Precise luminosity determination at CMS

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Abstract

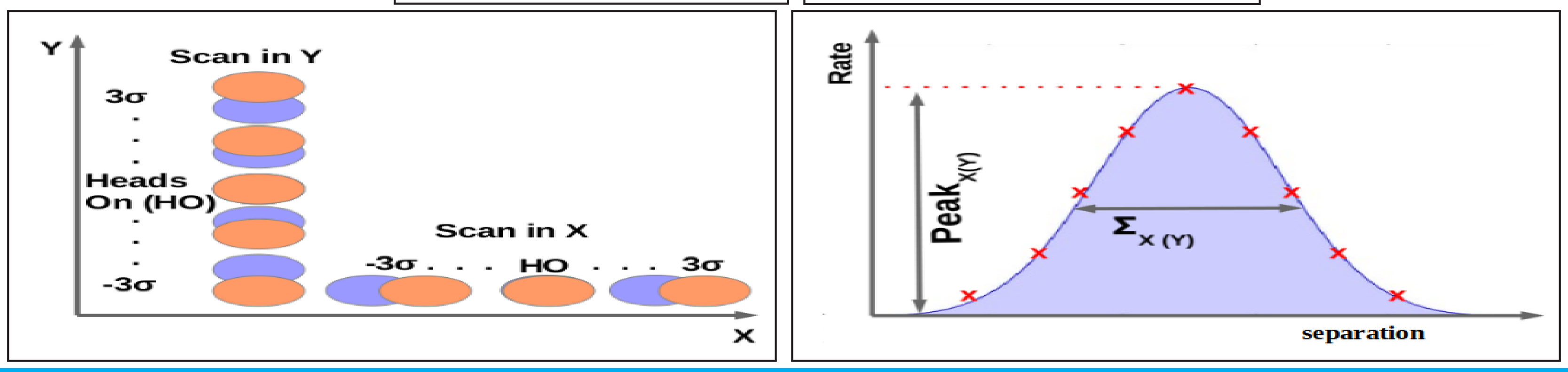
Precise luminosity calibration at bunched-beam hadron colliders like the Large Hadron Collider (LHC) is critical to determine fundamental parameters of the standard model and to discover or constrain beyond-the-standard-model phenomena. This poster shows the results of luminosity determination at LHC interaction point 5 with the Compact Muon Solenoid (CMS) detector, using proton-proton collisions in 2018. The leading sources of systematic uncertainty in the integrated luminosity measurement are shown.

The van der Meer (vdM) method

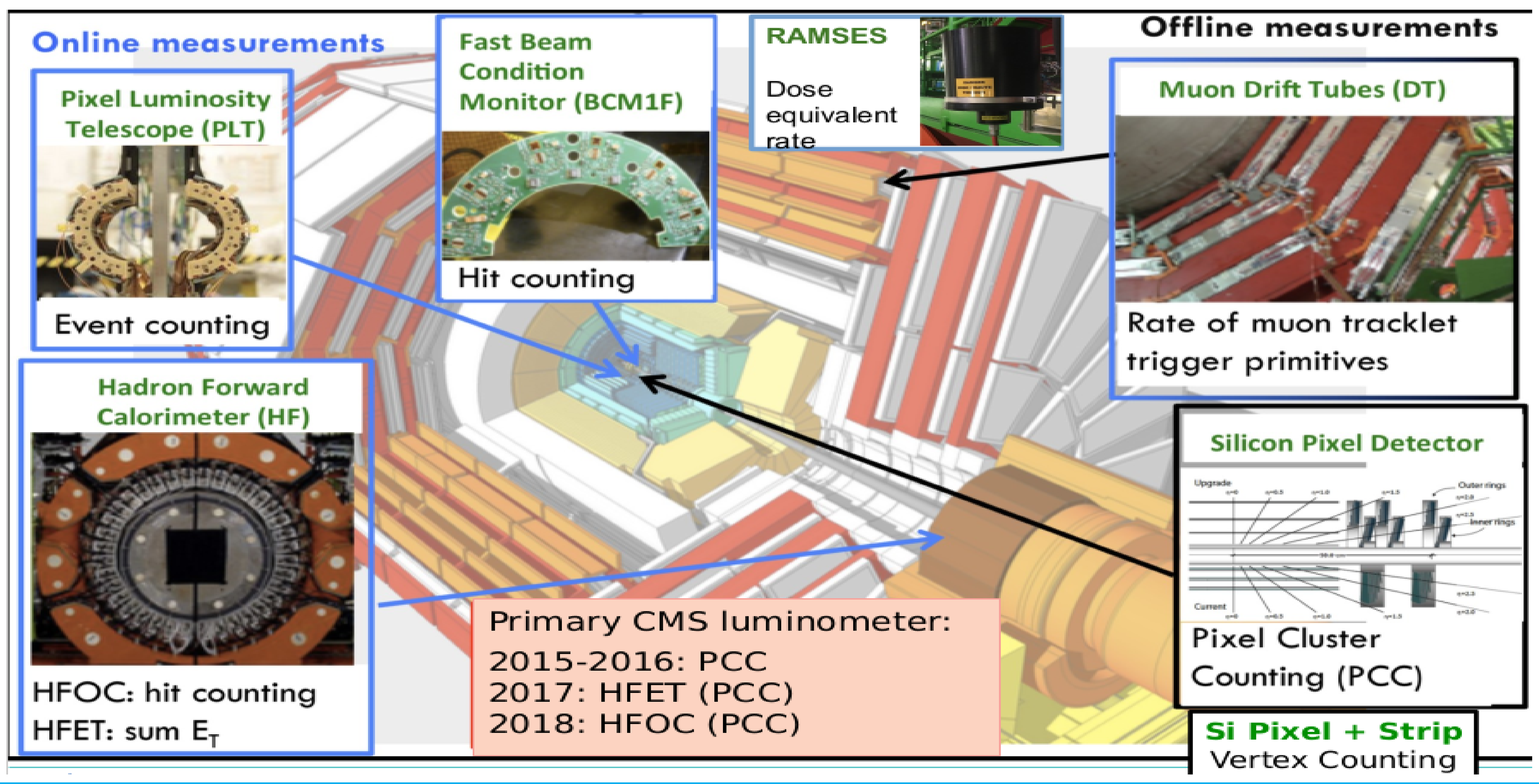
The rate R recorded by a luminosity detector ("luminometer") is measured as a function of beam separation in horizontal and vertical planes, x and y, in a fill with special beam conditions, and fitted with (typically) a Gaussian-like function to obtain the beam overlap widths Σ_x and Σ_y as well as R_{peak} at zero separation.

