Perspectives for the Phase II Upgrade of CMS

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The LHC Phase II upgrade (HL-LHC) will provide considerable increases in instantaneous and integrated luminosities, leading to a total of 3000 fb^{-1} by around 2035. This data will allow precision measurements of Higgs properties and vector boson scattering processes, and will provide substantially higher sensitivity to searches for new physics. Various subdetectors of CMS will need to be upgraded in order to operate efficiently in such a high rate and high radiation environment. CMS will receive new tracking detectors and new forward instrumentation for calorimetry and muon tagging along with an increase in the capability of the online trigger and data acquisition system. The CMS Phase II upgrade program and the expected performance of the replacement detectors will be reviewed.

1 Introduction

The CMS detector [1] has been designed to provide high performance in the harsh radiation environment of the LHC. During LHC Run I, the detector has recorded data with instantaneous luminosities close to the design goal of 1×10^{34} $\text{cm}^{-2}\text{s}^{-1}$, with an average number of simultaneous interactions per bunch crossing (pileup) of about 25. The excellent performance of the CMS detector and reconstruction algorithms in this environment has led to the discovery of a Higgs-like boson in 2012 [2].

The HL-LHC upgrade, planned for 2025, will significantly increase the instantaneous luminosity that can be provided to CMS, with a total integrated luminosity of 3000 fb^{-1} expected to be delivered by 2035. It has been shown [3] that the significantly larger dataset provided by HL-LHC can considerably expand the sensitivity and reach of CMS to various key physics signatures, including the precise measurement of Higgs boson couplings (including VBF processes), searches for supersymmetry and heavy vector gauge bosons, and precise measurements of electroweak processes.

The large instantaneous and integrated luminosities provided by the HL-LHC upgrade place stringent constraints on the performance, radiation tolerance and longevity of the CMS subdetectors and readout systems. Figure 1 shows the predicted fluence of neutrons in CMS after an accumulated dose of 3000 fb^{-1}. The fluence reaches 1×10^{16} n/cm^2 in the pixel detector and forward calorimeters. In addition, the level of pileup will increase significantly, with an average of about 140 interactions per bunch crossing expected at an instantaneous luminosity of 5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$. The modifications to CMS that will be required to maintain the current level of performance in this challenging enviromnent are summarised below.

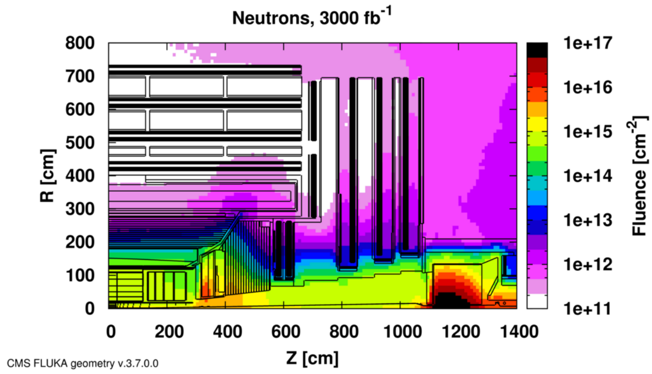

Figure 1: Neutron fluence in the CMS cavern after an integrated luminosity of 3000 fb^{-1}.

2 Upgrade Plans

2.1 Tracker and Pixel detectors

The CMS Tracker will suffer significant radiation aging and must be completely replaced for Phase II. The granularity of both the outer tracker and pixel detectors will be increased by about a factor of 4 in order to maintain adequate track reconstruction performance at the much higher pileup levels expected at HL-LHC luminosities. For the outer tracker, this will be achieved by shortening the lengths of silicon sensor strips relative to those in the current detector. The upgraded pixel detector will implement smaller pixels and thinner sensors to achieve improved impact parameter resolution and better two-track separation. The pixel coverage will also be extended close to $|\eta| = 4$ to provide increased tracking acceptance and improved suppression of pileup contributions in forward jets. Significant R&D activity is ongoing to identify suitable radiation tolerant silicon sensor technologies and to develop protoype readout modules and support structures.

The predicted performance of the Phase II detector at 140 PU is shown in Figure 2, and is compared to the performance of the Phase I tracker at 50 PU. A number of design improvements will lead to a much lighter outer Tracker providing significantly improved p_T resolution and a lower rate of photon conversions, compared to the present detector. In addition, the module design will be capable of providing fitted tracks with p_T >2 GeV to the Level-1 trigger at 40 MHz. This will ensure powerful background rejection at the earliest stage of the online event selection.

