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Precision luminosity measurement with the CMS detector at HL-LHC

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Gabriella Pásztor[a,b,*]

[a] *on behalf of the CMS Collaboration*

[b] *MTA-ELTE Lendület CMS Particle and Nuclear Physics Group , Eötvös Loránd University,*
Pázmány Péter sétány 1A, Budapest, H-1117, Hungary

E-mail: gabriella.pasztor@cern.ch

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 (TEPX) with an additional 75 kHz of dedicated triggers for online measurement of luminosity and beam-induced background. Real-time implementations of algorithms such as pixel cluster counting on an FPGA are explored for online processing of the resulting data. The potential of the exploitation of the outer tracker, the hadron forward calorimeter and muon trigger objects is also discussed.

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[*] Speaker

1. Luminosity measurement at HL-LHC

The precision measurement of the instantaneous luminosity relating the event rate of a process to its cross-section via $\mathrm{d}N_{\text{process}}/\mathrm{d}t = \mathcal{L} \cdot \sigma_{\text{process}}$ is essential for most physics measurements at collider experiments. The typical precision of luminosity calibration is around 2% at LHC Run 2 (for details see Ref. [1]) and it constitutes the dominant source of uncertainty in cross section measurements of W, Z, and top production in leptonic final states (e.g. Ref. [2]). The physics goals of HL-LHC (e.g. Ref. [3]) require a very challenging luminosity precision of 1% after final calibrations, at which level it becomes a subdominant uncertainty in most analyses. Real-time bunch-by-bunch measurements assisting beam optimisation and luminosity levelling are aimed to reach 2% uncertainty.

The experimental conditions at HL-LHC will become much harsher than those experienced at LHC Run 2 due to the increase of the peak instantaneous luminosity from $2 \cdot 10^{34}$ to $17 \cdot 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, levelled to about $(5 - 7.5) \cdot 10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by adjusting the beam parameter β^* and / or the beam separation. The resulting average number of pp collisions (also called pileup) will be around $\langle \mu \rangle \approx 140 - 200$ and constitutes a challenge for luminometer linearity requirements. Together with the installation of crab cavities, instrumental at reaching higher luminosity, and the larger crossing angle to minimise beam-beam effects, the collision environment will become more challenging.

The higher precision target and the more difficult experimental conditions require improved calibration techniques and bring stringent requirements for the Phase-2 HL-LHC upgrade of the CMS luminosity detectors. These are discussed in Ref. [5] in detail and are briefly summarised here.

Requirements for an ideal luminometer

The absolute luminosity scale is determined in van der Meer (vdM) beam separation scans [1] in special low pileup ($\langle \mu \rangle \approx 0.5$) conditions. To achieve negligible statistical uncertainty in the luminometer calibration constant, called visible cross section (σ_{vis}), the measured rate per bunch must correspond to sufficiently large number of events even at the maximum beam separation of 6σ over a time period of 30 s. In physics conditions, the statistical uncertainty in the per bunch rate should be below 1% with a fine measurement time window of 1 s.

To avoid systematic biases due to the bunch-by-bunch variation of beam properties, the luminometer must be operated at 40 MHz with all bunches equally sampled. If an online selection is required, it shall happen using a random or zero-bias trigger to remain unbiased by luminosity, pileup, and bunch location in the train. The measurement shall be published with a short latency of about 1 s and synchronised to centrally broadcasted timing signals from the trigger control distribution system, thus also synchronised to the central data acquisition (DAQ) timing.

The luminometer response shall be stable in time, linear from $\langle \mu \rangle \approx 0.5$ to 200, and uniform for single and train bunches. Any instability, nonlinearity, inefficiency or other response degradation (e.g. due to radiation damage) must be measured precisely and corrected for.

As feedback to the accelerator and protection of the experimental apparatus is required at all times, the luminometer must provide reliable measurement in the presence of beams independently of central DAQ issues.

Strategy for HL-LHC system design

In real life, detectors are not ideal, thus a robust multileg system is necessary to provide precise luminosity measurement. Based on the CMS [4] Run 2 experience [1], such a system shall have at least three independently calibrated, stability and linearity tracked luminometers, preferably using diverse technologies to avoid common biases. Such a design provides operational redundancy, allows the identification of outlier (potentially biased) measurements using a "majority" rule and the study of systematic effects. Multiple measurements enable disentangling correlated beam-related effects from detector specific issues (including dominant contributions from luminometer stability and linearity), as well as help to estimate and understand previously unknown biases.

