PROCEEDINGS OF SCIENCE

CMS upgrade plans & potential

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The CMS detector is undergoing a program of upgrades that will allow it to maintain or improve its current performance until the end of the HL-LHC program, in 2035. The status of the upgrade activities and the potential for physics measurements and discoveries are presented.

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1. Introduction

The spectacular performance of the LHC requires the LHC detectors to be continually tuned to maintain their performance at the highest possible level, compatibly with the running conditions and their natural aging in an environment permeated by radiation. The upgrades must also fit the schedule for LHC interventions.

The CMS detector, described in detail in [1], is currently undergoing two major upgrade efforts. The Phase-I upgrade program is on-going and is now reaching its completion, scheduled for the end of 2020. The Phase-II upgrade program is in its early stage of design and R&D. It is scheduled to take place in the 2024-2026 time frame, and prepare the CMS detector to take data in the HL-LHC period, 2025-2035, during which the total integrated luminosity will reach up to 3 ab^{-1}. The current time line of the LHC upgrades, in preparation for the HL-LHC runs, is presented in Fig. 1.

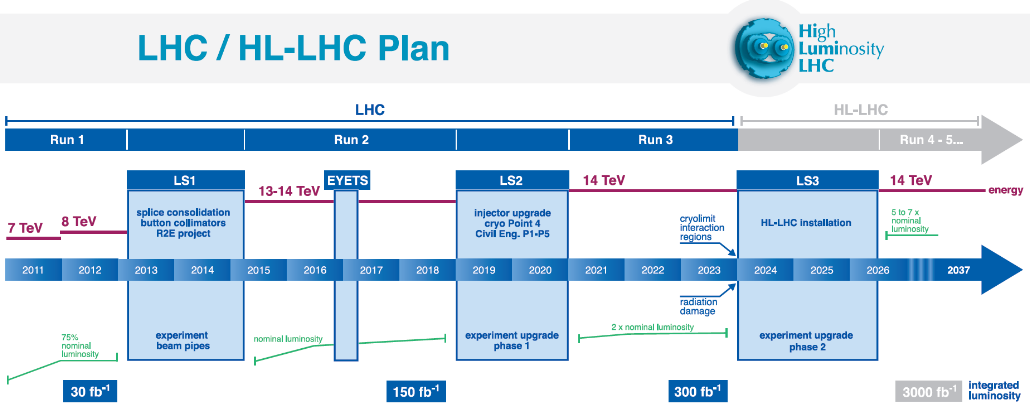

Figure 1: LHC schedule for long shutdowns and luminosity projections through HL-LHC. [2]

2. Phase-I Upgrades

The CMS Phase-I program consists of interventions in three areas of the CMS detector: the pixel tracker, the hadronic calorimeter, and the L1 trigger system. A detailed description of the upgrades in each area is presented in the respective technical design reports.[3, 4, 5]

2.1 Pixel Tracker

The pixel tracker is located in the innermost section of the CMS detector, in a hostile region with high levels of radioactivity. It is composed of silicon detectors that require a replacement. In order to cope with the higher track multiplicity expected in the LHC Run-3, the geometry of the pixel tracker is modified by adding a layer in the barrel region ($|\eta| < 2.16$) and a disk in the endcap region ($|\eta| < 2.5$). These will allow to decrease the fake rate and improve the tracking efficiency and resolution. The new layers will also allow to extend the possibility of associating four pixel hits to a track to the $|\eta| < 2.5$ range.

Two pairs of pilot modules, which will ultimately compose a pixel disk, have already been installed in the CMS pixel detector. Figure 2 shows, in a CMS simulated data sample, the location of the pilot modules. Figure 3 shows a picture of a fully-assembled endcap half-disk. The assembly is on-going, and the full pixel detector is expected to be ready for installation by the end of 2017.

