Precision Luminosity Measurement with the CMS detector at HL-LHC

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On behalf of the CMS Collaboration

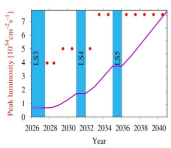
"El saber de mis hijos hará mi grandeza"

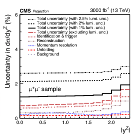
ABSTRACT:

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 Si-pad sensors.

Introduction

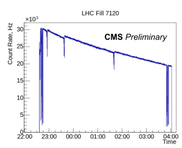
Precision LHC measurements have provided crucial input for the determination of fundamental parameters of the Standard Model, and a wide variety of searches have placed stringent constraints on new physics scenarios. The right figure shows a forecast for peak instantaneous luminosity (red dots) and integrated luminosity (purple line) in the HL-LHC era [1]. Also shown is the expected uncertainty on the Drell--Yan production cross-section for different assumed luminosity measurement uncertainties.

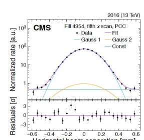




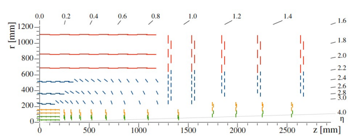
The luminosity precision achieved by CMS in Run 1 and Run 2 is shown the table below. Also shown is the luminosity measured for a typical LHC fill [2] and the calibration of the PCC luminometer using the Van der Meer scan method[3]. In Run 2, the luminosity uncertainty in proton-proton collisions was 2.3–2.5% per year in normal physics data taking using preliminary calibrations [3,4,5]. For the proton-proton (pp) case at 13 TeV, the luminosity uncertainty has improved to 1.2–1.6% per year for the 2015–2016 measurements. These results bring the preliminary combined Run 2 pp luminosity uncertainty to 1.6% at present. The HL-LHC physics program requires to further improve the uncertainty to 1.0%

Period [CMS-PAS Ref.]	2012 *pp* [LUM-13-001]	2015 *pp* [LUM-17-003]	2016 *pp* [LUM-17-003]	2017 *pp* [LUM-17-004]	2018 *pp* [LUM-18-002]
$\sqrt{s}$ [TeV]	8	13	13	13	13
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%] Normalization	2.3	1.2	1.0	1.5	2.1
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%] Integration	1.2	1.0	0.7	1.7	1.3
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%] Total	2.6	1.6	1.2	2.3	2.5





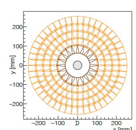
The CMS Phase 2 Tracker

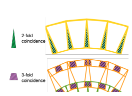


Sketch of one quarter of the CMS Phase-2 Tracker in r-z view[6]. In the Inner Tracker region the green lines correspond to pixel modules made of two readout chips and the yellow lines to pixel modules with four readout chips. The Tracker Endcap Pixel (TEPX) consists of the 4 disks at |z| > 1700 mm. In the Outer Tracker region (|r|>200 mm) the blue and red lines represent the two types of modules described in the ref. The Barrel Layer 6 consists of 2S modules arranged in sensor ladders covering up to |z| ~ 1200 mm (12 modules per ladder, 76 ladders per Tracker end).

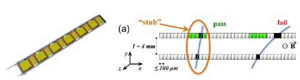
TEPX & D4R1

The relatively low pixel hit occupancy combined with a total active surface of ~2 m^2 allows for a very precise luminosity measurement using the pixel cluster counting (PCC) method. Each TEPX disk is made up of five individual rings with a varying number of pixel modules. The innermost ring of the last disk (D4R1) will be used as a dedicated luminosity and beam-induced-background measuring device. For both TEPX and D4R1, it is proposed to used dedicated firmware installed in the Phase-2 ATCA back-end system to reconstruct and count clusters online. The TEPX and D4R1 will be read out at 75 and 825 kHz, respectively. The sensor overlap regions, shown in the figure at the right, will allow to reconstruct coincidences for better background rejection.





