OVERVIEW OF CMS LUMINOSITY DETERMINATION IN RUN-2

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Abstract

The CMS experiment operates several detector systems dedicated to luminosity measurement. The requirements on luminosity systems and their features are summarized. The calibration methodology for nonlinear detector responses is reported. During 2015–2018 (Run-2), preliminary results of the luminosity measurement for all data-taking periods have been made public within a year of the van der Meer scans. The calibration strategy, applied corrections, and relevant uncertainties are determined for each year. This note reviews all four publications using proton-proton collisions at 13 TeV during Run-2. The calibration-related effects, common to all years, are explained and the impact on the uncertainty in the integrated luminosity is put in context.

INTRODUCTION

The measurement of the luminosity at CMS [1] is achieved using various detectors. The absolute calibration is performed once per collision system and year during calibration runs, during which each luminosity system is calibrated independently. The calibration uncertainties are common to all systems. Each system is limited by further sources of systematic uncertainty, such as linearity or stability, resulting in detector-specific uncertainty in the integrated luminosity. These proceedings present an overview of the requirements for a luminosity measurement and introduce the systems used. The uncertainties in the absolute calibration are summarized and compared among the different years.

LUMINOSITY MEASUREMENT SYSTEMS

Requirements

The intensity of the particle flux at the experiments scales with the instantaneous luminosity. The exceptions are radioactivity and beam-induced background, which are negligible at nominal operation and only have to be accounted for during the yearly van der Meer (vdM) calibration runs. Any particle rate measurement can therefore act as a luminosity measurement; however, to qualify as a useful luminosity system, certain requirements have to be met.

Bunch-by-bunch measurement capability During the calibration runs, the beam overlap is determined and is used to calculate the luminosity at a given moment. This is only possible if each bunch is measured separately due to different bunch sizes. This is a requirement on the readout electronics to provide these data and the detector design to provide a sufficiently precise measurement per bunch at very low luminosity.

Hit rate capability A reliable measurement is required at nominal luminosity and during the vdM scans, which usually feature about a factor of 50 less bunch-by-bunch luminosity during head-on collisions. During the vdM scans, the beams are partially separated and the rates are reduced even further. To allow for a useful fitting to the VdM data, the hit rate has to be measured precisely in higher beam-separation values compared to the head-on case.

Linearity The precise vdM based calibration is obtained at a luminosity much lower than the actual measurement. In order to have a reasonable calibration, at high luminosities, a linear response is required up to the nominal luminosity. The peak instantaneous luminosity in 2018 was around $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This requirement applies to both linearity in total luminosity measurement and linearity in bunch luminosity measurement. A nonlinear behaviour can be compensated for, however determining this nonlinearity is an additional calibration effort with an associated uncertainty in the final integrated luminosity.

Minimal out-of-time effects Out-of-time effects refer to anything that would change the measurement as an effect of a preceding bunch crossing. The effects can be grouped in:

Type-1: A detector might either have a certain dead time or exhibit an over-efficiency due to hits the preceding bunch crossing. Within an LHC train it results in the luminometer responding differently to the first bunch compared to all following bunches. The resulting under- or over-efficiency is rate depended and results in a nonlinear detector response. A detector-specific filling scheme dependent correction needs to be estimated to compensate the effect.

Type-2: Out-of-time particles produce detector hits during a bunch-crossing later than the one at which the collision has occurred. The particle composition determined by the collisions includes, on top of relativistic particles, slow particles such as thermalized neutrons and radioactive decay products from short-term material activation, which reach the detector with a significant time delay. This process, referred to as "afterglow", linearly depends on the instantaneous luminosity, and can be corrected by applying a parameterization of the effect on the detector.

Out-of-time effects on the bunch crossing following the actual collision had been classified in the past as Type-1 in general, taking different effects together, because it is not possible to disentangle the contributions from the different effects.

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Overview of each luminosity systems

CMS employs several luminosity systems. A quick introduction for each system with their features, relevant for luminosity, is given.

