminosity in LHC is expected to increase. In one scenario, the luminosity could reach $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 25 ns bunch spacing, while in other scenarios, the luminosity could be $4 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 50 ns bunch spacing. In Fig. 11 a ten year scenario for the luminosity with two planned long shutdown periods (LS1 and LS2) is shown. In order to optimize the physics coming from an increase of luminosity, CMS has already started a long and detailed upgrade programme, whose first steps will be put in place during LS1. A general overview and timeline of the main upgrade items through 2022 is reported in Table 1. The first phase of the upgrades is described in detail in the CMS Upgrade Technical Proposal [3].

5.1. Phase-1 Upgrades

During LS1, in addition to the standard maintenance tasks, CMS has to fulfill several upgrade activities. The 4^{th} muon endcap stations will be completed with their full set of CSC and RPC. As well, the electronics of the Muon System will be consolidated to avoid obsolescence problems of trigger and digital cards designed more than ten years ago. These improvements will allow the trigger to maintain the same rate while lowering

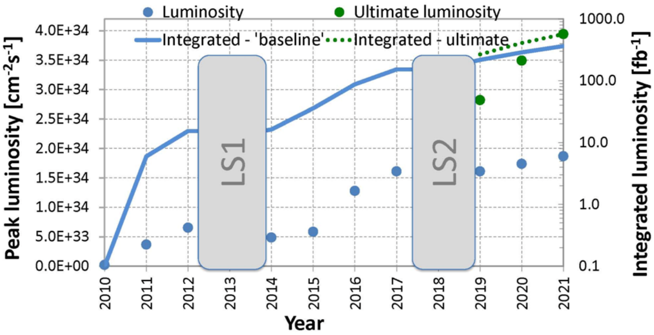

Figure 11: A 10-Year Luminosity Scenario for LHC. The two Long Shutdown periods are indicated (LS1, LS2)

Table 1: Summary of the CMS Upgrade Plan.

Year	System	Action
2013-14	Muon Stations	New RPC and CSC stations, new electronics
2013-14	Beam Pipe	New 45mm diameter pipe
2013-14	HCAL Outer	Replace HPDs with SiPM
2013-14	HCAL Forward	New PMT
2018	New Pixel Detector	4 Layers, 3 Disks, new readout chip
2018	HCAL Barrel-Endcap	Replace HPDs with SiPM
	μTCA	New electronics
2022 onward	Tracker Detector	Replace whole Tracker and Pixel
	Trigger	Replace Trigger
	Endcap Calo.	Upgrade Endcap calorimetry

the transverse momentum (p_T) threshold. The photodetectors in the hadron forward and outer calorimeters are planned to be replaced with multi-anode PMs (Photo Multiplier) and SiPM (Silicon Photo Multiplier); this replacement plan will be extended to the hadron barrel and endcaps in LS2, leading to higher gain and increased granularity in the calorimeters, with a beneficial effect on particle identification, calibration and background rejection. Another important achievement for LS1 is to be able to run the Tracker cooling at full power with coolant temperature at -20°C. The installation of the new 45 mm outer diameter beam pipe in LS1 will ease the replacement of the present pixel detector. This replacement is foreseen for LS2 at the latest, however, it could happen anytime after 2016 during a five months stop (such as an extended winter shutdown). The new pixel detector will have four barrel layers (with smaller inner radius) and three endcap disks, a new readout chip and a new CO_2 cooling system. In spite of the addition of new layers, which will yield a more robust track seeding and vertex finding capabilities in presence of multiple interaction vertices, a significant reduction of the material budget is foreseen in the pseudorapidity region $1 \lesssim \eta \lesssim 2$.

5.2. Phase-2 Upgrades

After 2021, the LHC will enter into the so-called High Luminosity (HL) stage, with peak luminosities expected beyond $\sim 10^{35}\,\mathrm{cm^{-2}s^{-1}}$ and integrated luminosities up to $3000\,\mathrm{fb^{-1}}$. The HL-LHC will require a totally new Tracker, and a substantial redesign and upgrade of both the trigger system and the forward calorimetry. The technical proposal for the Phase-2 upgrades should be ready by end of 2014, when the most important physics results from 2012 are well established, thus driving the technological choices for new detectors. Studies are ongoing on all aspects of a new Tracker that must satisfy stringent requirements in term of mass, power consumption, tracking capabilities in dense particle environment, and also produce tracking primitives for the CMS Level-1 trigger. To this extent, the idea of special trigger-capable modules, the so called p_T-modules, has emerged: p_T-modules will be made out of two superimposed finely segmented silicon sensors, the distance between them being of the order of one mm. The two sensors will be coupled to the same readout chip, in order to exploit the stiffness in the 3.8 T field of high p_T particle tracks to reject low momentum particles [4].

Concerning calorimetry, simulation programs and beam tests have shown that the ECAL barrel is not expected to degrade significantly. The endcaps, however, will be more affected by the High Luminosity, hence efforts are directed towards radiation resistant photodetectors and new scintillating materials suitable to the high radiation environment.

To be prepared for HL-LHC a big effort on R&D and simulation has started and must be maintained, gaining thrust, to build a detector capable of obtaining the best possible physics results over the next twenty years.

6. Conclusions

The CMS experiment has collected $5.6\,\mathrm{fb^{-1}}$ in 2011 and $6.1\,\mathrm{fb^{-1}}$ through June 2012, with 91% collection efficiency and more than 98% of the detector operational. The continuous work done to maintain the detector in optimal conditions, the efforts spent to develop software tools, and the growing understanding of the detector behaviour have all together led to extremely good physics results. CMS has shown the ability to robustly reconstruct physics events in high pileup and luminosity conditions, with energy and tracking resolution which go beyond the expectations of the design. In short, an impressive outcome of a collaborative effort of about 3500 scientists and engineers from 40 countries worldwide, an experiment of unprecedented size.

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