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Precision luminosity measurement with proton-proton collisions at the CMS experiment in Run 2

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A precise luminosity measurement is critical to determine fundamental parameters of the standard model and to constrain or to discover beyond-the-standard-model phenomena at LHC. The luminosity determination at the LHC interaction point 5 with the CMS detector, using proton-proton collisions at 13 TeV during Run 2 of the LHC (2015–2018), is reported. The absolute luminosity scale is obtained with the Van der Meer method using beam-separation scans. The dominant sources of systematic uncertainty are related to the knowledge of the scale of the beam separation provided by LHC magnets and the nonfactorizability between the spatial components of the proton bunch density distributions in the transverse direction. When applying the Van der Meer calibration to the entire data-taking period, a substantial contribution to the total uncertainty in the integrated luminosity originates from the measurement of the detector linearity and stability. The reported integrated luminosity in 2016–2018 is among the most precise luminosity measurements at bunched-beam hadron colliders.

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1. Introduction

Luminosity $\mathcal{L}$ is a measure of the collision rate in a collider experiment, and relates the event rate $\mathrm{d}N/\mathrm{d}t$ of a process with its cross section σ:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mathcal{L} \cdot \sigma. \tag{1}$$

A precise knowledge of the integrated luminosity of a collision data set is a crucial requirement for precision cross section measurements.

In Run 2 (2015–2018) of the CERN LHC, the CMS experiment [1] employs a two-step strategy to measure the integrated luminosity of its collision data sets. First, the visible cross section σ_{vis} of the rate measurement with a luminosity detector is calibrated. Second, the rate measurement is integrated over the data-taking period and normalized with σ_{vis} to obtain the integrated luminosity.

In these proceedings, the methodology and dominant sources of systematic uncertainty are discussed. The presentation is based on the preliminary luminosity measurements for the proton-proton (pp) collision datasets recorded at $\sqrt{s} = 13$ TeV [2–5].

2. Luminosity detectors

Several subdetectors of the CMS experiment are employed for the luminosity measurement. The results presented here rely mainly on the offline measurements with the pixel cluster counting (PCC) method and with the forward hadron calorimeter, using the transverse energy sum (HFET) or the fraction of occupied towers (HFOC). A discussion of all luminosity detectors is presented in Ref. [6].

3. Calibration

The luminosity detectors are calibrated once per data-taking period in a special LHC fill by calculating σ_{vis} as:

$$\sigma_{\mathrm{vis}} = \frac{2\pi \Sigma_x \Sigma_y}{N_1 N_2 f_{\mathrm{LHC}}} \cdot R_0, \tag{2}$$

where Σ_x, Σ_y are the width and height of the transverse luminous region in which the collisions take place, N_1, N_2 are the numbers of protons per beam, f_{LHC} is the revolution frequency, and R_0 is the measured rate for head-on beam collisions.

The width and height of the luminous region are measured with the Van der Meer (VdM) method [7] from beam separation scans where the two proton beams are separated in the transverse plane and then moved in steps across each other. From a fit to the measured rate as a function of the beam separation during a VdM scan in the horizontal (vertical) plane, Σ_x (Σ_y) is obtained as the width of the fitted Gaussian function. At the CMS experiment, single- and double-Gaussian functions are used in the fit of the VdM scan data. Background contributions to the measured rate are either subtracted before the fit as measured from noncolliding, unpaired bunches or from periods during which the beams were kept at a large distance, or determined in the fit as a constant term added to the fit function. An example fit result is shown in Fig. 1.

PoS(ICHEP2020)748

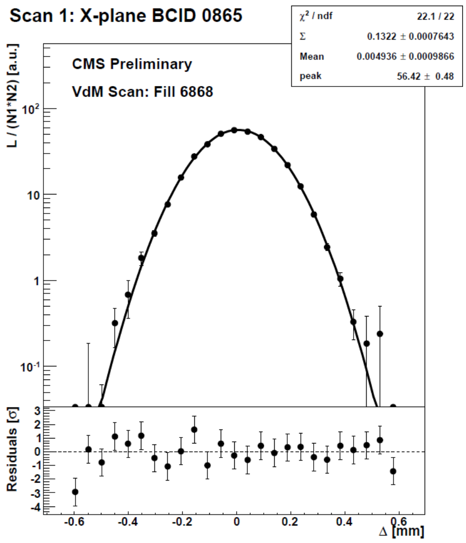

Figure 1: Single-Gaussian fit to the measured PCC rate normalized by the beam currents and with background contributions subtracted as a function of the corrected beam separation, for a horizontal VdM scan from the 2018 calibration. [5]