HF zero counting (HFOC) The hadron forward calorimeter (HF) features a dedicated data stream for luminosity measurement. The HFOC luminosity measurement is based on counting hits in the individual channels with a zero-counting algorithm (detailed in the next section).

HF transverse energy (HFET) For HFET, the transverse energy measurement is used. This algorithm is expected to be more reliable at high pileup compared to HFOC. Although the same detector is used, this luminosity system is treated independently from HFOC. While some systematic effects are the same, the comparison between HFOC and HFET is useful to improve on algorithm specific effects.

Fast Beam Condition Monitor (BCM1F) The BCM1F detector [2] is designed as a pad detector with an analog front-end and a particle discrimination in the back-end. The front-end amplifier is designed such that the pulse recovery is within 25 ns and therefore it does not suffer from Type-1 out-of-time effects. Over the course of Run-2, single crystal diamond, polycrystalline diamond and silicon diodes have been used as sensors. Irradiated diamond show, to a varying extent, a rate-dependent behavior calling for a linearity correction. One complication was that the nonlinearity depends on the total particle rate and cannot be corrected for with only a bunch-by-bunch measurement. Additional corrections were necessary to obtain a comparable measurement at different bunch filling schemes. Silicon diodes have shown the best luminosity performance due to a linear response; however, the basic design of BCM1F was optimized for diamond and hence the longevity was relatively poor.

Pixel Luminosity Telescope (PLT) The PLT consists of 16 telescopes using 3 layers of CMS phase-0 pixel detector planes [3] pointing directly at the interaction point (IP). Each plane features a so-called "fast-or output", i.e., a 40 MHz trigger signal, active if the plane registers a particle hit anywhere. Threefold coincidences between all fast-or signals are used for the luminosity measurement in a zero-counting algorithm. In contrast to HFOC, HFET and BCM1F, PLT does not suffer from Type-2 out-of-time effects, because afterglow hits are not linked to particle tracks pointing towards the IP. The disadvantage of coincidences are accidental coincidences originating from several particles hitting different planes. This effect is more likely at high pileup and hence leads to a nonlinear response. In the PLT detector, a Type-1 effect leads to a reduced efficiency of the fast-or at high pileup in the following bunch crossing, resulting in a different linearity behavior of the first bunch in a train compared to each following bunch crossings.

Pixel cluster counting (PCC) The PCC algorithm uses zero-bias trigger [4] data and makes use of the number of pixel clusters. A post processing of the data is necessary hence the data are promptly reconstructed and available about 48 hours after the fill. Based on Monte Carlo simulations the response is expected to be linear at the expected pileup range [5]. During the vdM calibration runs, only five bunches are read out due to trigger bandwidth limitations.

Cross-calibrated systems Luminosity measurements, not independently calibrated, can be of high value when studying systematic effects of other detector systems, such as long-term stability or linearity. To that end, CMS uses a measurement based on hits in the muon barrel drift tubes (DT) [6] and the cavern radiation monitoring system called RAMSES [7].

ONLINE CORRECTIONS AND CALIBRATION

Each detector provides a measurement that can be converted into a luminosity measurement by considering a detector event as a physics event with a given probability. The relation to luminosity is given as for any physics event by:

$$\mathcal{L} = \frac{R}{\sigma_{\text{vis}}}, \tag{1}$$

with R being the hit rate measured in the detector and σ_{vis} the cross-section for a hit to appear in the detector.

Zero counting

In detectors that count individual particle hits, the systems are not able to distinguish between one or more particles hitting the system at the same time. This pileup-dependent effect is corrected for when calculating μ_{b} from raw detector data based on a Poisson distribution function. It is given by

$$\mu_{\text{b}} = -\ln(1 - \frac{R_{\text{b}}}{R_{\text{max}}}), \tag{2}$$

where R_{b} is given by the measured detector hits in a given bunch crossing b and R_{max} denotes the maximum number of possible hits in the detector; R_{max} is typically given by the number of LHC turns in the integration period of the recorded data, as per LHC orbit only one hit can be counted per bunch crossing. The result of Eq. 2 expresses the hit probability per LHC turn. Using μ_{b} as a measure of the detector hit rate, Eq. 1 becomes:

$$\mathcal{L}_{\text{b}} = \frac{f_{\text{LHC}}}{\sigma_{\text{vis}}}\mu_{\text{b}}, \tag{3}$$

where f_{LHC} denotes the LHC revolution frequency to convert the time unit from the "per turn" normalization of μ_{b} to Hz, as needed for the value of luminosity. The final result $\mathcal{L}_{\text{b}}$ is the so-called single bunch instantaneous luminosity (SBIL).