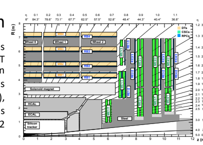
Outer Tracker Barrel Layer 6



The Phase-2 Outer Tracker (OT) system will provide a source of high-rate physics objects relying on two-hit coincidences on closely spaced silicon sensors ("L1 track stubs") detected by the front-end ASIC. The above figure shows one 2S sensor ladder and a diagram showing the stub reconstruction with the two layers in the module. In the designed OT back-end architecture, these objects are sent to the L1 track reconstruction system at 40 MHz frequency. Studies using CMS Phase-2 simulations show excellent linearity in the counting of these objects up to a pileup of 200. Together with the best statistical uncertainty in the whole BRIL Phase-2 portfolio, makes this an excellent candidate for a precision luminometer.

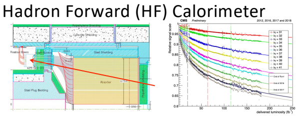
Muon System

The detector comprises a total of 250 DT chambers distributed in five CMS barrel wheels (designated YB=0,1,2), four radial stations (MB1-MB4), and 12 sectors [7].



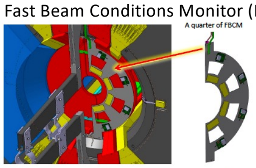
During Run 2, counting of muon track candidates from the CMS L1 trigger system, the Barrel Muon Track Finder (BMTF), has proven to be useful for the luminosity measurement because of its excellent linearity and stability [3]. The uncertainty in the BMTF track luminosity measurement at the HL-LHC instantaneous luminosity of 7.5x10^{34} cm^{-2}s^{-1} is expected to be about 25% per bunch per second. An improved luminometer based on muon trigger primitive counting at 40 MHz will provide higher count rates [2]. Muon trigger primitives will be available from the Phase-2 back-end of the barrel system for each of the muon Drift Tube (DT) chambers.

Hadron Forward (HF) Calorimeter



The measurement of luminosity based on a dedicated readout of the hadron forward calorimeter (HF) uses two algorithms, implemented in dedicated back-end firmware in the HF Phase-1 back-end electronics at 40 MHz. Both methods employ a set of towers corresponding to the pseudorapidity range 3.15 < |eta| < 3.50 (rings 31 and 32); the diagraph above shows the HF system). The HFOC method is based on "zero counting", which tracks the fraction of crossings with no energy depositions above a threshold per bunch. The mean tower occupancy can then be inferred by inverting the Poisson distribution: ln p(0), where p(0) is the fraction of bunch crossings that have no towers hit above threshold. The right plot shows the efficiency loss due to aging as a function integrated luminosity, expected to be more significant for HL-LHC.

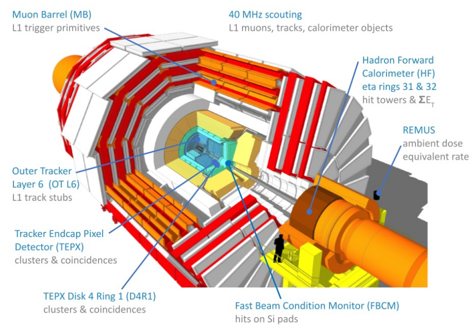
Fast Beam Conditions Monitor (FBCM) System



A standalone luminometer capable of running independently from CMS data taking is essential for the overall BRIL luminosity measurement program. A study is ongoing to install a "Fast Beam Condition Monitor" (FBCM) based on silicon-pad sensors with the fast front-end chip used by the Phase-2 Tracker project. A possible position for the FBCM is behind Disk 4 of the TEPX system, as illustrated by the figure, with the silicon-pad sensors at a radius of 14.5 cm. Each quarter of the FBCM uses four Inner Tracker port cards, allowing the use of 84 sensor channels per quarter for a total of 336 sensors. The required histogramming and digital processing at the back end will be performed in the ATCA architecture. The FBCM luminosity measurement uses the zero-counting method, with each sensor-pad as the counting unit.

