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

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Introduction to luminosity

- Luminosity relates the cross section of a process to the event rate

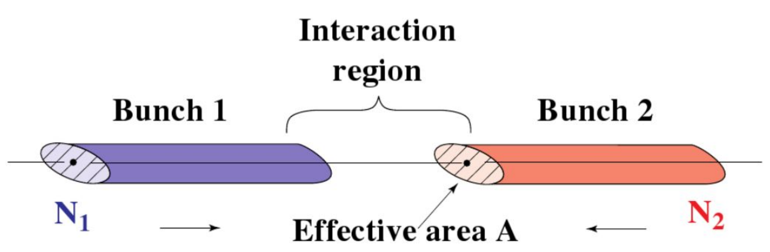
$$R_{proc} = \frac{dN_{proc}}{dt} = L \cdot \sigma_{proc}$$

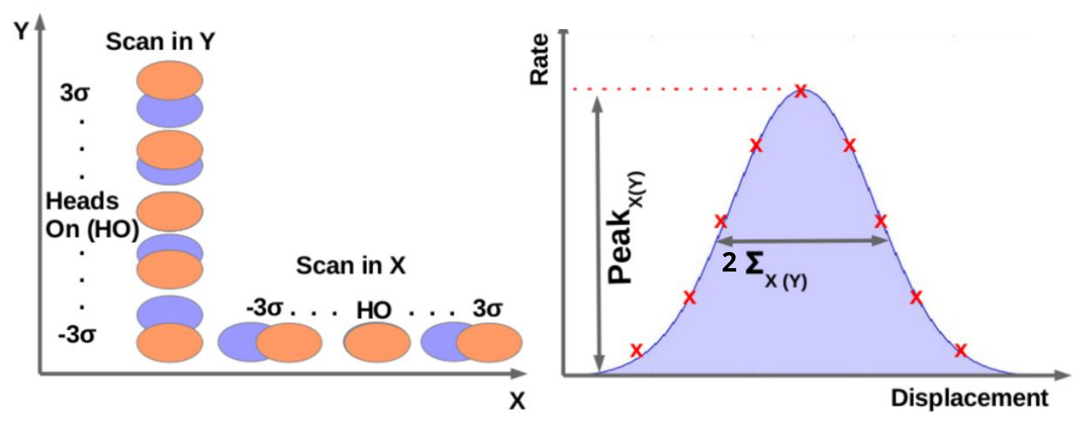
- Good understanding of luminosity precision is crucial to minimize systematic uncertainty on cross-section measurements
- To determine luminosity, the rate of a specific process with cross section σ_0 using a *luminometer* with a linear response is measured
- The *visible cross section* $\sigma_{vis} = \sigma_0 \cdot A \cdot \varepsilon$ of the luminometer, with A being the geometric acceptance and ε the efficiency to detect the signal process, provides the luminosity normalisation

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

Van der Meer (VdM) method

- The visible cross section for PbPb period is measured during dedicated fills with physics like adjustments
- During vdM scans, the two beams are separated in transverse direction in several steps