Nonlinearity treatment

Equation 3 is valid, if the zero counting corrected detector data are linearly proportional to luminosity. However, various detector effects can lead to a pileup dependence of σ_{vis}.This can be measured in so-called emittance scans, which are short calibration scans taken during nominal operation at different pileup [8]. While more complex dependencies are possible, a linear fit is applied to the data:

$$\sigma_{\mathrm{vis}}(\mathcal{L}) = m \times \mathcal{L}_{\mathrm{b}} + \sigma_{\mathrm{vis},0}. \quad (4)$$

The zero crossing value $\sigma_{\mathrm{vis},0}$ gives the calibration factor at the limit of zero luminosity, which is close to the conditions of the vdM fill. The nonlinearity "*nl*" is usually quoted as the fractional change per unit of SBIL relative to the value at zero luminosity. It is therefore calculated from the fit parameters m and $\sigma_{\mathrm{vis},0}$ as: $nl = m/\sigma_{\mathrm{vis},0}$. To make nl an integral part of the calibration, the following derivation is considered.

Equation 3 is expressed as:

$$\mu_{\mathrm{b}} = \frac{\sigma_{\mathrm{vis}}(\mathcal{L})}{f_{\mathrm{LHC}}}\mathcal{L}_{\mathrm{b}} \quad (5)$$

Equation 4 is then inserted in Eq. 5:

$$\mu_{\mathrm{b}} = \frac{nl \times \sigma_{\mathrm{vis},0}}{f_{\mathrm{LHC}}}\mathcal{L}_{\mathrm{b}}^2 + \frac{\sigma_{\mathrm{vis},0}}{f_{\mathrm{LHC}}}\mathcal{L}_{\mathrm{b}}. \quad (6)$$

This quadratic relation is difficult to solve. The quadratic luminosity term can be alternatively replaced by Eq. 3, although as $\sigma_{\mathrm{vis}}(\mathcal{L})$ is dependent on luminosity, hence it can't be solved analytically either. As a simplification, $\sigma_{\mathrm{vis},0}$ is used in the quadratic term, with the substitution expected to introduce negligible difference, since σ_{vis} slightly depends on luminosity. Solving for $\mathcal{L}_{\mathrm{b}}$ we finally arrive at:

$$\mathcal{L}_{\mathrm{b}} = -nl\left(\frac{f_{\mathrm{LHC}}}{\sigma_{\mathrm{vis},0}}\right)^2 \mu_{\mathrm{b}}^2 + \frac{f_{\mathrm{LHC}}}{\sigma_{\mathrm{vis},0}}\mu_{\mathrm{b}}. \quad (7)$$

To implement this relation during the online and offline data processing, we make use of a quadratic function with three parameters, i.e.,:

$$\mathcal{L}_{\mathrm{b}} = c_2 \times \mu_{\mathrm{b}}^2 + c_1 \times \mu_{\mathrm{b}} + c_0. \quad (8)$$

These parameters are interpreted as:

- c_0: corrects for a constant term, e.g., a noise level. In practice, we set $c_0 = 0$, and correct the raw detector data to provide an uncalibrated data that are zero in the absence of collisions. This allows for more complex online corrections, e.g, subtraction of the beam-induced-background.
- c_1 is the main calibration factor and is given as $c_1 = f_{\mathrm{LHC}}/\sigma_{\mathrm{vis},0}$.
- c_2 corrects for the nonlinear detector response as a result of μ_{b} being dependent on σ_{vis}. The functional form $c_2 = -nl \times c_1^2$ is used as estimated from Eq. 7, where nl is the nonlinearity in the fractional change of σ_{vis} per SBIL in units of Hz/μb; it can be obtained either from emittance scans or cross-calibrated from a luminometer whose response is expected to be linear.

