Precision Luminosity Measurement with the CMS detector at HL-LHC

Cristina Oropeza Barrera
On behalf of the CMS Collaboration

ABSTRACT

The high-luminosity upgrade of the LHC (HL-LHC) is foreseen to reach an instantaneous luminosity a factor of five to seven times the nominal LHC design value. The resulting, unprecedented requirements for background monitoring and luminosity measurement create the need for new high-precision instrumentation at CMS, using radiation-hard detector technologies. This contribution presents the strategy for bunch-by-bunch online luminosity measurement based on various detector technologies. A main component of the system is the Tracker Endcap Pixel Detector with dedicated triggers for online measurement of luminosity and beam-induced background using pixel cluster counting on an FPGA. The potential of the exploitation of the outer tracker, the hadron forward calorimeter and muon trigger objects is also discussed, as well as the concept of a standalone luminosity and beam-induced background monitor using silicon-pad sensors.

LUMINOSITY MEASUREMENT STRATEGY

For the HL-LHC period, scheduled to begin in 2027, a baseline instantaneous luminosity of $5 \times 10^{34}\ cm^{-2}s^{-1}$ with an average pileup of 140 is expected, with a maximum performance scenario of $7.5 \times 10^{34}\ cm^{-2}s^{-1}$ and an average of 200 interactions per bunch crossing [1]. These extreme conditions will require a major upgrade of the CMS detector, often referred to as Phase-2.

A precise measurement of the luminosity is key to the physics program of the HL-LHC, since it has become one of the dominant systematic uncertainties in some analyses. The goal is to achieve a 1% luminosity uncertainty.

Luminosity measurements rely on the precise determination of event rates observed within the acceptance of a given luminometer. Rates that scale linearly with luminosity can be converted to a luminosity measurement via the visible cross-section (obtained from VdM scans). For Phase-2, CMS will exploit several of it subsystems for luminosity measurements using dedicated readout streams, as well as a dedicated luminometer that can be operated independently from the rest of CMS in all LHC beam conditions. Phase-1 experience [2-4] has shown the importance of having multiple systems for luminosity measurements to provide redundancy and to minimize the bias originating from detector effects.

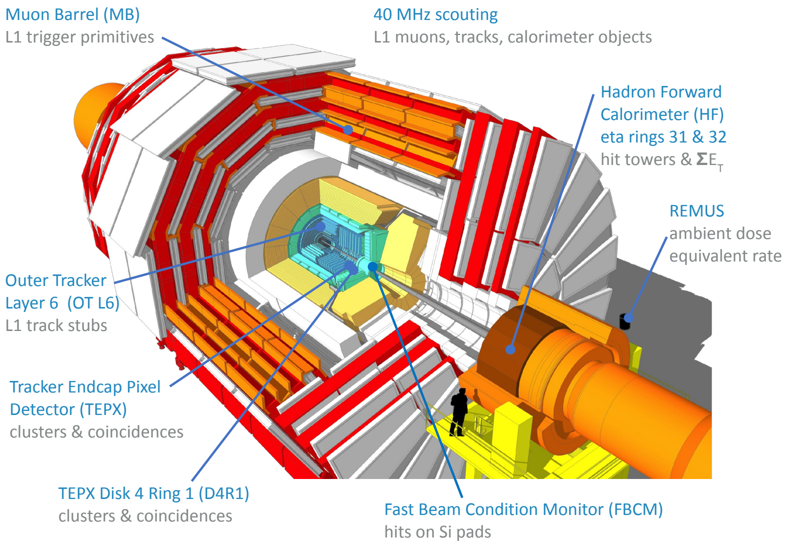


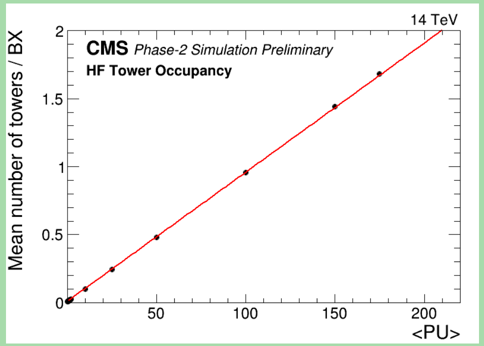
Figure 1. Subsystems for CMS Phase-2 luminosity measurement.