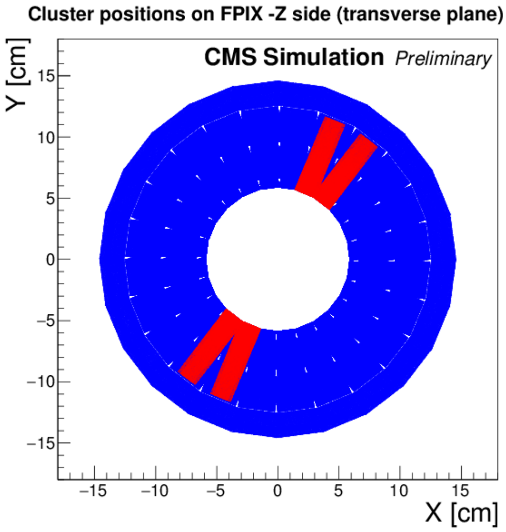

Figure 2: Global positions of clusters on the $-Z$ side of the Forward Pixel and the Pilot Blade detectors in the transverse plane. Disk 1 and Disk 2 are shown in blue and the Pilot Blades in red. The Pilot Blades are behind the disks in this view.

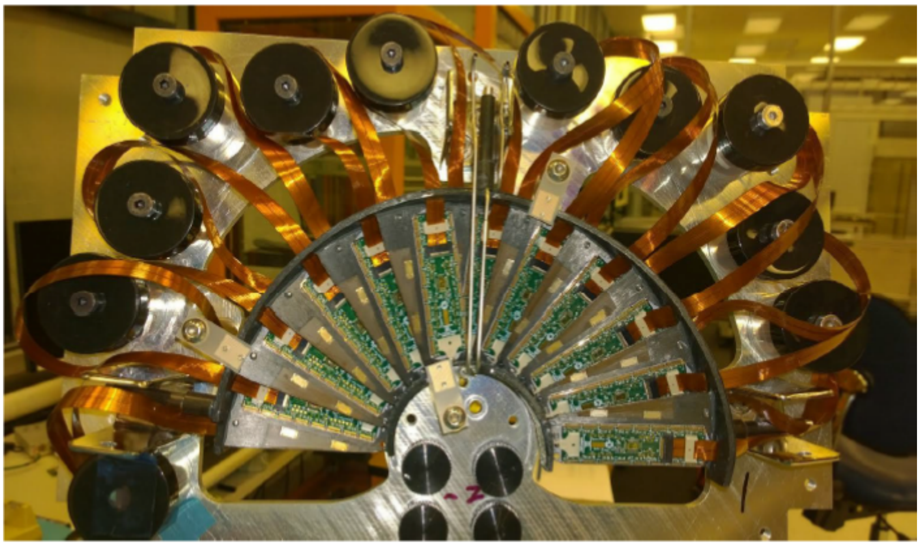

Figure 3: Complete assembly of a pixel half-disk detector.

The second direction of the pixel upgrade is the replacement of the front-end electronics. The bandwidth of the current readout chip introduces an inefficiency as the hit rate increases. This dynamic inefficiency would hamper operations at the rack multiplicity expected during Run-3. A new readout chip has been designed to offer higher bandwidth and operates efficiently at higher rates. This is achieved by multi-plexing the data stream.

2.2 Hadronic Calorimeter

The Phase-I upgrade of the hadronic calorimeter involves all the aspects of the signal measurement and acquisition. The CMS hadronic calorimeter is a brass/plastic-scintillator sampling calorimeter in the barrel (HB) and endcap (HE) region ($|\eta| < 3$) and a steel/quartz-fiber calorimeter in the forward (HF) region ($3 < |\eta| < 5$).

The photodetectors in the barrel and endcap regions are hybrid photodiodes (HPD). They will be replaced by silicon photomultipliers (SiPM), which offer a vastly improved signal-over-noise ratio, and operate reliably in the presence of magnetic fields of any magnitude. These features have already been tested with collision data during 2015. A set of SiPM had been installed in the CMS cavern in 2013, in place of the HPDs that equip the hadronic outer (HO) calorimeter, a tail-catcher detector composed of a ring of scintillator covering the $|\eta| < 1.3$ range. The intermediate value of the magnetic field in the HO region caused the HPDs to malfunction, while SiPM proved to work flawlessly.

A similar upgrade is foreseen for the HF detector. Its single-readout PMTs will be replaced by multi-anode PMTs, with a thinner glass window. The higher granularity offered by multi-anode readout allows for a better discrimination against anomalous signals due to charged particles hitting the PMT windows directly, and generating a signal spike earlier than the expected arrival of scintillation light.

