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Luminosity measurements for heavy ion and proton-proton collisions at 5.02 TeV at the CMS experiment in Run 2

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Cross section measurements for heavy-ion collision processes require a precise estimate of the integrated luminosity of the recorded data set. During the 2015 - 2018 data-taking period ("Run 2") of the LHC, lead-lead, proton-lead, and proton-proton collisions at the reference energy of 5.02 TeV per nucleon pair were recorded with the CMS experiment. For these data sets, the luminosity measurements are reported. The absolute luminosity scale is calibrated with beam-separation ("van der Meer") scans, performed separately for each collision system. Several sources of systematic bias are studied and corrected for in the analysis of the van der Meer scan data to improve the precision of the luminosity measurement. When applying the calibrations to the entire data-taking period, a substantial contribution to the total uncertainty in the integrated luminosity originates from the measurement of the detector stability. A total systematic uncertainty of 1.5% has been reached for the PbPb data recorded in 2018.

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1 Introduction

Luminosity measurement at the LHC assumes that the observed rates of the interactions between initial-state particles are linear with luminosity. The rate of physical observables is measured by dedicated detectors, called luminometers. For absolute luminosity measurement, the detectors are calibrated using the Van der Meer (VdM) method. The calibration constant is referred to as the visible cross section, σ_{vis}. These proceedings give a review of the systematic uncertainties affecting the VdM calibration and the integration of the luminosity over the physics data-taking periods.

2 Van der Meer method

Each luminometer — with close to linear response — measures the rate of some observable, such as hits, energy clusters, tracks, energy sum, etc.:

$$R_{\mathrm{obs}} = \frac{dN_{\mathrm{obs}}}{dt} = L \cdot \sigma_{\mathrm{vis}}.$$

The visible cross section is specific to the luminometer and counting method and is determined in special conditions. The measured rate $R(t)$ at data taking for high energy physics should then be proportional to the instantaneous luminosity $L(t)$ according to the following relation:

$$L(t) = \frac{R(t)}{\sigma_{\mathrm{vis}}}.$$

With the Van der Meer method [4], σ_{vis} is determined in a dedicated fill separately for each type of physics data. In the case of PbPb calibration, the beam parameters are set as in physics data taking, with small bunch sizes. During VdM scans, the two beams are separated in the transverse direction in several steps to determine the beam overlap widths (Σ_x and Σ_y) by fitting the measured rates as a function of the beam separation in *x* and *y* planes. The main assumption of the method is that the bunch particle densities are factorizable into independent *x* and *y* terms. The bunch-by-bunch luminosity is thus determined directly from machine parameters, which then leads to the measured value of

$$\sigma_{\mathrm{vis}} = \frac{2\pi \cdot \Sigma_x \cdot \Sigma_y}{N_1 \cdot N_2 \cdot f} \cdot R_{\mathrm{peak}},$$

where N_1, N_2 are the numbers of protons (ions) in the colliding bunches, f is the orbit frequency and R_{peak} is the rate measured at zero transverse beam separation.

3 Luminometers at CMS

In the CMS experiment [1] there were five online luminometers [2]; the forward hadron (HF) calorimeter provides transverse energy sum (HFET) and occupancy, i.e., hit counting (HFOC) measurements, the Pixel Luminosity Telescope (PLT) counts three-fold coincidences [3], the Beam Condition Monitor (BCM1F) counts hits on pad sensors, and the muon drift tubes (DT) provides trigger primitive (stub) counts. Besides them, there are also offline luminometers such as the pixel tracker with pixel cluster counting (PCC), with RAMSES giving the ambient dose equivalent rate measurement close to the HF [2].

4 Corrections to σ_{vis}

There are several sources of systematic bias which can be grouped into two categories: *normalization uncertainties*, which affect the absolute luminosity calibration derived by the VdM method; and *integration uncertainties* (discussed in the next section) coming from the detector operation instabilities over the year.

The background contribution to the luminometer rates is determined either by super-separation scans or using empty bunch crossings, the former meaning that the beams are separated by $6\sigma_{\mathrm{beam}}$ distance both in x and y resulting effectively in no collisions. There are multiple sources of background: intrinsic detector noise, beam-inducted background (BIB) or material activation and late-arriving-particles ("afterglow") [5].