HADRON FORWARD CALORIMETER (HF)

Two algorithms, using a limited number of calorimeter towers corresponding to the pseudorapidity range $3.15 < |\eta| < 3.50$, are used to measure luminosity: HFOC & HFET. HFOC uses "zero-counting" to track the fraction of bunch crossings with no energy depositions above a threshold. HFET measures the transverse energy per bunch crossing.

Main features of HF as a luminometer:

- Full 40 MHz readout rate.
- Online & offline luminosity measurements.
- Available outside stable beams.
- Independent of central CMS DAQ.



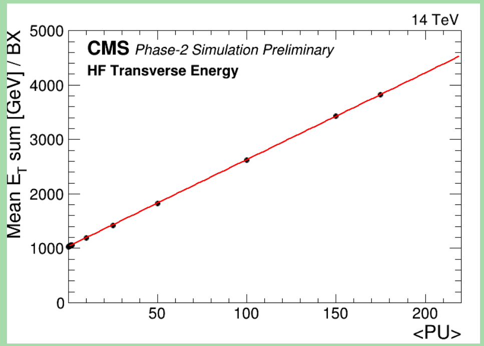


Figure 2. Left: Simulated HF occupancy versus average pileup. Right: Simulated HF transverse energy sum versus average pileup. Simulations were done using a neutrino gun event generator to obtain a sample of zero-bias triggers and include the effects of $1000\ fb^{-1}$ radiation damage. Points are fitted with a straight line.

INNER TRACKER: TEPX & D4R1

In Phase-2, the Inner Tracker Endcap Pixel Detector (TEPX) [5] will be installed, spanning a |z| range from 175 to 265 cm and a radius between 63 and 255 mm. It will comprise four large double disks per end of CMS, each made up of five individual rings with a varying number of pixel modules.

The relatively low occupancy allows for a precise luminosity measurement using the Pixel Cluster Counting (PCC) algorithm, developed in Run 2. Due to the geometry of detector, overlaps between modules enable the reconstruction of two and three-fold coincidences. These observables are of interest since they are less sensitive to contamination arising from noise, albedo, or even from previous bunch crossings.

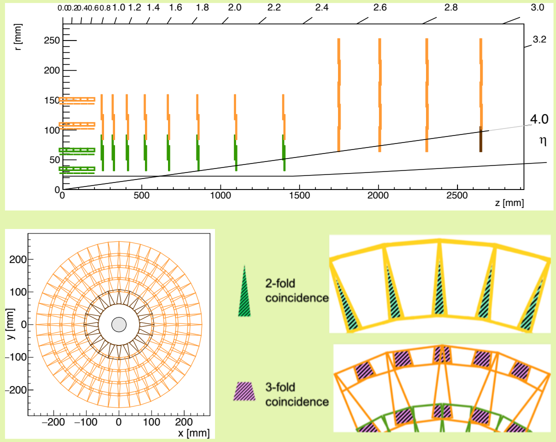


Figure 3. Schematic layout of TEPX.

Disk 4 Ring 1 will be dedicated exclusively to luminosity and beam-induced background (BIB) measurements using the full available trigger rate and readout bandwidth (825 kHz). The rest of TEPX will be read out at 75 kHz.

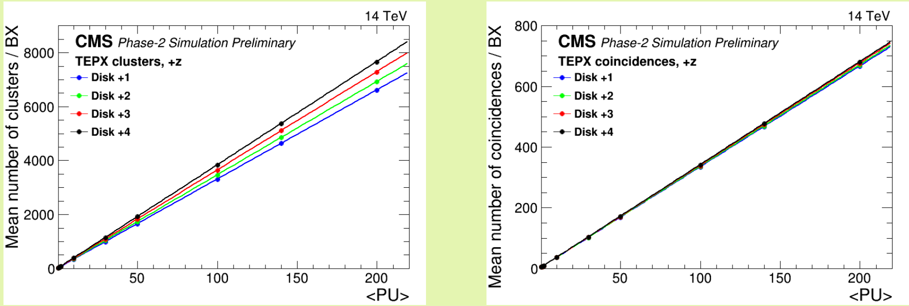


Figure 4. Mean number of clusters (left) and total 2-fold coincidences (right) for each disk as a function of pileup. A line is fitted between pileup values of 0 and 2 and then extrapolated up to a pileup of 200.