The front-end electronics (charge-integration board, calibration module, clock-and-control module) will be replaced to match the new type of photodetectors, and to implement improvements and additional features. The charge-integration board will be able to measure signal timing, with a resolution of 0.5 ns. The resolution has been measured at the CERN H2 test-beam facility. The clock-and-control module will feature a redundant interconnection among modules. If a module suffers a hardware failure, a close-by module can replace it and allow for seamlessly maintaining the full detector under control.

Finally, the back-end electronics is scheduled for a replacement. The new system is based on the μTCA architecture. With respect to the current system, based on the traditional VME architecture, the new system offers a higher backplane bandwidth and hot-swapping features. In addition, the new system will also satisfy the bandwidth and latency requirements of operations in the HL-LHC runs. During the course of 2015 a μTCA-based crate has been thoroughly tested in the CMS data acquisition chain. The optical signal originating from the front-end electronics was split and fed to the default VME-based system, and the new μTCA-based system, and their output compared to guarantee they matched.

A section of the HF is already equipped with upgraded front-end and back-end electronics. The plot in Fig. 4 shows that the new system allows for the separation of early hits, coming from particles hitting directly the photodetector, from signal hits, delayed by the scintillation time.

2.3 L1 Trigger System

The upgrade of the L1 trigger system has been completed. The new system has been deployed in stages, in order to guarantee that CMS operations after the long shutdown in 2013-2014 would not be affected. The L1 trigger upgrade is motivated by the need to maintain the Run-1 performance during Run-2 (the current period of data-taking) and Run-3. This is achieved by

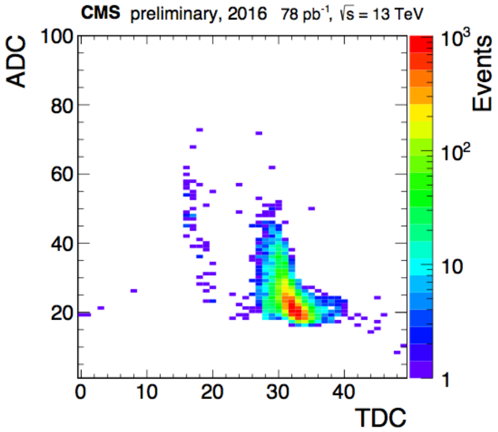

Figure 4: Distribution of leading edge TDC versus ADC, shown for a single QIE10 channel. Earlier events are consistent with noise from particles incident on quartz PMT windows and quartz fibers; later events are consistent with signals from particle showers QIE10 has a non-linear response and no transformation has been applied to linearize the integrated charge measurements. [6]

moving to an FPGA-based trigger architecture, and a μTCA-based back-end electronics. The new system also includes the replacement of copper connections with faster optical connections, and additional connections between the muon and calorimetry trigger. The increased amount of information available, and the flexibility offered by an FPGA, allows for the definition of more complex trigger algorithms.

The upgraded trigger system is currently in a commissioning stage with 2016 collision data. Figure 5 contains the turn-on curves of an electron and a muon triggers. The performance of these triggers is already at the same level as the previous system.

3. Phase-II Upgrades

The CMS Phase-II program consists of interventions in the following areas of the CMS detector: pixel and strip trackers; barrel and endcap calorimeters; muon system; trigger and data-acquisition system. The details of the Phase-II upgrades are presented in the Phase-II technical proposal [9] and scope document.[2] The upgrade schedule foresees the publication of technical design reports for each upgrade area in the course of 2017.

The Phase-II upgrades respond to the requirement of maintaining the CMS performance during the HL-LHC at the current level, thus allowing for the full exploitment of the physics potential of the HL-LHC data samples. The tracker and part of the calorimeters will be replaced to counter radiation-induced aging effects; the front-end and back-end electronics, and the trigger and DAQ systems will be upgraded to cope with the high–pile-up running conditions foreseen for Run-4 and Run-5.

Benchmark physics analyses that demonstrate the impact of the upgrades are presented in detail in [2].