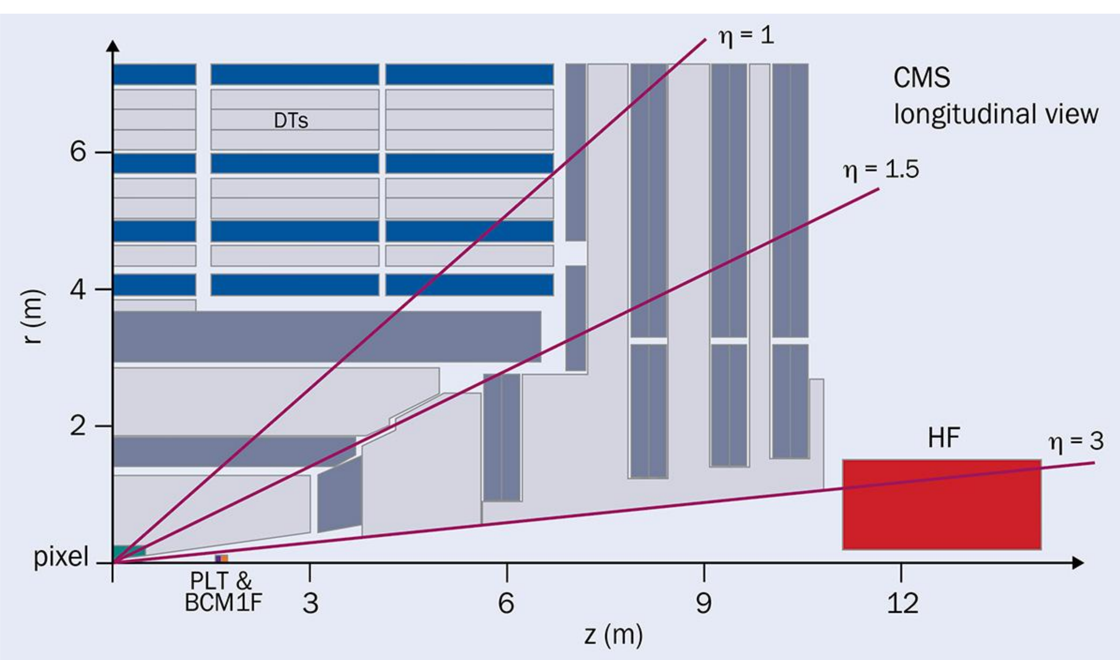


- The bunch proton density function is assumed to be factorizable into independent x and y terms
- The rate is measured as function of separation in x and y planes to determine the beam overlap widths Σ_x and Σ_y and the luminosity is determined directly from machine-related parameters

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

Luminometers in CMS

- **Hadronic Forward Calorimeter (HF)**: transverse energy sum (HFET) and occupancy, i.e., hit counting (HFOC) measurement
- **Pixel Luminosity Telescope (PLT)**: three-fold coincidence counting
- **Beam Condition Monitor (BCM1F)**: hit counting
- **Pixel Tracker**: cluster counting (PCC)
- **Muon Drift Tubes (DT)**: muon tracklet trigger primitive counting
- **RAMSES**: ambient dose equivalent rate measurement close to the HF



[1]

References

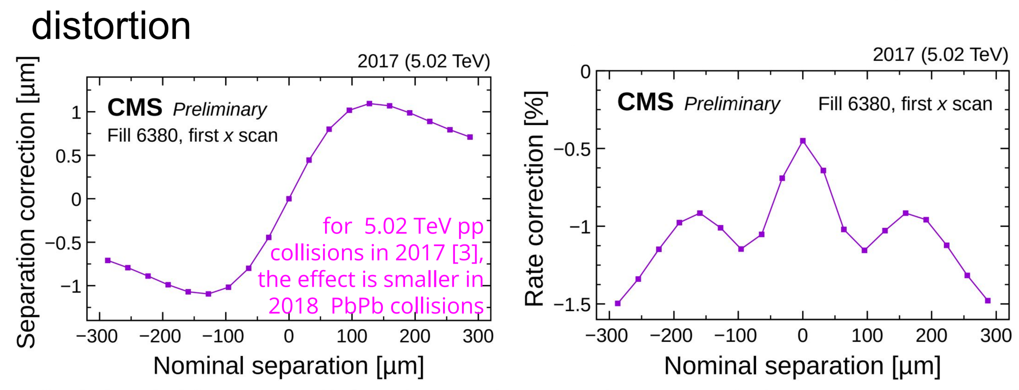
[1] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at √s = 13 TeV in 2015 and 2016 at CMS, CMS LUM-17-003, *Eur. Phys. J. C 81 (2021) 800*

[2] CMS Collaboration, CMS luminosity measurement using nucleus-nucleus collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in 2018, CMS PAS-LUM-18-001