FAST BEAM CONDITION MONITOR (FBCM)

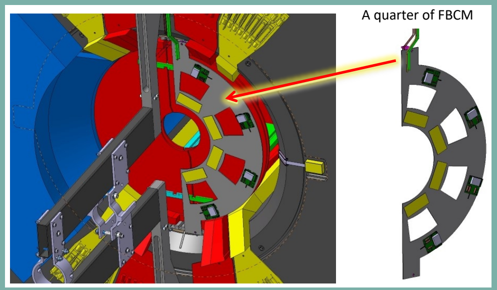


Figure 5. 3D model of a quarter of FBCM.

A standalone luminometer able to operate continuously and provide bunch-by-bunch luminosity measurements, independent from the central trigger and data acquisition services, is proposed. The Fast Beam Condition Monitor (FBCM) will be based on silicon-pad sensors with a fast front-end chip for Phase-2.

A possible position for the FBCM is behind Disk 4 of the TEPX system, with the silicon-pad sensors at a radius of 14.5 cm. The FBCM will be divided into four quarters, where one quarter covers one half at one end of the detector.

The FBCM will use the zero-counting algorithm an will also be able to transmit the time-of-arrival (ToA) and time-over-threshold (ToT) of hits with a sub-ns resolution at a rate of 40MHz, providing additional capability to measure BIB.

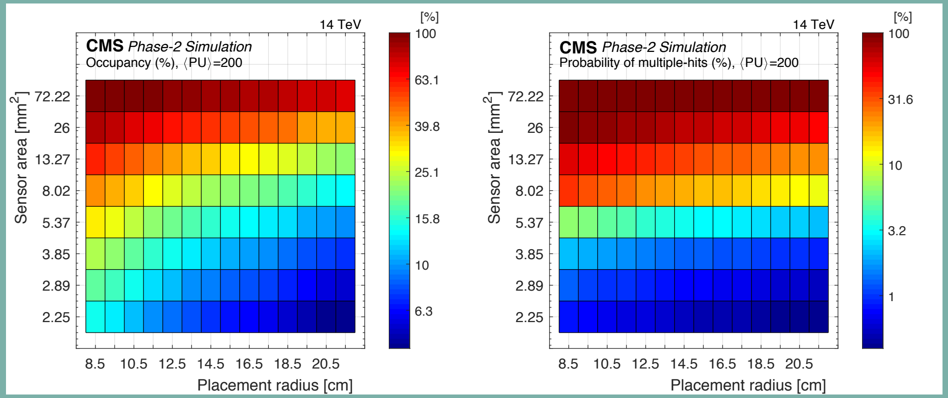


Figure 6. Occupancy (left) and the probability of multiple-hit occurrence (right) estimated at average pileup 200, for different sensor sizes and placement radii, assuming 336 sensors in FBCM located at z=±283.5 cm. The color bars are presented in logarithmic scale.

OUTER TRACKER

The Phase-2 Outer Tracker (OT) system [5] will provide a source of high-rate physics objects called stubs (two-hit coincidences on closely spaced silicon sensors). These objects are sent to the back end at the full bunch-crossing frequency of 40MHz.

The performance of the OT has been studied using detailed detector simulations. These studies show that the best precision can be obtained by counting stubs from barrel layer 6.

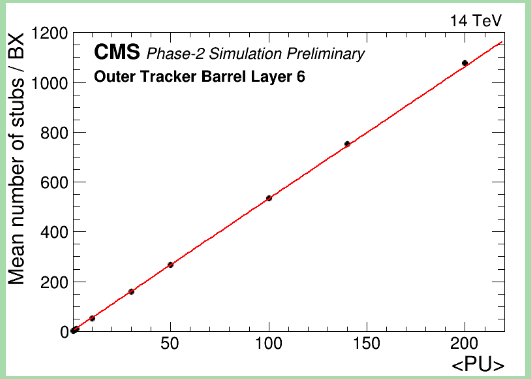


Figure 7. Simulated average number of stubs per event as a function of pileup for OT barrel layer 6. The points between 0 and 2 are fitted using a straight line, which is then extrapolated up to a pileup of 200.