While not strictly necessary, additional luminometers featuring long-term stability and linearity, even if not independently calibrated or bunch-by-bunch measurements, provide important benefits. They allow cross-calibration of luminometers in case of unforeseen problems and give further insights to systematic effects. Alternative techniques, e.g. precision luminosity determination using well understood physics processes (such as fiducial Z boson production) are complementary and provide an independent cross-check.

In CMS, the Beam Radiation Instrumentation & Luminosity (BRIL) project is responsible for the design, operation, and calibration of dedicated luminometers, as well as for the exploitation and optimisation of various CMS subsystems for luminosity measurement. BRIL also provides a dedicated data path for online processing of luminosity data via BRILDAQ.

2. CMS subsystems for luminometry at HL-LHC

CMS will use a number of subsystems for luminosity measurement at HL-LHC as shown in Fig. 1. Proceeding from the inner to the outer detectors, these are the Tracker Endcap Pixel Detector (TEPX) and its disk 4 ring 1 (D4R1) providing cluster and coincidence counts, the outer tracker layer 6 (OT L6) providing two-fold hit coincidensce (stub) counts, the hadron forward (HF) calorimeter proving occupancy and transverse energy sum measurements, the muon system and in particular the drift tubes (DT) providing track candidate (stub) counts, and finally the 40 MHz first level (L1) trigger scouting providing track, muon and calorimeter cluster information. A dedicated luminometer is

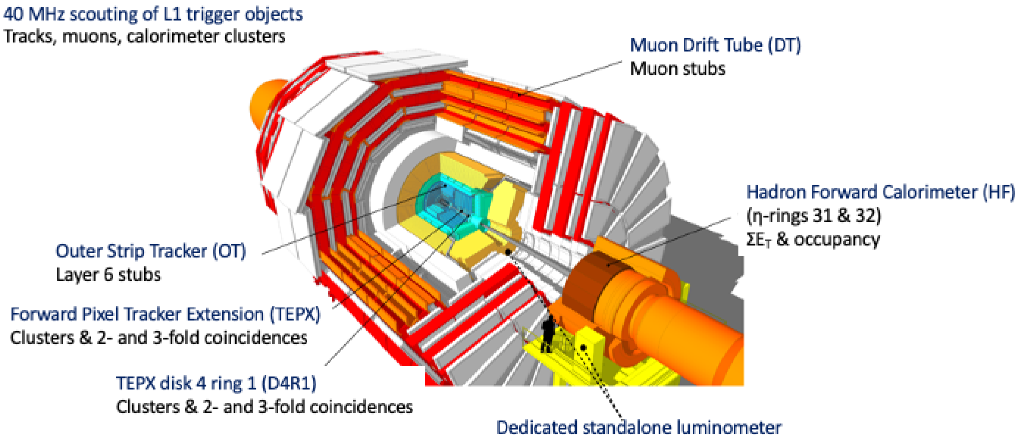

Figure 1: CMS subsystems for HL-LHC luminometry

also under development and could either be placed inside the tracker volume or on the CASTOR table. The CMS detector and its subsystems are described in Ref. [4].

2.1 Tracker endcap pixel detector

The Tracker Endcap Pixel Detector shown in Fig. 2 (top) will have a major role in luminometry at HL-LHC. The Run 2 experience with offline pixel cluster counting as well as HL-LHC simulations show excellent linearity up to high pileup as illustrated in Fig. 3 (top left).

Disk 4 Ring 1 will be operated as a fully independent luminometer with the full L1 trigger bandwidth (750+75 kHz) using dedicated backend electronics. A dedicated control stream with independent triggers and LHC clock will measure the beam-induced background during LHC ramps. The rest of TEPX will get an additional 10% L1 rate (75 kHz) for independent luminosity triggers. The data will be split in the backend and processed in a dedicated luminosity board. Real-time implementation on an FPGA of cluster counting is being explored. Cluster counting will also be complemented by measuring the rate of two- and three-fold coincidences within a disk (see Fig. 2, bottom left). Coincidence counting was used in Run 2 by the PLT (pixel luminosity telescope) system and promises to be a useful monitoring tool for TEPX at HL-LHC.