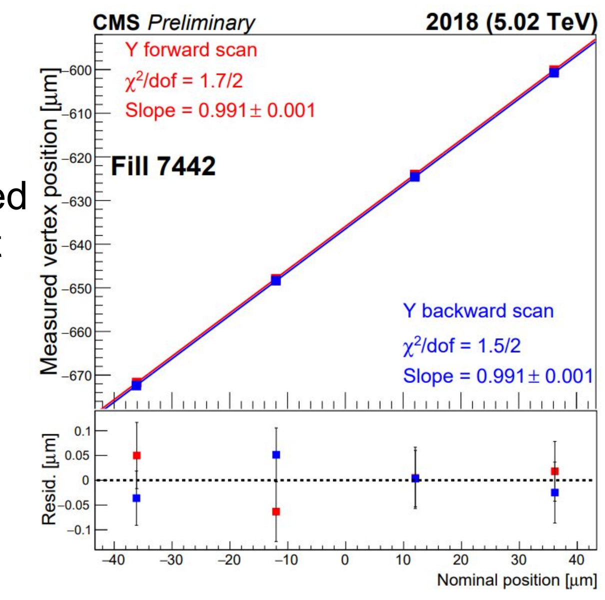
[3] CMS Collaboration, Luminosity measurement in proton - proton collisions at 5.02 TeV in 2017 at CMS, CMS PAS-LUM-19-001

Corrections to σ_{vis}

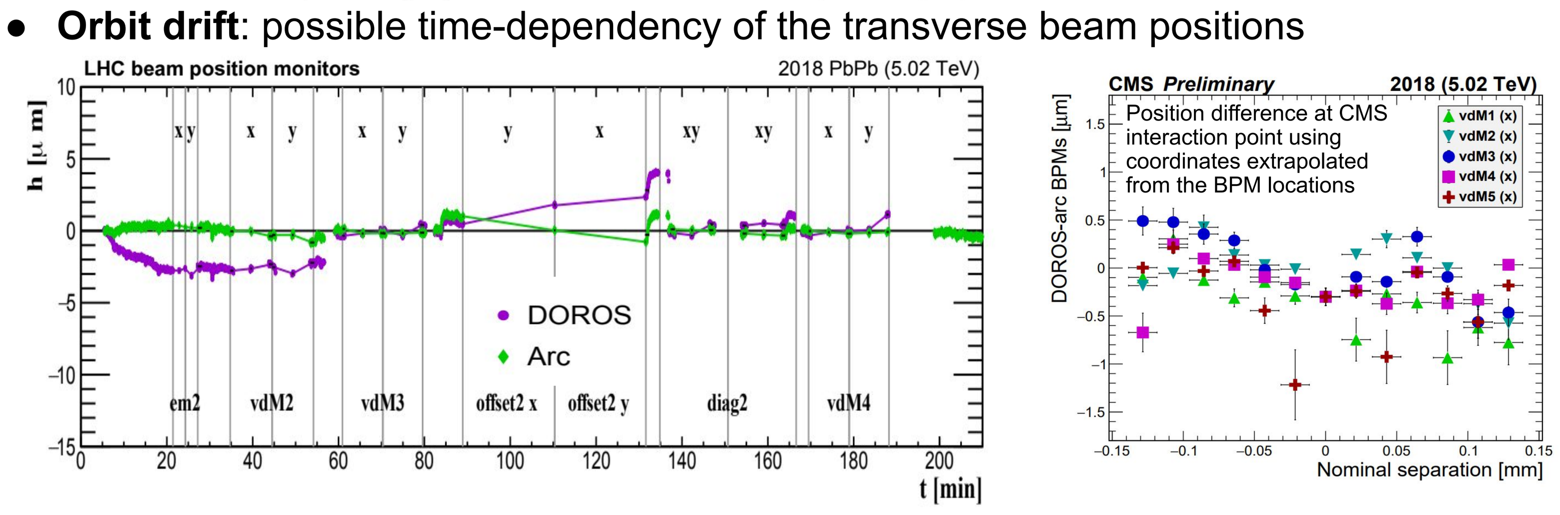
- **Background estimation**: intrinsic detector noise, beam-induced (BIB), material activation ("afterglow")
- **Beam-beam effects**: deflection and incoherent optical distortion



- **Length-scale calibration** of the nominal beam separations provided by the LHC magnet currents