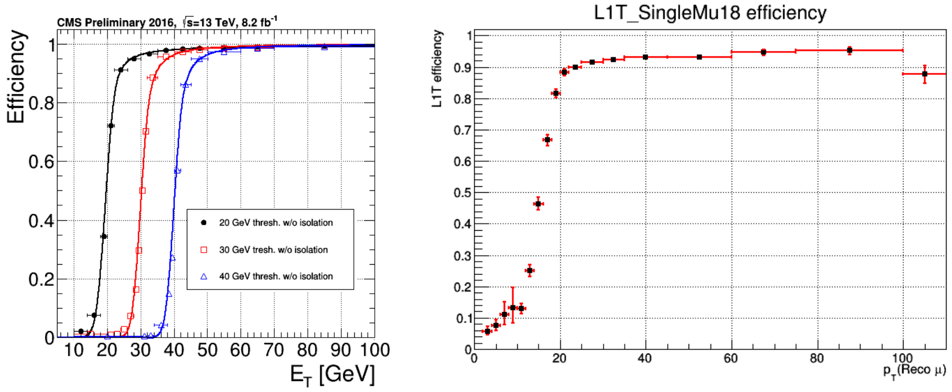

Figure 5: (Left) L1 trigger efficiency for an e/γ object as a function of the offline reconstructed supercluster transverse energy (E_T), inclusively in barrel and endcaps, for L1 thresholds of 20 (black), 30 (red) and 40 GeV (blue) without isolation requirement. Events used are those passing the $Z \rightarrow ee$ tag-and-probe selection. A geometrical matching between the electron supercluster and the L1 candidate is applied. The lines correspond to the result of an unbinned maximum likelihood with a Crystal-Ball integral function. [7] (Right) L1 trigger efficiency for a μ object as a function of the offline reconstructed transverse momentum (p_T), inclusively in barrel and endcaps, for the L1 threshold of 18 GeV. Reconstructed muons have $p_T >$ 22 GeV; the last bin contains all muons with reconstructed p_T above 100 GeV. Events used are those passing the $Z \rightarrow \mu\mu$ tag-and-probe selection.[8]

3.1 Tracker

Both the pixel and the outer trackers will be replaced. The pixel detector will have 10 disks that will increase the tracking coverage to $|\eta| \simeq 3.8$; the inner layer will be at a distance of less than 3 cm from the beam line. The outer tracker will be composed of six barrel double-layers and five forward double-disks. A drawing of the tracker layout is presented in Fig. 6. The granularity of the detector will be incremented by a factor of four. The double-layer structure, exploiting the very high magnetic field provided by the CMS solenoid, will allow for an over-threshold measurement of the transverse-momentum of charged tracks usable by the L1 trigger. The new tracker will also use lighter support structures, thus increasing the track resolution, and decreasing the rate of photon conversions. The detector is designed to operate at the temperature of -30°C.

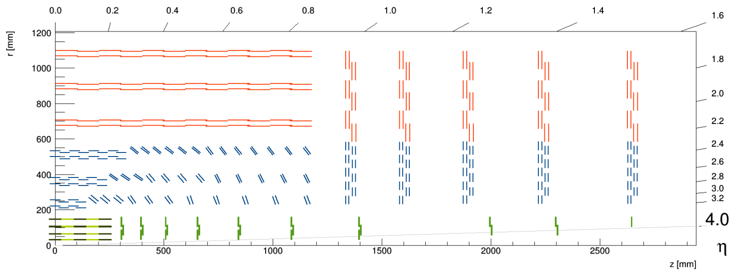

Figure 6: Layout of the Phase-II tracker: outer tracker (red), pixel detector (blue).

3.2 Barrel Calorimeter

The barrel calorimeter is composed of two sections: an homogeneous lead-tungstate electromagnetic calorimeter, followed by a brass/plastic-scintillator hadronic section. In order to satisfy the trigger requirements of HL-LHC operations, the electronics of both the electromagnetic and hadronic calorimeters will be replaced. The front-end of the electromagnetic calorimeter will also need to be replaced. A new very-front-end board, and the cooling of the detector to 8°C will contribute to reducing the noise.

The measurement of radiation-induced aging on the plastic scintillator of the CMS barrel and endcap hadronic calorimeters performed with 2012 data indicates that the inner layers of the hadronic barrel calorimeter will suffer for a large reduction in light yield before the end of Run-4 and Run-5. The Phase-II upgrade of this detector thus include the replacement of the inner layers with a more radiation-tolerant scintillator.

