CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s}$ =13 TeV

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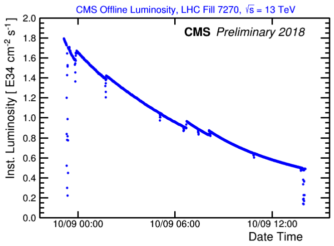
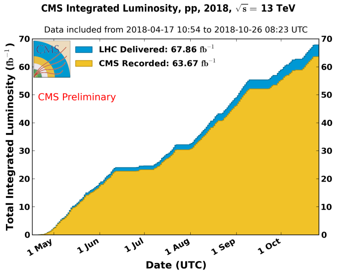
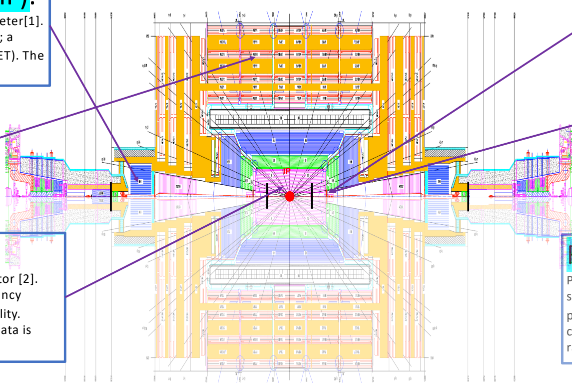


Abstract

Maximally precise calibration of the CMS luminosity measurement is critical for many physics measurements. To guarantee high quality absolute calibration, a complete van der Meer scan program was carried out at the CMS experiment in 2018. The systematic uncertainty on the absolute calibration from the van der Meer scans is derived with a precision of 2.1%. The performance and stability of the CMS luminometers is also evaluated using emittance scans taken throughout the course of the year, which allows for independent nonlinearity measurements and correction for each luminometer. Cross-detector stability and linearity, together with the normalization uncertainty from the van der Meer scans, results in a total luminosity uncertainty of 2.5%. The dominant systematic uncertainty arises from the x-y correlations of the beam shape, with other major contributions from stability and linearity effects.



CMS Luminometers



Hadronic Forward Calorimeter (HF):

Two algorithms use the data from the forward Cherenkov calorimeter[1]. The original one (HFOC) relies on the fraction of occupied towers; a second method is based on the sum of the transverse energy (HFET). The primary luminometer for 2018 is HFOC.

Muon Drift Tubes (DT):

Uses the rate of muon track stubs in the muon barrel track finder. The DT algorithm does not provide bunch-by-bunch measurements and is thus cross-calibrated to HFOC.

Pixel Cluster Counting (PCC):

The PCC method uses the rate of clusters in the CMS pixel detector [2]. The large area of the pixel detector and the relatively low occupancy provides a measurement with good statistical precision and stability. Because the CMS trigger bandwidth available for collecting this data is limited, the counting is done per 23-second luminosity sections.

Pixel Luminosity Telescope (PLT):

A dedicated system using silicon pixel sensors [3]. There are a total of 48 sensors arranged into 16 "telescopes" outside the pixel endcap. Each telescope contains three sensor planes. PLT measures the rate of "triple coincidences", where a hit is observed in all three planes.

Beam Conditions Monitor (BCM1F):

Consists of 10 silicon, 10 polycrystalline diamond (pCVD), and 4 single-crystal diamond (sCVD) sensors [4]. A precise time measurement (6.25ns), in conjunction with the position of BCM1F, allows hits from collision products to be separated from hits from machine induced background.

RAMSES:

Part of the CERN radiation and environmental monitoring system, the sensor is a cylindrical plastic ionization chamber and primarily detects photons within the energy range of 50 keV to 7MeV [5]. It is cross-calibrated as it does not detect individual bunch luminosity. The overall rate is small and exhibits excellent linearity and stability.

Luminometer Calibration:

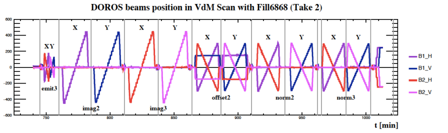
Each detector rate ***R*** should be proportional to the instantaneous luminosity $\mathcal{L}_{\text{inst}}$ with a constant of proportionality $\boldsymbol{\sigma}_{\text{vis}}$:

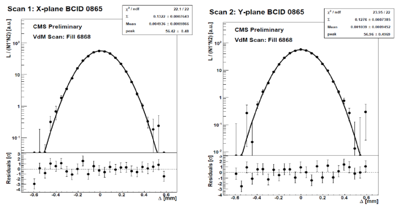
$$R = \mathcal{L}_{\text{inst}} * \boldsymbol{\sigma}_{\text{vis}} \qquad (1)$$

The instantaneous luminosity for a single colliding bunch i, L^{i}_{inst}, can be expressed in terms of the number of protons per bunch in each beam (N^{i}_{1}, N^{i}_{2}), the LHC revolution frequency *f*, and the normalized particle densities $\boldsymbol{\rho}$(x,y):

$$\mathcal{L}^{i}_{\text{inst}} = N^{i}_{1}N^{i}_{2}f\int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y = N^{i}_{1}N^{i}_{2}f\int \rho_{x1}(x)\rho_{x2}(x)\mathrm{d}x\int \rho_{y1}(y)\rho_{y2}(y)\mathrm{d}y, \qquad (2)$$

In practice it is assumed that the densities are factorizable in x and y and their overlaps are measured in special van der Meer (VdM) scans performed by the LHC.