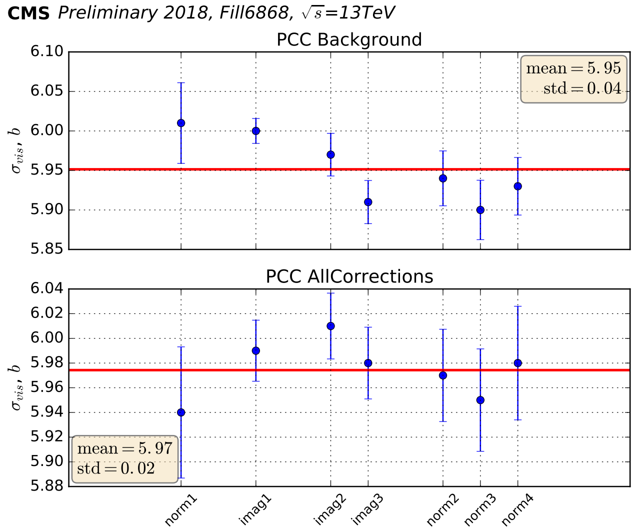

Figure 2: Visible cross sections derived for all VdM scan pairs from the 2018 calibration with only background subtraction (upper panel) and all corrections applied (lower panel). The agreement between the different scan pairs improves after the application of corrections. [5]

The beam separation in the fit is obtained from the current settings of the LHC steering magnets (nominal separation), and is subject to several effects analyzed separately. The absolute beam separation scale is calibrated with length scale scans by comparing nominal beam positions with the measured position of reconstructed interaction vertices with the CMS tracker. A time-dependent movement of the proton beams away from their nominal orbit (orbit drift) is monitored with LHC beam position monitors and corrected for in the fit.

Electromagnetic interactions between the beams are described with two beam-beam effects: The beam separation is increased for transversely separated beams due to electric repulsion, and the size of this deflection depends on the nominal separation [8]. The transverse shape of the proton beam changes due to focusing and defocusing (dynamic β^* effect), resulting in a separation-dependent increase of the collision rate. The impact of beam-beam effects on the beam separation and rate is calculated and corrected for in the fit. The prescription for the calculation of the dynamic β^* effect is currently under re-evaluation by a taskforce involving all LHC experiments.

Several VdM scan pairs are performed during a calibration, and the level of agreement of calibrations derived from different scan pairs, at different bunch crossing, and using different detectors is used to evaluate the systematic uncertainty of the VdM calibration. An example of the consistency between different scan pairs is shown in Fig. 2.

The proton numbers of the beams are taken into account in the VdM fit by normalizing the measured rate with the beam currents as measured with LHC devices and corrected for contributions from spurious charges.

In Eq. (2), the transverse area of the luminous region is calculated as $2\pi\Sigma_x\Sigma_y$. However, if the transverse proton densities of the beams do not factorize into horizontal and vertical components,

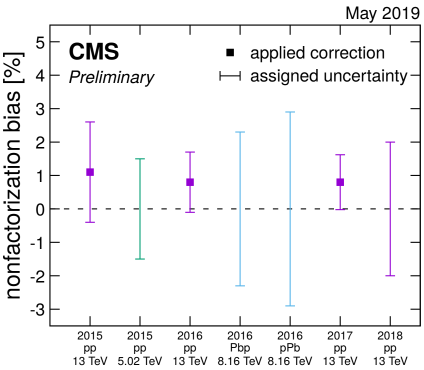

Figure 3: Factorization bias evaluated for the Run 2 data sets. [12]

Uncertainty sources [%]	2015	2016	2017	2018
Beam current	0.4	0.5	0.3	0.2
VdM fit & consistency		0.3	1.1	0.5
Length scale	0.5	0.8	0.3	0.2
Orbit drift	0.4	0.4	0.2	0.1
Beam-beam effects	0.6	0.6	0.6	0.2
Factorization bias	1.5	0.9	0.8	2.0
Total calibration	1.8	1.5	1.6	2.1

Table 1: Sources of uncertainty in the luminosity calibration of the pp collision data sets at $\sqrt{s}$ = 13 TeV. [2–5]

this assumption does not hold and introduces a bias in the luminosity calibration. At the CMS experiment, the beam-imaging method [9, 10] is applied to estimate the factorization bias and to apply a correction to σ_{vis}. In the beam-imaging method, the full transverse proton densities are reconstructed from reconstructed interaction vertices measured during a set of special beam separation scans. The method and its application as well as complementary methods that are currently being investigated by the CMS experiment are discussed in Ref. [11], and the results are shown in Fig. 3.