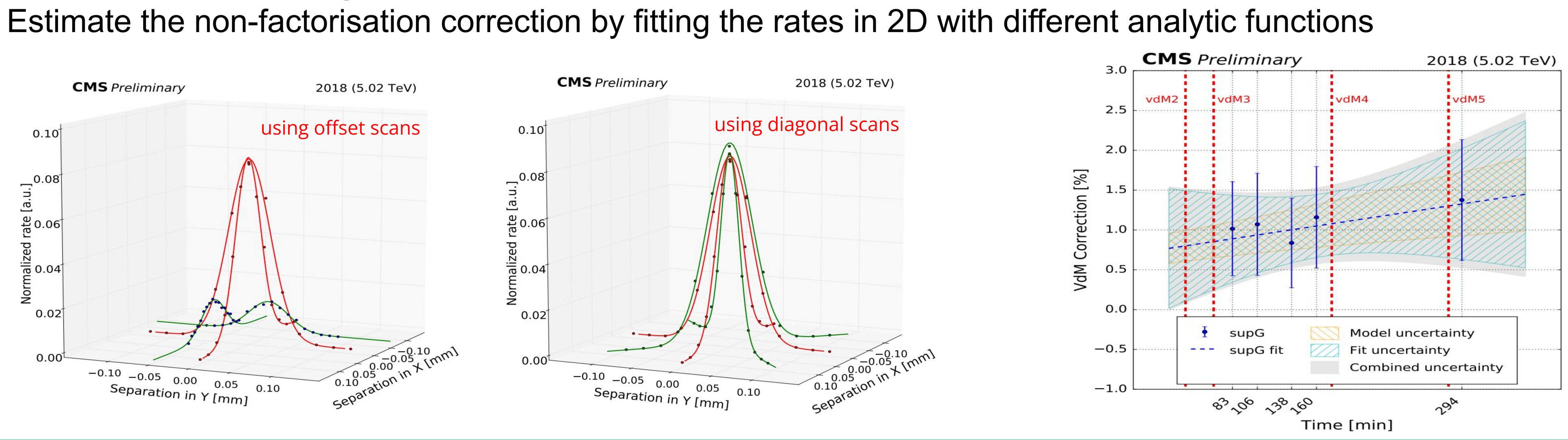
- **Orbit drift**: possible time-dependency of the transverse beam positions



- **Bunch current normalization** and correction of spurious "ghost" and "satellite" charges outside the colliding bunch pair and the nominally filled bucket

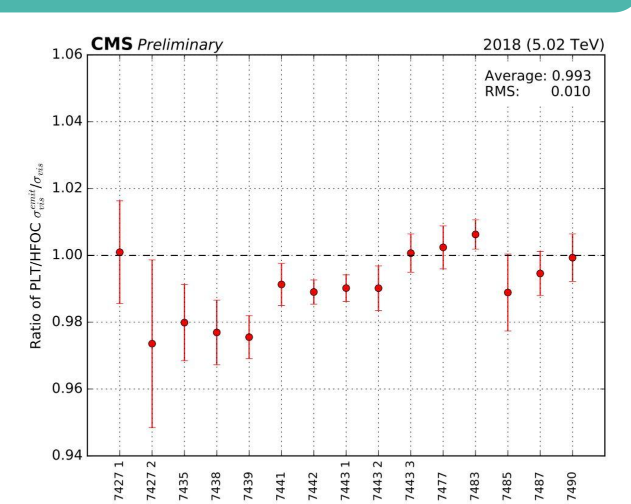
Transverse factorizability of bunch proton density profiles