Luminometers Overview

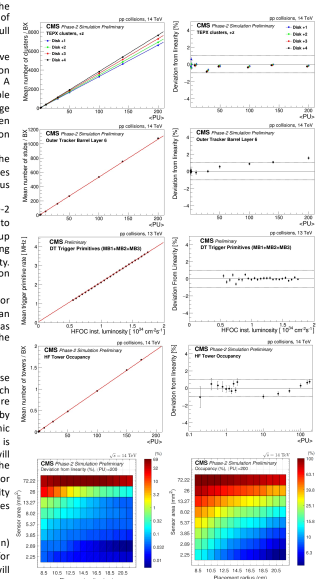
Luminosity measurements rely on the precise determination of event rates observed within the acceptance of a given detector (luminometer). Contributions to the uncertainty arise from the absolute calibration (normally from the vdM scan), as well as the response linearity and stability over time during physics runs. The figure below shows the different luminometers proposed for the Phase 2 upgrade. The TEPX & D4R1 continue on the excellent performance of the current PCC luminometer. The HF and REMUS continue with their current algorithms. Two algorithms will be derived from the current Muon barrel system: MB trigger primitives and Scouting of BMTF tracks. The Outer Tracker Layer 6 is a new luminometer with high statistical precision. The FBCM replaces the current PLT and BCM luminometers.



Expected Performance

A linear response over a large dynamic range of approximately 4 orders of magnitude is necessary due the extreme pileup conditions at the HL-LHC. The estimation of the luminometer count rates and linearity is based on full detector simulations and Run 2 data as follows:

- **TEPX and OT**: detailed detector simulation samples have been centrally produced using the CMS official simulation software (CMSSW) with the Phase 2 Tracker geometry. A single-neutrino event process is overlaid with a variable number of minimum-bias events to simulate the average pileup from 0.5 to 200. The samples are then reconstructed with the standard CMS reconstruction algorithms.
- **Muon Barrel**: Run 2 data are used to count the rates of the muon L1 trigger primitives and BMTF tracks, these rates are extrapolated to HL-LHC expected instantaneous luminosity.
- **HF**: standard CMSSW full simulation assuming Phase-2 conditions. A "neutrino gun" event generator was used to obtain a sample of zero-bias events with average pileup up to 175. The response of the HF is simulated assuming aging corresponding to 1000 fb^{-1} of integrated luminosity. The Run 2 algorithms are used with additional selection optimization.
- **FBCM**: A full CMSSW simulation with a proposed detector design and position described above, including an appropriate model for the front-end electronics, was performed to assess the performance. Various sizes of the sensors and positions at different r were studied.



The linearity response for each luminometer using these event samples is shown in the graphs at the right for each luminometer. For all luminometers the count rates are graphed vs pileup or instantaneous luminosity measured by HFOC. A linear behavior is observed over the entire dynamic range, the deviations from linearity are below 1.5%. It is expected that further corrections obtained from real data will bring this systematic significantly lower. In the case of the FBCM, the performance is optimized by varying the sensor size and position, the color plots show a map of the linearity deviations and detector occupancy for different sensor sizes and positions.

The statistical precision expected for physics (vdM calibration) conditions is below ~0.3% (~0.2%) per bunch per second for all except the muon based algorithms, these latter will achieve below 0.1% (0.4%) for an orbit integrated measurement.

Summary

The CMS Phase-2 luminosity instrumentation upgrade by the BRIL project is an extensive program including upgrades to current luminometers as well as new precise systems, with a goal to achieve a final precision below 1% needed for the CMS physics program over the next decades. Several systems have been describe above including the TEPX, D4R1, Muon Barrel, HF, and FBCM with specialized DAQ to provide precise online and offline measurements. The precision expected based on studies described above is on track to achieve the goals of the upgrade program.

References

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