2.2 Calorimeters

The electromagnetic and hadronic endcap calorimeters will also suffer significant radiation damage, and must be replaced for Phase II. Two concepts are currently under consideration, with the potential for higher radiation tolerance and finer granularity to mitigate pileup effects. These include an Electromagnetic Endcap calorimeter, with a Shashlik design (LYSO or CeF_3 crystals interleaved with tungsten plates) followed by a Hadronic Endcap (HE) which would be a rebuild of the present brass/scintillator detector with more radiation tolerant components. The second concept is a High Granularity Calorimeter (HGC) with planes of silicon sensors and

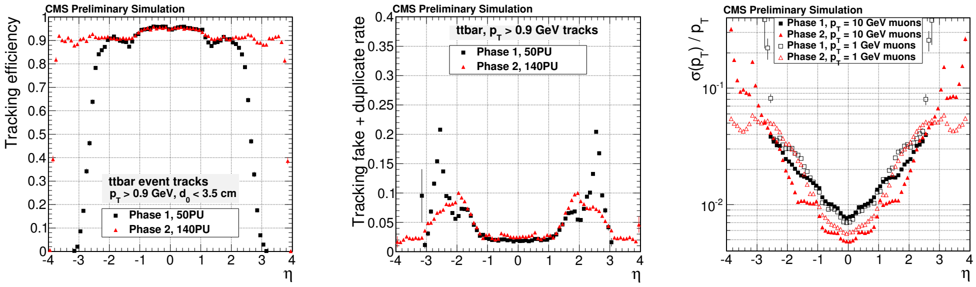

Figure 2: Projected performance of the Phase II tracker for events with an average pileup of 140. The performance of the Phase I tracker for 50 PU is shown for comparison. Left: tracking efficiency; Centre: rate of fake/duplicate tracks; Right: track momentum resolution. The plots assume no detector ageing.

tungsten or brass absorber, organised in electromagnetic and hadronic sections, followed by a rebuilt brass-scintillator HE to provide a total depth of $10\lambda_I$. A more detailed description of these designs can be found in [4].

The front-end electronics of the barrel electromagnetic calorimeter will also be replaced. The data will be transferred off-detector at 40 MHz, simultaneously overcoming present limitations in trigger latency (6.4 μs) and acceptance rate. A new front-end chip will be designed with a shorter shaping time to mitigate the anticipated aging-induced noise increase in the avalanche photodiodes (APD), and for better out-of-time pileup rejection.

2.3 Muon detectors

To maintain good Level-1 muon trigger acceptance in the endcap regions ($1.5 < |\eta| < 2.4$) it is proposed to enhance the existing muon stations with additional chambers that make use of new detector technologies with higher rate capability. The front two stations are in a region where the magnetic field is still reasonably high and will use Gas Electron Multiplier (GEM) chambers for good position resolution. The two rear stations will use low-resistivity Resistive Plate Chambers (RPC) with lower granularity but good timing resolution to mitigate backgrounds. In addition, the implementation of a GEM station behind the new endcap calorimeters is being proposed in order to increase the coverage for muon detection to $|\eta| \simeq 3$.

2.4 Trigger

The Level-1 (L1) trigger accept rate will be increased to provide maximum acceptance for interesting physics events during Phase II running. The trigger latency will also be increased to 12.5 μs to provide sufficient time for the hardware track reconstruction and the matching of tracks to muons and calorimeter energy deposits. This change will require upgrades of the readout electronics in several of the existing subdetectors that will be retained for Phase II. With these modifications, CMS is expected to be able to operate up to 200 PU without significant data loss.

Based on the expected performance of the trigger with track information, we propose to operate with a L1-trigger acceptance rate of 500 kHz for beam conditions corresponding to 140

PU. This will allow us to maintain similar thresholds to those anticipated for use in Phase I.

2.5 Online and offline computing

The Data Acquisition (DAQ) system will be upgraded to provide the increase of bandwidth and computing power needed to accommodate the larger event size and L1 trigger rate. The bandwidth and computing power requirements will increase relative to Phase I by factors of about 10 and 15 respectively for operation at 140 PU. This is within the projected network and computing technology capabilities that are expected to exist at the time of Phase II. The rate of recorded data will increase at 140 PU to about 5 kHz from the corresponding LHC Run 1 levels of between 0.5 and 1.0 kHz. To minimize the computing needs, both for online and offline reconstruction, a significant R&D effort has started to improve the algorithms used for data reconstruction and to adapt the CMS software and computing model to new technologies and resources.

2.6 Infrastructure

Planning for the installation of the new subdetectors for Phase II is still at an early stage, but an initial evaluation of the work sequence and time estimates indicates that the full scope of work can be accomplished in a shutdown of approximately 30 months duration. This is anticipated to take place during LHC Long Shutdown 3 (2023-2025).

3 Summary

The HL-LHC upgrade will provide a large additional dataset that will allow the full exploitation of the physics potential of the LHC. CMS has conducted a detailed study to determine the necessary requirements to operate efficiently in such a high rate and high radiation environment. New tracking devices and forward calorimeters with enhanced radiation tolerance and granularity will be required. Significant upgrades to the capability of the online trigger and data acquisition systems are also needed to maintain and enhance the acceptance to interesting physics signals. Dedicated R&D programmes and prototyping steps are ongoing to identify suitable technologies and to finalise detector designs. These will be documented in a Technical Proposal, to be released in 2015, and in Technical Design Reports, to be completed in 2016-17.

References

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