MUON SYSTEM

Muon barrel track segments (trigger primitives) have shown excellent linearity and stability in Run 2 [2-4]. Despite the increased particle rates at HL-LHC conditions, the expected hit occupancy for the DT chambers will remain low. The readout rate for Phase-2 is expected to be of 40 MHz and it is foreseen to expand the functionality to provide bunch-by-bunch information.

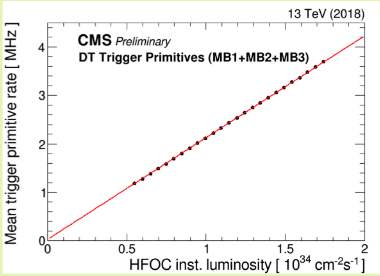


Figure 8. Total DT trigger primitive rate as a function of the instantaneous luminosity measured by HFOC in one LHC fill during 2018. The linear dependence is fit to a straight line.

REFERENCES

[1] I. Béjar Alonso et al., “High-Luminosity Large Hadron Collider (HL-LHC): Technical design report”, CERN (2020) doi:10.23731/CYRM-2020-0010.
[2] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at √s = 13 TeV in 2015 and 2016 at CMS”, 2021. arXiv:2104.01927.
[3] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at √s = 13 TeV”, CMS-PAS-LUM-17-004, 2018.
[4] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at √s = 13 TeV”, CMS-PAS-LUM-18-002, 2019.
[5] CMS Collaboration, “The Phase-2 upgrade of the CMS tracker”, Technical Design Report CERN-LHCC-2017-009, CMS-TDR-014, 2017.

SUMMARY

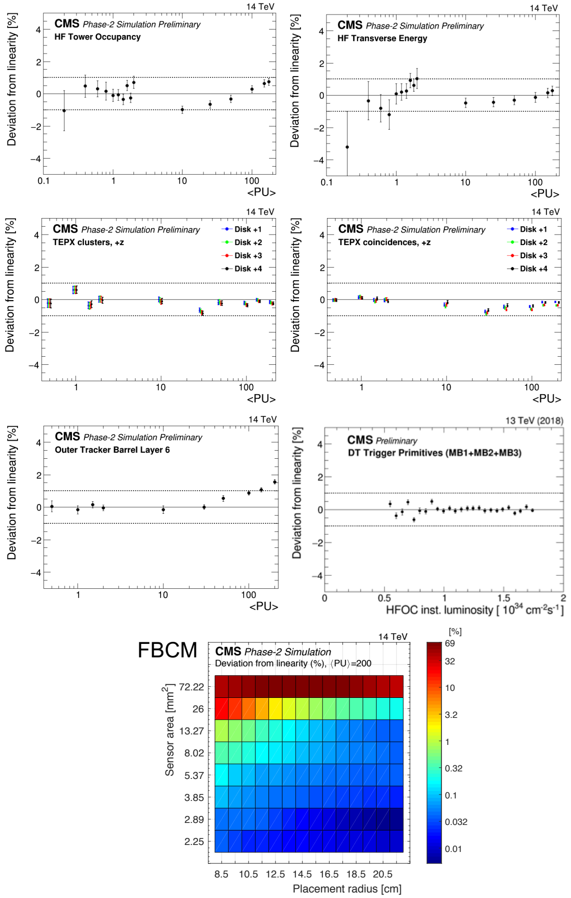


Figure 9. Deviation from linearity for the observables in the different luminometers. The nonlinearity is calculated as the relative difference between the points and the values of the fit function at the respective pileup value. For FBCM, the performance is evaluated for various sensor sizes and positions, as shown in the bottom panel.

For luminosity measurements under the extreme conditions of the HL-LHC, the CMS experiment has designed a strategy that uses upgraded existing CMS subsystems as well as a dedicated standalone luminometer.

The linearity of the different observables reconstructed in each of these luminometers has been studied using detailed detector simulations or, in the case of the muon barrel, extrapolations from Run 2 data. In all cases, the deviation from a perfectly linear behavior is under 1.5% across a pileup range up to 200. It is expected that further corrections obtained from real data will bring this systematic significantly lower.

In order to achieve the 1% accuracy required by precision physics analyses the statistical component of the uncertainty must be kept negligible. The expected statistical precision per bunch per second for physics conditions is of the order of 0.3% for all luminometers, except for the muon detector, becoming less than 0.1% for orbit integrated measurements.