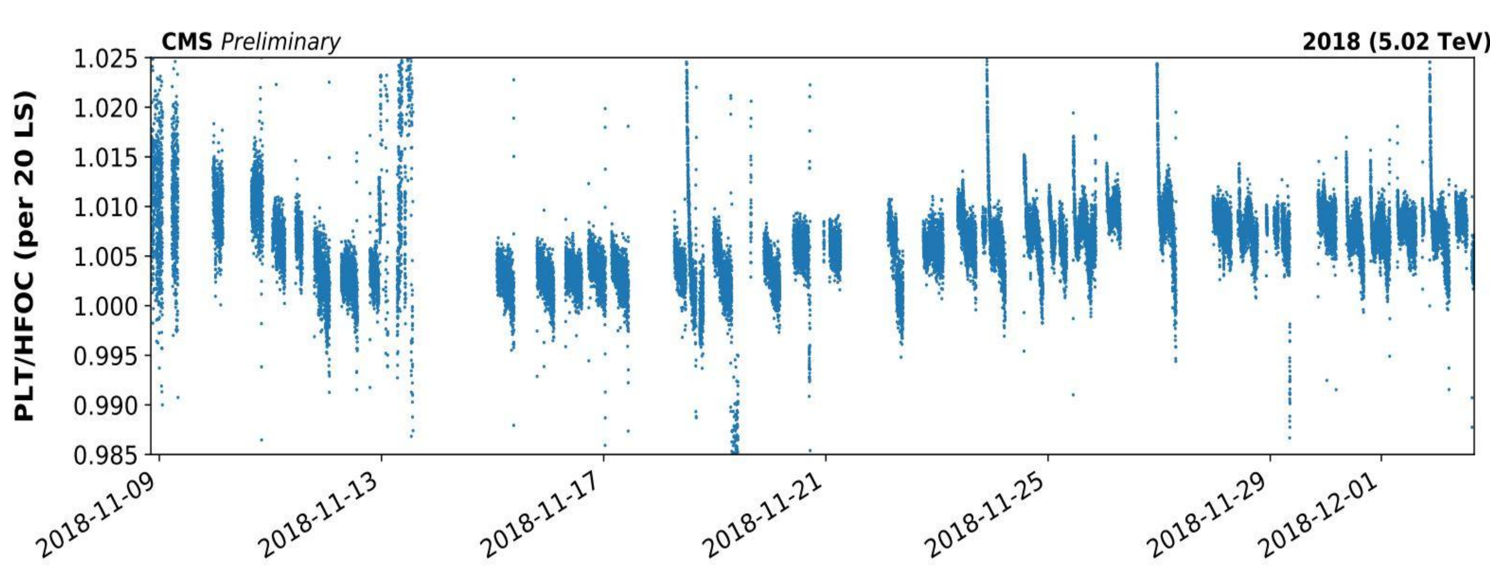
- In vdM scan method we assume that bunch density is factorizable in x and y
- **Special offset and diagonal scans**: to sample the tails of the distribution and determine the correlation
- Estimate the non-factorisation correction by fitting the rates in 2D with different analytic functions

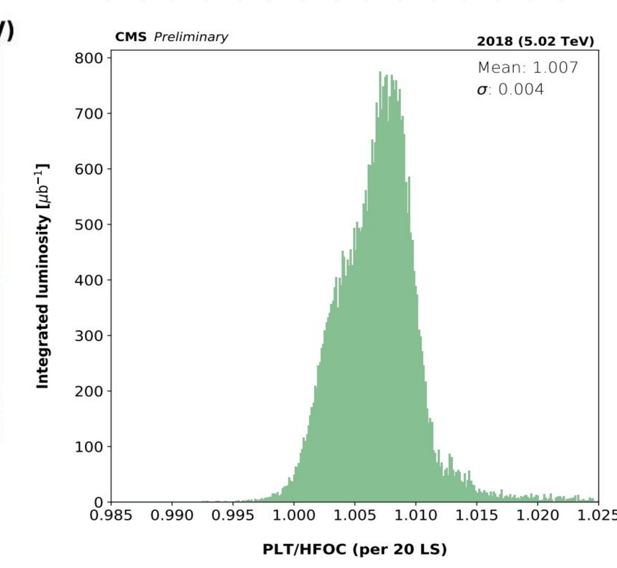


Cross-detector consistency and stability

- **Emittance scans**
  vdM-like scans at the beginning and end of fills during physics data taking to test the stability of luminometer response by performing relative measurements of σ_{vis}
- **Cross-detector stability**
  - Instantaneous luminosity from the different luminometers are compared as a function of time
  - Ratio of two luminometers weighted by luminosity histogrammed → stability







Luminosity uncertainty in 2018 for PbPb and pp collisions at 5.02 TeV

- Normalization uncertainties affect the absolute luminosity calibration derived by the vdM method
- Integration uncertainties come from detector operation instabilities over the year
- Total uncertainty 1.5% for PbPb in 2018 [2] and 1.9% for pp in 2017 [3] at 5.02 TeV
- 2017 pp uncertainty is dominated by contributions from the effect of the residual orbit drift, the length-scale calibration, transverse factorization measurement, the correction of the electromagnetic interactions between colliding proton bunches
- 2018 PbPb uncertainty is dominated by contributions from transverse factorization and cross detector stability

Source	PbPb [2]		pp [3]
	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 factorization	+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**