Beam-beam effects due to electromagnetic interactions between the charged particle bunches lead to beam-beam deflection and incoherent optical distortion of the bunch shapes (Figure 1).

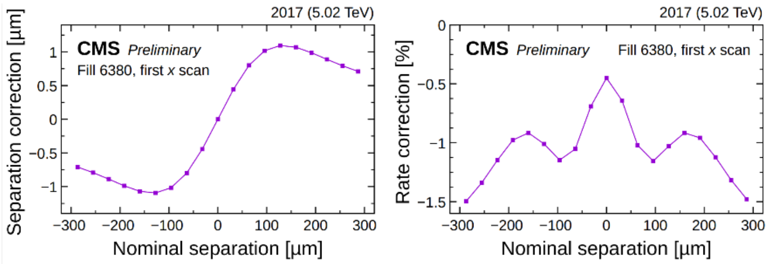

Figure 1: Correction to the beam separation due to beam-beam deflection (left) and to the rate from incoherent beam-beam effect causing a distortion of the bunch shapes (right) for pp collisions. [4]

Orbit drift corrections account for the time-dependence of the transverse beam positions. It can be measured by two types of beam position monitors (BPMs): the DOROS and arc BPM (Figure 2) systems.

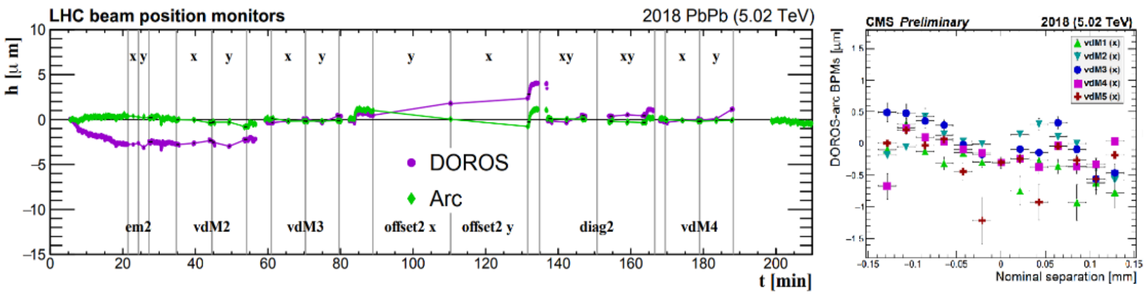

Figure 2: Difference of the horizontal and vertical beam positions with respect to the nominal position at head-on collisions in PbPb data (where the time axis is divided in intervals corresponding to scans, and the scans are grouped into pairs; em, vdM, offset and diag) before, in the middle, and after each scan as measured by the DOROS and arc BPMs (left). The absolute difference in the displacement of the two beams as measured by the DOROS and arc BPMs as a function of the nominal beam separation (right). [5]

Length-scale calibration compares the nominal positions determined from the magnet currents to the luminous region positions as measured by the CMS tracker in case of PbPb collisions (Figure 3).

Bunch current normalization adjusts the measured rates by the number of charged particles in the colliding bunches, and there is also a correction for the "ghost" and "satellite" charges, which are found outside the colliding bunch pairs and the nominally filled buckets [5].

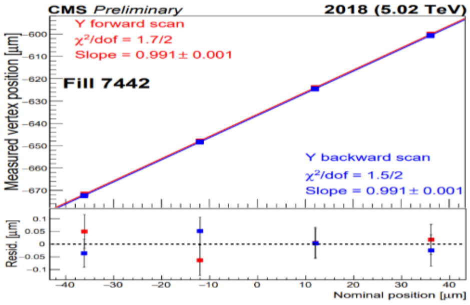

Figure 3: The mean reconstructed vertex positions as a function of the nominal position, moving the beams in the forward and backward y directions. The slopes provide the applicable length scale calibration. [5]

The transverse factorizability of the bunch proton density profiles is the main assumption of the VdM method. For this correction in PbPb collisions, we use special scans: offset scans where there is a fixed separation in the non-scanning direction, and diagonal scans with equal separation in x and y directions. These sample the tails of the distribution and thus enable the determination of the non-factorisation between x and y coordinates in the bunch density function. To estimate the size of the bias, different two 2D analytic functions are fit to the measured rates (Figure 4).