Higher-order polynomials are possible, however, usually not used as their impact on the total integrated luminosity is low, and calculating a correction parameter that is valid over an extended period of time is difficult.

The total instantaneous luminosity $\mathcal{L}$ is finally obtained by summing $\mathcal{L}_{\mathrm{b}}$ over all colliding bunch crossings.

Afterglow correction

Type-1 and Type-2 out-of-time effects are entangled in the detector hit data. The linear afterglow corrections therefore include Type-1 effects. Difference in linearity due to nonlinear Type-1 effects are treated separately.

To correct for afterglow, we model the afterglow tail of a single colliding bunch, normalized to the luminosity of the colliding bunch crossing. To correct a bunch-by-bunch histogram containing bunch trains, the afterglow models is multiplied with the luminosity of each colliding bunch pair and subtracted from all following bunches. This correction is performed iteratively over all colliding bunch pairs such that a given bunch crossing is fully corrected before it is used to correct the succeeding bunch crossings. This calculation is relatively computationally intense. An afterglow contamination fraction can be calculated by dividing the corrected by the uncorrected data. This fraction can be then applied to individual bunch-by-bunch histograms without recalculating the correction. The fraction can be recalculated in regular intervals, e.g., in the BCM1F online processing, or during the offline processing, where an average for the entire fill can be alternatively used.

Beam-induced background correction

Particles not originating from the collisions are produced by the LHC beam interacting with the residual gas inside the beam pipe or with the apertures. The so called beam-induced background (BIB) is proportional to the beam intensity, but not luminosity. In nominal operation, the effect is low, and hence neglected. However, in a vdM fill, the luminosity is very low, and the BIB contamination is more significant, making a correction is necessary when analyzing the vdM scan data. The BIB contamination can be estimated from unpaired bunches or during a time of high beam separation. As a dedicated measurement, the beams were brought into "super-separation" for a few minutes during the 2018 vdM fill. It is found to be beneficial to subtract the BIB contamination from the data before applying any fit to the vdM data. Using a constant term in the fit equally compensates for this effect, but if the tails of the beam shape are not sufficiently probed it can lead to overestimation of the constant term, and hence a bias in the fit result.

ABSOLUTE CALIBRATION

Once a year, several vdM scans are performed during a dedicated LHC fill. The beam parameters are modified to allow the vdM result to be as accurate as possible. The process of the vdM scans is detailed in Refs. [9–14].

Various effects bias the vdM calibration result, and each effect on the vdM calibration needs to be estimated along with the associated uncertainty. In the following, the various effects are summarized, and their uncertainty on the calibration is given as a range of the observed magnitude over the four operational years during Run-2.

Beam intensity

The bunch intensity (number of protons in each bunch), is needed for the normalization of the measured rates during vdM scans. The measurement is provided by various LHC beam instruments. The fast beam current transformer (FBCT) provides a bunch-by-bunch measurement, however, the absolute calibration is not accurate at the level of the aimed precision. The DC current transformers (DCCT) provide a total beam intensity measurement in a reliable calibration. The sum of the FBCT measurement is scaled to the DCCT measurement, and the scaling is applied per bunch. Additional effects influencing the beam intensity are ghost charge and satellite charge. Ghost charge (beam particles not part of a bunch) is included in the DCCT measurement, but not in the FBCT measurement, hence it needs to be subtracted from the DCCT measurement. Satellite charge (beam particles within a filled bunch crossing but not in the colliding RF bucket), is measured by the FBCT, but do not contribute to the collision, hence it needs to be subtracted from the FBCT measurement. One average correction factor for ghost charge is used, while for satellite charge a per-bunch correction is applied; their stability over time is included. The final bunch intensity I_b is given by:

$$I_\mathrm{b} = I_\mathrm{b,FBCT}(1 - f_\mathrm{satellite})\frac{I_\mathrm{DCCT}(1 - f_\mathrm{ghost})}{\sum_i^n I_{i,\mathrm{FBCT}}}, \qquad (9)$$

where n are all the filled bunches, $f_\mathrm{satellite}$ and f_ghost are the satellite and ghost charge fractions, respectively. The satellite fraction is available as bunch-by-bunch measurement and can be applied as such, but it also has been used as an average value applied to all bunches in the past.

