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Luminosity measurement in proton-proton collisions at the CMS experiment

Oleksii Turkot* **(on behalf of the CMS Collaboration)**
DESY
E-mail: oleksii.turkot@cern.ch

Precision in the luminosity calibration is critical for determining fundamental parameters of the standard model and constraining or discovering beyond-the-standard-model processes at LHC. The luminosity determination at the LHC interaction point 5 with the CMS detector, using proton-proton collisions at 13 and 5.02 TeV during LHC Run 2 (2015–2018), is reported. The absolute luminosity scale is obtained using beam-separation ("van der Meer") 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 factorizability 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 linearity and stability of the CMS luminosity detectors.

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*Speaker.

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1. Luminosity detectors at CMS

During the LHC Run 2 period, up to eight systems were used to monitor and measure luminosity at CMS. These include two dedicated luminosity measurement systems: the Pixel Luminosity Telescope (PLT), consisting of eight three-layer telescopes, located at 1.8 m from the interaction point in both directions, and the Fast Beam Conditions Monitor (BCM1F), silicon and diamond sensors with 6.25 ns time resolution mounted on the same carriages as PLT. Another luminosity detector that provides online luminosity for each bunch crossing uses a dedicated readout system installed in the forward hadron calorimeter (HF). HF measures luminosity with two algorithms—one based on the fraction of occupied towers (HFOC), and the other on the sum of the transverse energy E_T (HFET). The silicon pixel and strip tracker is used in pixel cluster counting (PCC) and vertex counting (VTX) methods. The PCC is used for offline luminosity determination, while the VTX method is used for cross checks in low-pileup conditions. The rate of the muon track stubs in the muon barrel track finder and the rate of photons in ionization chambers are measured from the barrel drift tubes (DT) and the CERN radiation and environmental monitoring system (RAMSES), respectively. Both DT and RAMSES are not sensitive to bunch-by-bunch measurements and their rates are cross-calibrated in special scans (see Section 2), providing stable luminosity measurements during the data-taking periods.

2. Luminosity calibration, stability, and linearity

Each detector measures a rate as a function of time, $R(t)$. This rate is proportional to the instantaneous luminosity $\mathcal{L}(t)$ with a proportionality constant σ_{vis}:

$$R(t) = \sigma_{\text{vis}}\mathcal{L}(t) \ . \tag{2.1}$$

As described, e.g., in Refs. [1, 2, 3], σ_{vis} can be accurately calibrated in dedicated scans with the van der Meer (vdM) technique under the assumption of factorizability of the beam shape in the transverse plane. The assumption of factorizability of the proton bunch density in x and y is tested, leading to a fill-dependent correction. Other corrections applied to σ_{vis} are due to the beam-separation length scale, beam-beam interaction effects, normalization of the measured beam currents, drifts in the position of the LHC orbit, spurious charges in nominally empty bunch slots ("ghost" charges) or RF buckets adjacent to the colliding bunches ("satellite" charges), and detector background. Additional sources of systematic uncertainty are assigned due to variations of the derived visible cross sections ("scan-to-scan" and "bunch-to-bunch"), as well as the difference in the integrated luminosity ("cross-detector consistency") for the nonscanning periods in vdM fills with zero beam separation at CMS.

After determining σ_{vis}, the luminosity can be evaluated in the regular physics fills for all data-taking periods. Most of the detector measurements include out-of-time contributions that arise from the electronic spillover or material activation. The luminosity detectors exhibit nonlinear response to the instantaneous luminosity, and corresponding corrections are derived. The PCC method, chosen as a main luminosity measurement method in 2016 [1], exhibits dynamic inefficiency and layer-dependent ("internal") stability. In later years these effects are included in the overall stability systematic uncertainty. After applying all corrections the overall consistency of the

	Source	Uncertainty (%)		
		2016 [1]	2017 [2]	2018 [3]
Normalization	x-y nonfactorization	0.9	0.8	2.0
	Length scale	0.8	0.3	0.2
	Beam-beam effects	$0.4 \oplus 0.5$	$0.4 \oplus 0.5$	0.2
	Beam current normalization	0.3	0.3	0.2
	Orbit drift	0.4	0.2	0.1
	Ghost and satellite charges	0.4	0.1	0.1
	Background subtraction	–	< 0.1	0.1
	Scan-to-scan variation	–	0.9	0.3
	Bunch-to-bunch variation	0.3	0.1	0.1
	Cross-detector consistency	–	0.6	0.5
Integration	Cross-detector stability	1.5	0.5	0.6
	Linearity	0.6	1.5	1.1
	Out-of-time effects	$0.7 \oplus 0.5$	$0.2 \oplus 0.3$	$0.1 \oplus 0.4$
	Internal stability	0.5	–	–
	Dynamic inefficiency	0.3	–	–
	CMS deadtime	0.5	0.5	< 0.1
	Total uncertainty	2.5	2.3	2.5

Table 1: Summary of the sources of systematic uncertainty in the CMS luminosity measurements using pp collisions at $\sqrt{s} = 13$ TeV collected in 2016, 2017, and 2018.

measurements by the individual luminosity detectors with respect to each other is evaluated, and the "cross-detector stability" uncertainty is assigned. In addition, the uncertainty associated with the deadtime of the CMS data acquisition system is included.

3. Summary of sources of systematic uncertainty

The sources of systematic uncertainty in the luminosity calibration due to the vdM scan procedure ("normalization") and the detector operations ("integration") over the course of data-taking periods in 2016, 2017, and 2018 are summarized in Table 1.

References

[1] CMS Collaboration, *CMS Luminosity Measurements for the 2016 Data Taking Period*, CMS-PAS-LUM-17-001 (2017)

[2] CMS Collaboration, *CMS luminosity measurement for the 2017 data-taking period at* $\sqrt{s} = 13$ TeV, CMS-PAS-LUM-17-004 (2018)

[3] CMS Collaboration, *CMS luminosity measurement for the 2018 data-taking period at* $\sqrt{s} = 13$ TeV, CMS-PAS-LUM-18-002 (2019)