3.3 Endcap Calorimeter

The endcap calorimeter is composed similarly to the barrel calorimeter: a lead-tungstate homogeneous electromagnetic section, followed by a brass/scintillator hadronic section. The requirement that the detector withstands radiation aging is more stringent, due to the higher level of radiation. The integrated dose by the electromagnetic calorimeter near shower max in the $\eta \simeq 3$ region, for an integrated luminosity of 3000 fb^{-1}, is estimated to be 150 Mrad, with a neutron fluence of 10^{16} n/cm^2.

A completely new type of detector is being proposed for the Phase-II upgrade of the CMS endcap calorimeters. Inspired by the ILC/CALICE detector, it is foreseen to build a silicon-based high-granularity calorimeter, composed as follows: a tungsten/silicon electromagnetic section; a brass/silicon hadronic section; a brass/plastic-scintillator hadronic backing section.

The silicon sensors cover an area of about 600 m^2, the total number of readout channel is 6.1 million. The electromagnetic section has a thickness of about 26 X_0 and 1.5 λ, and a total of 4.3 million readout channels. The forward hadronic section has a thickness of 4.5 λ, and a total of 1.8 million readout channels. The 5 λ-deep backing section, composed of plastic scintillator and brass, brings the total depth of the calorimeter close to 10 λ.

A complete prototype of a silicon sensor with readout electronic has been produced (Fig. 7), and is being prepared for commissioning in a test beam.

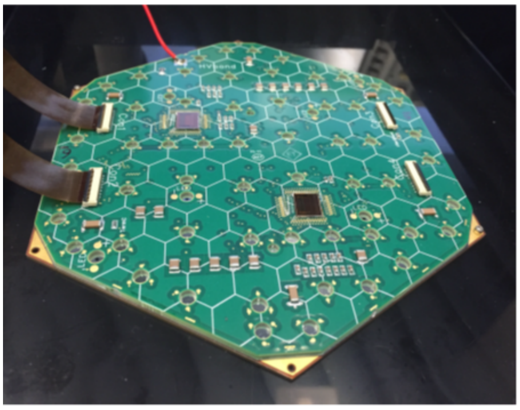

Figure 7: An hexagonal silicon sensor, with included readout electronics.

3.4 Muon System

The muon chambers are predicted to maintain their performance throughout the full HL-LHC period. The Phase-II upgrade consists in the extension of the coverage of the current system. Fine-pitch resistive-plate chambers (RPC) will complete the coverage of the muon trigger up to $|\eta| \simeq 2.4$. New gas-electron multiplier (GEM) chambers will be installed in the $1.6 < |\eta| < 2.4$ region to improve the trigger efficiency and muon reconstruction. Figure 8 shows the reduction in fake-muon triggers obtainable by adding GEM information to the L1 trigger. A GEM chamber right behind the hadronic calorimeter will allow to extend muon tagging up to $|\eta| \simeq 3.0$.

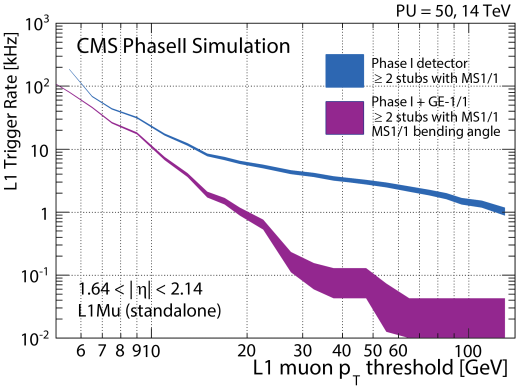

Figure 8: L1 muon trigger rate at a luminosity of $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ as a function of p_T threshold. For the Phase-I system, 2 or more stubs, one of which is in the ME1/1 station are required. With the addition of GE1/1, the bending angle between the two stations can be used and the trigger rate is greatly reduced. [2]

The readout electronics of the muon tracking chambers, drift tubes (DT) in the central region and cathode-strip chambers (CSC) in the endcap region, will be replaced, to satisfy the bandwidth and latency requirements of the HL-LHC trigger and data-acquisition system. An insight into the HL-LHC running conditions is provided by a test performed at the CERN GIF++ facility. CSC chambers are installed along a muon beam, and a ^{137}Cs source is used to mimic the high-luminosity HL-LHC running conditions. Figure 9 shows a comparison between the average number of reconstructed CSC segments in Run-2 collision data, and at the GIF++ in Run-2 conditions, and HL-LHC conditions. The good agreement between the collision data and GIF++ data obtained when the GIF++ is mimicking the same conditions make us confident in the extrapolation to HL-LHC conditions.