The sources of systematic uncertainty in the calibration of the luminosity measurement are summarized in Table 1. The total calibration uncertainty ranges between 1.5% and 2.1% per year, where the largest contribution is from the factorization bias in 2015, 2016, and 2018, and from the VdM scan fit and consistency in 2017.

4. Integration

The rate measurement of the luminosity detectors is integrated over the data-taking periods, and normalized with the calibrated σ_{vis} to obtain a measurement of the integrated luminosity for the data set. Uncertainties in the integration arise due to the extrapolation of the calibration from the special conditions of the LHC fill in which the calibration took place to regular data-taking conditions (linearity), and due to changes in the detector conditions over time (stability). Corrections for nonlinearity and instability are derived separately for each detector. A powerful tool for this are emittance scans which are short VdM-like beam separation scans performed at the start and end of fills in 2017 & 2018 at the CMS experiment and allow to monitor changes in detector efficiency. Residual nonlinearity and instability are then evaluated with cross-detector comparisons.

Out-of-time pileup, e.g. spurious signals originating from the activation of detector material after collisions, has no impact on the VdM calibration due to the large spacing of proton bunches in the calibration fills. For regular data-taking conditions, however, out-of-time pileup causes a nonlinear detector response. Linearity corrections are determined from the measured rate in nominally empty bunch crossings, and using the dependence of the efficiency determined with emittance scans at different levels of instantaneous luminosity. Cross-detector comparisons are used to evaluate residual nonlinearity, as shown in Fig. 4, and to estimate the systematic uncertainty.

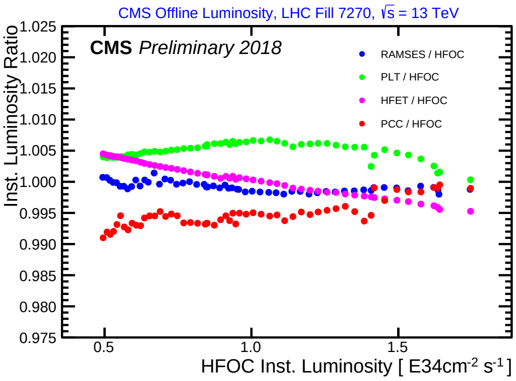

Figure 4: Ratio of luminosity measured by different detectors as a function of instantaneous luminosity for one LHC fill in 2018. The slopes of the ratios indicate the relative nonlinearity between the detectors. [13]

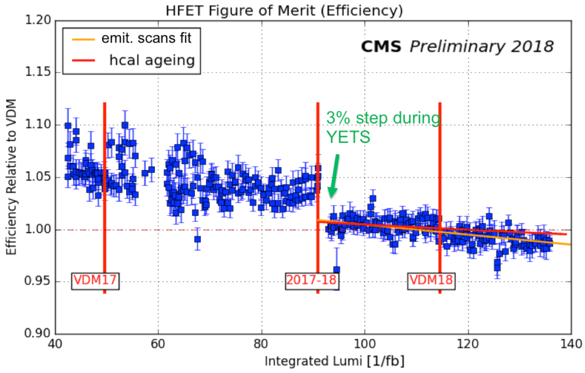

Figure 5: Relative efficiency of the HFET detector response as determined from emittance scans as a function of integrated luminosity for all LHC fills in 2017 and 2018. The slope indicates the instability. [14]

		2015	**2016**	**2017**	**2018**	**2015–2018**	**2016–2018**
Recorded luminosity	[fb^{-1}]	2.3	35.9	41.5	59.7	139	137
Total uncertainty	[%]	2.3	2.5	2.3	2.5	1.8	1.8
Calibration uncertainty	[%]	1.8	1.5	1.6	2.1		
Normalization uncertainty	[%]	1.5	2.0	1.7	1.3		

Table 2: Recorded integrated luminosity and its relative uncertainty for the proton-proton collision datasets at $\sqrt{s}$ = 13 TeV, also split into calibration and normalization uncertainty sources. [2–5]

An example of changing detector conditions over time is the gain loss from the aging of PMTs and fibers in the forward hadron calorimeter, leading to instabilities in the HFET and HFOC response. In Fig. 5, the efficiency of the HFET response as determined from emittance scans is shown for 2017 and 2018, showing a clear reduction of efficiency over time. After stability corrections have been applied to all detectors, residual instabilities are evaluated in cross-detector comparisons.

The total uncertainty in the integration of the luminosity due to linearity and stability ranges between 1.3% and 2.0% per year.

5. Summary

The integrated luminosity measurement of the CMS experiment is calibrated with the VdM method, using several systematic studies to improve the precision of the method, and corrected for nonlinearity and instability of the detector response. The recorded luminosity and its uncertainty for the pp collision data sets at $\sqrt{s}$ = 13 TeV are listed in Table 2.

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