Outer tracker

The double silicon strip sensor modules of layers 4–6 of the outer tracker barrel provide two-fold hit coincidences (shown in Fig. 2 (bottom right)) at module level to the L1 track finder at 40 MHz. Simulations show a linear layer 6 (OT L6) stub rate up to $\langle\mu\rangle = 200$, low module-to-module variations, and good bunch-by-bunch statistical precision as illustrated in Fig. 3.

For luminosity measurement, histograming will be implemented in the OT backend using a generic firmware developed by BRIL that can be adapted to each subsystem. Dedicated luminosity

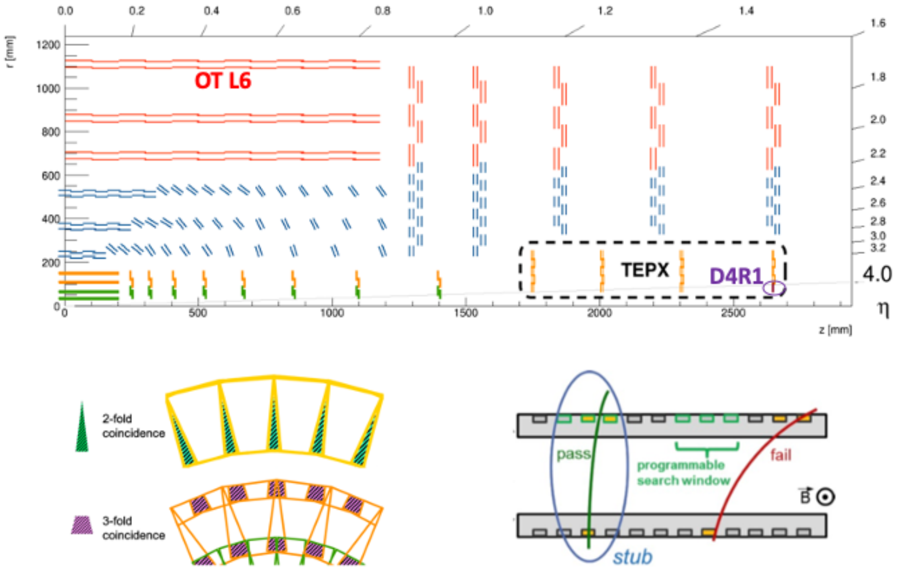

Figure 2: (Top) CMS tracker layout indicating the positions of TEPX, D4R1, and OT L6 systems. (Bottom) Graphical representation of TEPX two- and three-fold coincidences and OT stubs. [5]