The beam intensity-related corrections lead to the following correction factors and uncertainties: In 2018 the correction for the beam current calibration was 2.3 %. The uncertainty on the beam current was between 0.2 and 0.3 %. The ghost and satellite corrections were applied in 2018 resulting in a 0.4 % correction. The uncertainties from ghost and satellites were between 0.1 and 0.4 %

Orbit drift

The position of the LHC beam orbit is prone to slow drifts. Usually, this can be corrected for by bringing the beams to full overlap. With an individual vdM scan taking about 45 minutes, the stability of the beam position is not guaranteed. Each scan step is implemented as a relative change, hence the drift cannot be corrected for while the scan is ongoing. The beam position monitor (BPM) systems at LHC is used to measure the orbit drift, and to calculate correction factors. The DOROS system [15] specifically targets the beam position at the IP, however it is mainly used while the beams are head-on, since the beam steering for the scan dominates the orbit drift effect. The BPMs in the LHC arc section close to IP5, referred to as arcBPMs, are outside of the beam steering, and the measurement is valid during the whole scan, but does not necessarily reflect the exact magnitude of the drift at the IP. The DOROS system and the arcBPMs are usually in good agreement and the average of both is used for the correction while the difference is used to estimate the uncertainty in the method.

Beam beam and dynamic β

Both beams affect each other in each interaction point. (As the bunches in a vdM fill are widely separated, there are no interactions from bunches not paired at the IP, as occurs with bunch trains during nominal operation.) A bunch will exert an electromagnetic force on its collision partner. While the bunches are not colliding head on, but are separated as occurring during the VdM scan, the bunches are displaced and not at their nominal separation. When the bunches are close to head on a defocusing effect occurs, changing the β^*, leading to a change in collision rate. Both effects, the displacement and the rate change due to a change of focusing, have to be corrected for. As presented at this conference, detailed studies are ongoing to improve the level of understanding of these effects. The corrections used in the Run-2 Luminosity publications of CMS thus far are based on Refs. [16, 17].

Effect of x/y factorization

During the vdM scan, the beams are scanned across in horizontal (x) and vertical (y) directions to measure the beam width along these dimensions. To obtain the area of the full beam overlap, we assume that the beam shape is factorizable in both axes. Observations have shown that the width of the beam is not always stable in the dimension orthogonal to the scanning direction, implying a nonfactorization in X and Y coordinates [18]. The method to calculate the correction factors during Run-2 was the beam-imaging scans. As an alternative, offset scans are studied. Both methods are detailed in Ref. [18]. The necessary correction for the vdM scans ranginges from 0.8 to 1.1 % between 2015 and 2017. The additional uncertainty in the final vdM result was between 0.8 and 1.5 %. In 2018, the analysis did not yield a precise result. No correction was applied and an uncertainty of 2 % was assigned. Improvements to this are under development.

Length scale

The nominal beam displacement is not identical to the actual movement of the beam due to imperfections in the steering magnets. In a length scale scan, the collision point

	Systematic	Correction [%]	Uncertainty [%]
Normalization	Beam current calibration	0.0 – 1.3	0.2 – 0.3
	Ghost and satellites	0.0 – 0.4	0.1 – 0.4
	Orbit drift	0.0 – 0.2	0.1 – 0.4
	Beam-beam effects	1.0 – 1.8	0.2 – 0.6
	x/y factorization (2015 – 2017)	0.8 – 1.1	0.8 – 1.5
	x/y factorization (2018)	—	2.0
	Length scale calibration	0.5 – 1.6	0.2 – 0.8
	Background subtraction	0.0 – 0.8	0.1
	Scan to scan variations	—	0.3 – 0.9
	Bunch to bunch variations	—	0.1
	Cross-detector consistency	0.0 – 0.6	0.5 – 0.6
Integration	Cross-detector stability	none	0.5 – 1.0
	Linearity	none	0.6 – 1.5
	Out-of-time hit correction	0 – 12	~0.4
	CMS deadtime (recorded luminosity only)	—	<0.1 – 0.5