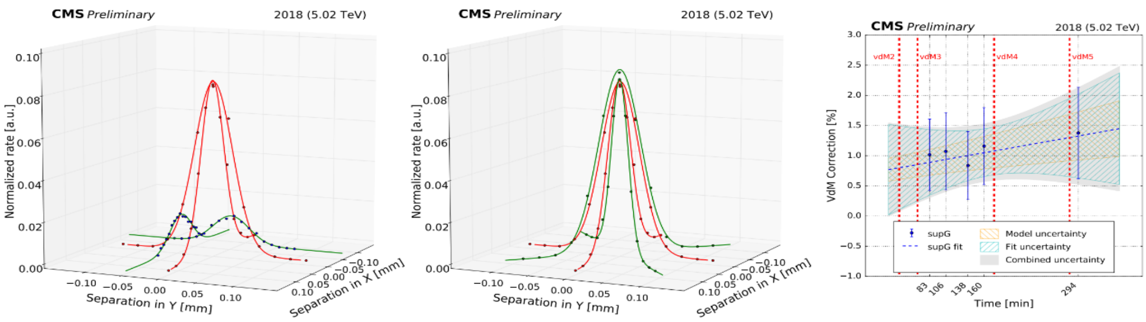

Figure 4: The normalized collision rate as a function of the corrected beam separations in x and y for vdM+offset (left) and vdM+diagonal (middle) scan combinations, and the calculated correction as a function of time during the fill for all studied vdM+offset scan combinations (right) for PbPb data. [5]

5 Cross-detector consistency and stability

Integration uncertainties come from the detector operation instabilities over the year, and arise as luminometers age due to the high radiation and their operating conditions change during the data-taking period. Integration uncertainties result in efficiency changes in the measurements, which can be monitored with short VdM-like scans during physics fills called *emittance scans*, taken regularly at the beginning and at the end of the fills. The relative change in the σ_{vis} can be used to monitor and correct as necessary the luminometers responses.

After applying the corrections described above the measured luminosities from different luminometers can be compared to each other to estimate the cross-detector stability. [5]

6 Summary

In Table 1, the 2018 PbPb and 2017 pp luminosity determination uncertainties are presented at 5.02 TeV. The total uncertainty for PbPb is 1.5% [5] and for pp 1.9% [4].

For the 2018 PbPb collisions, the uncertainty is dominated by contributions from transverse factorizability and cross-detector stability.

The 2017 pp uncertainty is dominated by contributions from the residual orbit drift, the length-scale calibration, and the transverse factorizability measurement, as well as the correction for the effect of the electromagnetic interactions between the colliding proton bunches.

Luminosity measurements are also available for pPb/Pbp data in 2017 [6] and pp at 5 TeV in 2015 [7].

Source	**PbPb [5]**		**pp [4]**
	Correction [%]	**Uncertainty [%]**	**Uncertainty [%]**
Normalization		**1.3**	**1.9**
Beam current calibration	-	0.2	0.2
Ghost and satellite charge	+3.9	0.5	
Linear orbit drift	-0.1	0.1	0.3
Residual orbit distortion	-	0.2	1.0
Length-scale calibration	-1.5	0.5	0.8
Transverse factorizability	+1.0	0.8	0.8
Beam-beam effects	-	0.3	0.8
Scan-to-scan variation	-	0.5	0.4
Bunch-by-bunch variation	-	<0.1	0.4
Cross detector consistency	-	0.4	0.4
Noncollision rate	-0.6	0.2	negligible
Statistical uncertainty	-	0.1	< 0.1
Integration		**0.8**	**0.2**
Out-of-time corrections		0.1	<0.1
Cross detector stability	-	0.8	0.1
Cross detector linearity		negligible	<0.1
CMS deadtime	-	negligible	<0.1
Total	**-**	**1.5**	**1.9**

1. Table Summary of the sources of systematic uncertainty in the CMS luminosity measurement for PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in 2018 [5], and for proton-proton collisions at 5.02 TeV in 2017 [4].

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