The upgrade of the muon system will happen in two stages. First GEM detector is scheduled for installation during the LS-2 shutdown (2019-2020), while the fine-pitch RPC, the muon tagger and the second GEM station will be installed during LS-3 (2024-2026).

3.5 Trigger and DAQ

In order to fully exploit the high-luminosity HL-LHC runs, the trigger and data-acquisition systems need to be upgraded to increase the available time for taking a trigger decision and the output rate. The L1 trigger latency will increase from 3.4 μs to 12 μs. The output rate of the L1 trigger will increase from 100 kHz to 750 kHz, and the output rate of the high-level trigger (HLT),

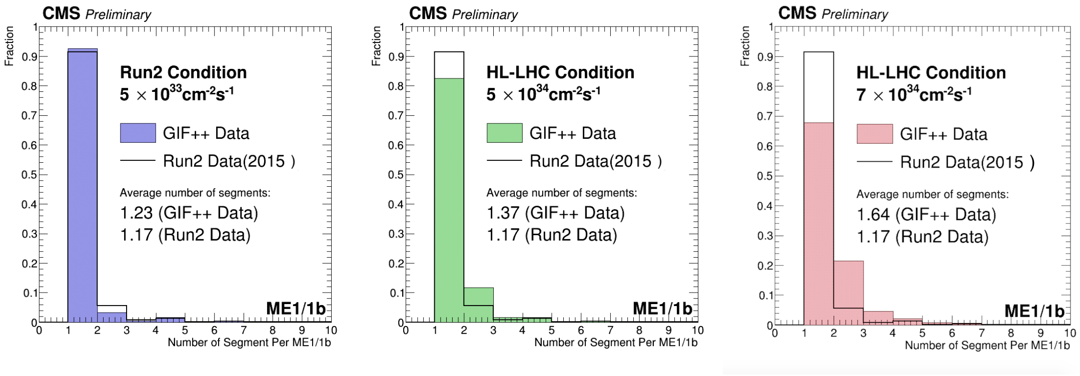

Figure 9: Number of reconstructed segments in ME1/1 when at least one segment is found in the chamber. The open histograms are CMS 2015 collisions data. The blue histogram is GIF++ muon beam data with gamma source emulating $5 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ instantaneous luminosity condition. GIF++ reproduces fairly well the present LHC luminosity condition in terms of average number of reconstructed segments. The green (pink) histogram is GIF++ muon beam data with gamma source emulating $5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) instantaneous luminosity conditions. It can be seen that on average more reconstructed segments are found at HL-LHC conditions.

corresponding to the rate at which events are saved to disk for analysis, will increase by about an order of magnitude to 7.5 kHz.

The increase in L1 trigger latency and rate will be supported by the new readout electronics that is part of the tracker, calorimeter, and muon system upgrades. The processing power of the HLT will be scaled up to cope with the increase in L1 rate and event size, due to pile-up. It is estimated that the HLT processing power needs to be incresaed by a factor of 50 with respect to Run-1 conditions. Similarly, the bandwidth of the data-acquisition system will be increased with the adoption of 100 Gbps links to reach a 30 Tbps throughput.

4. Conclusion

The CMS collaboration is actively pursuing a complete plan of upgrades that will allow for the full exploitation of the LHC data samples until 2035.

It shall not be neglected that upgrade projects are a continuous effort which overlaps with detector operations. It is crucial to establish a strong community to share the knowledge of key personnel, and to ensure the growth of the next generation of physicists, who will be operating the uppgraded detectors.

The Phase-I upgrade is very well underway. In each upgrade area (tracker, calorimeter, trigger) parts of the new systems have already been installed and are being commissioned with collision data. In particular, the L1 trigger system upgrade is fully completed, and it is entirely in its commissioning stage.

The Phase-II upgrade is in its early stages; its current main focus is R&D, and will culminate in the publication of technical design reports during 2017. The Phase-II upgrade is about an order of magnitude larger than the Phase-I; the experience gained during the Phase-I upgrade is already proving invaluable in driving the Phase-II upgrade project.

The HL-LHC will provide numerous opportunities for physics discoveries and precision measurement. A successful upgrade program is crucial to be able to fully exploit them.

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