Table 1: Overview of the magnitude of the different corrections in the calibration with their resulting uncertainty in the final luminosity measurement. The ranges give the minimal and maximal values observed over the four operational years of Run-2. The table is compiled from Refs. [9–12].

Year	Normalization [%]	Integration [%]	Total [%]
2015	2.3	1.8	1.5
2016	2.5	1.5	2.0
2017	2.3	1.5	1.7
2018	2.5	2.1	1.3

Table 2: Uncertainties in the integrated luminosity in each year.

is moved along the x or y axis by moving both beams in the same direction. The absolute position of the collision point is reconstructed by the CMS tracker. The length scale is given by the difference in nominal and measured position. To improve the precision of the measurement, two different methods are used: In a fixed separation scan, the beams are kept at one σ separation. A change in luminosity during the scan would indicate an instability in the measurement and at the separation of one σ the effect is most visible. In the variable separation scan a three point optimization is performed to ensure a precise position. The length scale is expected to be stable over a long time, as long as there is no change to the steering magnets. The scale corrections has been resulting in corrections between 0.5 and 1.6 % with an uncertainty of 0.2 to 0.8 %.

Consistency

During a vdM fill, several scans are performed, with many bunches being measured. The difference in the results from bunch to bunch, or scan to scan is used as an estimator of the quality of the result and each gives an uncertainty on the final result.

In addition, the consistency between different luminosity systems is checked. The calibration obtained in a vdM scan is most applicable to the fill in which the scan was performed since any effect leading to a change in the calibration, e.g., calibration transfer or time-dependent changes, are not present. The luminosity measured by each system should therefore be consistent. The differences in the measured luminosity during the vdM fill is used as an estimate of the precision of the calibration.

Background correction

Accounting for beam-induced background rates, corrections between 0 and 0.8 % with an uncertainty of 0.1 % are obtained.

INTEGRATION-RELATED EFFECTS

The vdM measurement corresponds to a calibration point at a specific point in time, luminosity, and bunch structure. A good luminosity system is capable of extrapolating to nominal beam conditions with minimal departure from the vdM calibration, although corrections need to be made to the detector response. Also, maintaining the vdM calibration over the year is challenging. After all corrections related to linearity and stability are implemented, the impact of these effects on the final luminosity is estimated by a cross-comparison between the available luminosity systems. One system is selected to be the reference system and a ratio is formed for the whole year. The average changes over one fill reflect the quality of the linearity, while the change over the year quantifies the stability. The impact on the integrated luminosity is calculated and used as the uncertainty in the cross-detector stability. Further details about the long-term stability can be found in Ref. [19].

SUMMARY OF SOURCES OF SYSTEMATIC UNCERTAINTY

The various corrections and uncertainties are summarized in Table 1 giving the range of corrections and associated uncertainty in the integrated luminosity. Table 2 shows separately for each year the uncertainty due to normalization effects and the integration-related uncertainties along with the total uncertainty. Various studies are ongoing to reduce the different uncertainties, promising an improved Run-2 result. Combining the different years for a full Run-2 luminosity result, a series of uncertainties can be treated as uncorrelated leading to a reduced total uncertainty.

SUMMARY

Much progress has been made in obtaining a precise luminosity measurement over the course of Run-2. Additional measurement systems are identified and improvements in the vdM calibration analysis are achieved. A separate linearity and stability determination method is developed using emittance scans. The efforts of applying all up-to-date analysis methods to each year and to further improve the total Run-2 uncertainty by studying the correlation of the year to year uncertainties are still ongoing.

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