Left plot shows part of the LHC VdM scan program during fill 6868 used to calibrate the luminometers [5]. The different colored curves show the position of the two beams (B1,B2) in the horizontal (H) and vertical directions (V).
Top plot shows the rate observed in the PCC luminometer for a pair of X and Y scans used to determine the beam overlap integrals.

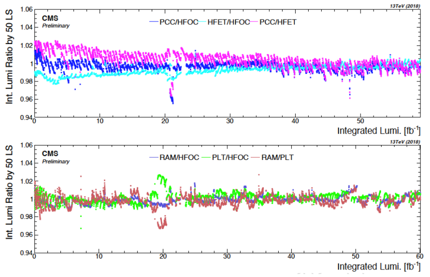
The following corrections are applied to the calibration constants:

- **Length scale calibration** is a correction on the order of 0.7% (0.3%) in the beam x (y) separation measured with the help the CMS tracker.
- An **orbit drift** correction is applied to the beam separation, measured using DOROS and arc Beam Position Monitors, and is less than 10 **μ**m (5 **μ**m) in x (y).
- **Beam-beam effects** of repulsion and defocusing, due to electrical interaction between the beams, result in a correction of +1.0%.
- A **bunch current normalization** correction of -0.9% (-1.4%) for beam 1 (2) is determined using the DCCT and FBCT systems [5].

The results of the calibration analysis are shown in the table. The third and fourth columns show the average bunch uncertainty and the error on the mean after averaging all bunches, respectively.

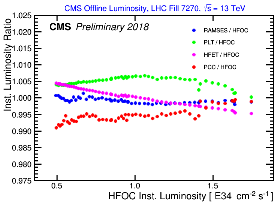
Luminometer	Measured σ_{vis}	Bunch spread	Bunch uncertainty
BCM1F	210.3 μb	1.3 μb (0.62%)	0.1 μb (0.06%)
HFET	2503.6 μb	13.9 μb (0.56%)	1.3 μb (0.05%)
HFOC	805.9 μb	5.4 μb (0.67%)	0.5 μb (0.06%)
PLT	261.8 μb	1.6 μb (0.61%)	0.1 μb (0.05%)
PCC	5982 mb	37 mb (0.62%)	16.5 mb (0.3%)
VTX	29.12 mb	0.14 mb (0.49%)	0.06 mb (0.2%)

Stability, Linearity, and Systematic Uncertainties:



Due to variations in performance of the different luminometers, a ranking is performed which gives the best accuracy over the entire data taking period. For 2018 the luminometers are ranked in the following order: HFOC, PCC, PLT, RAMSES, DT, BCM. The main uncertainties on the luminosity measurement arise due to the following:

- **Detector linearity** causes possible deviations as the instantaneous luminosity increases. The linearity is checked by comparing ratios of luminometers as a function of the instantaneous luminosity as shown on the right. The ratios are fit with linear functions and the average slope per detector is shown in the table below. The estimated systematic uncertainty on the integrated luminosity is 1.1%.
- **Cross-detector consistency** in the VdM calibration, **HFOC "afterglow"** corrections, and **time dependent instabilities** (see graph at left) lead to systematic uncertainties of 0.5%, 0.4%, and 0.6%, respectively. The graphs at the left show the ratios of different detectors over the course of the year used to estimate the variations shown in the table below.
- **x-y correlations** in the beam densities **ρ**(x,y) are assumed to be Gaussian and factorizable; a 2.0% systematic uncertainty is assigned to cover possible deviations [5].



Luminometer pair	Mean ratio	SD ratio (%)	Mean slope (%/(Hz/μb))	SD slope (%/(Hz/μb))
PCC/HFOC	0.997	0.37	0.20	0.11
PLT/HFOC	1.001	0.44	−0.07	0.17
RAMSES/HFOC	1.000	0.48	0.04	0.09
DT/HFOC	1.000	0.40	0.01	0.07
BCM1F/HFOC	0.967	0.65	−0.20	0.15
HFET/HFOC	0.992	0.52	−0.09	0.07

Summary:

A preliminary analysis of the 2018 luminosity measured by CMS luminometers has been performed. The VdM scan program in LHC fill 6868 was used to measure the calibration constants for the different algorithms. Stability and linearity variations are estimated by analyzing the full year dataset. A total uncertainty of 2.5% is derived on the integrated luminosity.

References

[1] CMS Collaboration, "CMS luminosity measurement for the 2015 data taking period", CMS-PAS-LUM-15-001
[2] CMS Collaboration," CMS Luminosity Based on Pixel Cluster Counting ", CMS PAS LUM-13-001
[3] P. Lujan, "Performance of the Pixel Luminosity Telescope for luminosity measurement at CMS during Run 2", PoS 314 (2017) 504,
[4] M. Hempel, "Development of a Novel Diamond Based Detector for Machine Induced Background and Luminosity Measurements". PhD thesis, DESY, Hamburg, 2017.
[5] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at √s= 13 TeV", CMS-PAS-LUM-18-002