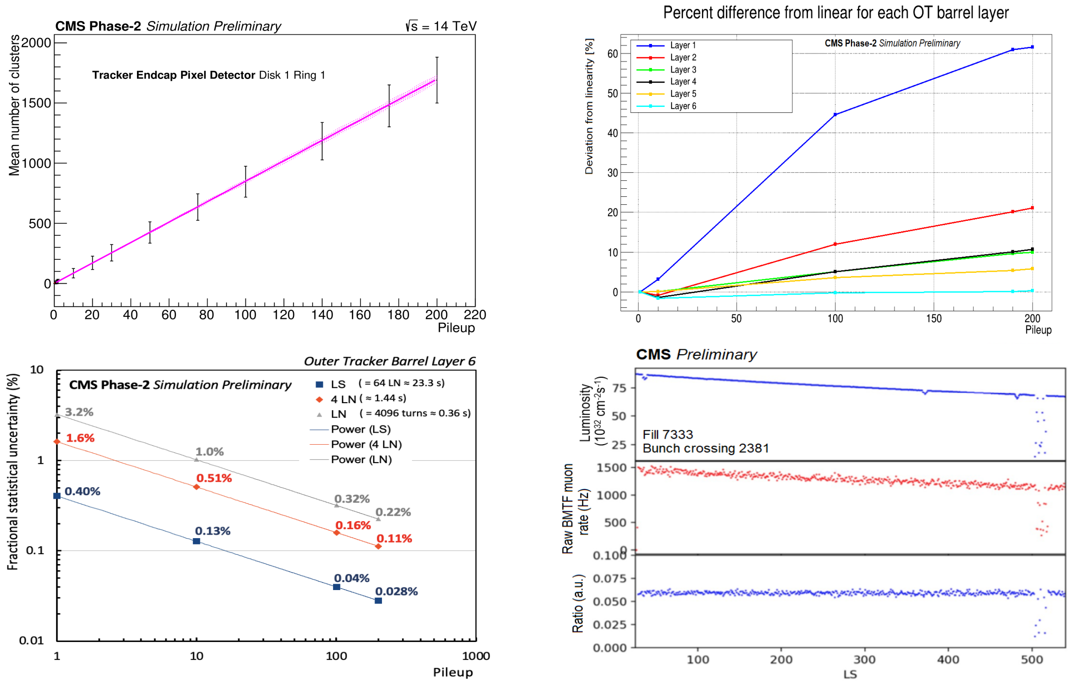

Figure 3: (Top left) Simulated mean number of clusters per event for TEPX disk 1 ring 1 as a function of pileup. (Top right) Measured deviation from linearity in percent for the OT stub counting rate as a function of pileup for different layers. (Bottom left) Expected statistical precision of the luminosity measurement using OT L6 for a single bunch crossing as a function of pileup for three different time integration periods. (Bottom right) Instantaneous luminosity as measured by the BRIL luminometers for a single bunch crossing in LHC fill 7333 in 2018 compared to the uncalibrated BMTF muon rate for all muons with transverse momentum above 2.5 GeV. The ratio in the bottom panel demonstrates the excellent BMTF linearity. [5]

readout is foreseen over the control network. While the OT does not guarantee luminosity data outside of global CMS data taking, it will provide a highly reliable independent measurement.

Hadron forward calorimeter

The hadron forward calorimeter was a main (and frequently primary) luminometer in Runs 1 and 2. It measures Cherenkov light collected by quartz fibers embedded in a steel absorber. As the best linearity is provided by the two rings in the pseudorapidity range of $|\eta| = 3.15 - 3.50$ their signals are read out by dedicated electronics as a part of BRILDAQ. Two algorithms are implemented in HF uTCA backend using dedicated lookup tables (LUTs): one measures the occupancy above a threshold (HFOC), the other calculates the transverse energy sum (HFET).

For HL-LHC performance, studies towards the mitigation of radiation damage and the understanding of differences between the parametric HF aging model and the in-situ emittance scan results are important. No major changes are planned, but the energy threshold of HFOC shall be retuned to avoid zero-starvation but still maintain linearity at the expected high luminosity conditions.

Muon system and L1 trigger scouting

The barrel muon track finder (BMTF) provides orbit-integrated muon candidate rates real time at the L1 trigger for 23 s time intervals. The Run 2 experience shows excellent linearity and stability, as well as an almost background-free measurement.

Developments have started in preparation for the HL-LHC upgrade to count the DT trigger primitives at the backend per bunch for 1.44 s intervals (2^{14} LHC turns). A demonstrator system is planned for Run 3. Moreover, the 40 MHz L1 trigger scouting system can also be used for luminometry. The Run 3 demonstrator provides access to BMTF muons and the eight best global trigger muon candidates with bunch-by-bunch histogramming. At HL-LHC, scouting measurements could be extended to the track trigger objects and calorimeter primitives, giving further tools for luminosity calibration.

Standalone luminometer

CMS works toward the development of a standalone bunch-by-bunch precision luminometer for HL-LHC. The main requirements for such a detector are fast (< 25 ns) timing with asynchronous front-end electronics and completely independent operation from the rest of CMS, with preferably orthogonal systematics due to detector technology to the existing subsystems. Currently two proposals are considered:

A *Cherenkov detector* (similar to and building on the extensive experience with HF) on the CMS CASTOR table that will be optimised for luminometry and feature remote read-out using modern front- and back-end electronics.

A *silicon-pad sensor based detector* with fast digital read-out and active cooling in tracker volume, supported by the excellent experience with the Run 2 BCM1F (fast beam condition monitor) system.

3. Summary of CMS luminosity strategy for HL-LHC

CMS aims to ultimately reach a 1 (2)% precision on offline (real-time) luminosity measurement to provide the best possible physics performance and prompt feedback to LHC. The strategy, based on optimal exploitation of data from existing subsystems and the development of an additional fully independent luminosity detector, enables the experiment to have three (almost) ideal luminometers and about six independently calibrated measurements. The design will be documented by the CMS BRIL in the Luminosity & Beam Instrumentation Technical Design Report in 2021.

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