Assumming that the bunch proton density function is factorizable into independent x and y terms, the measured value of σ_{vis} is used during physics fills to calculate the per bunch instantaneous luminosity $\mathcal{L}(t)$:

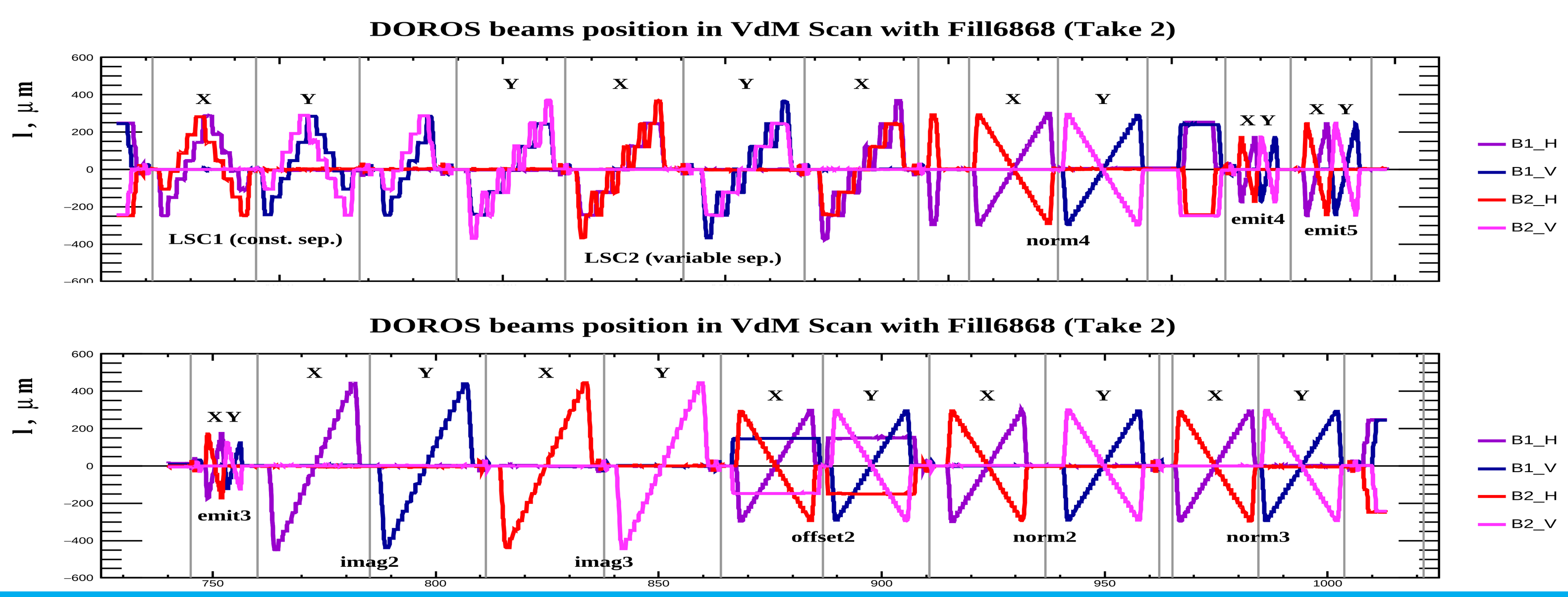
$$\mathcal{L}(t) = \frac{R_{detector}(t)}{\sigma_{vis}} \qquad \sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y}{N_1 N_2 f n}.R_{peak}$$



Luminometers at CMS



2018 proton-proton vdM fill



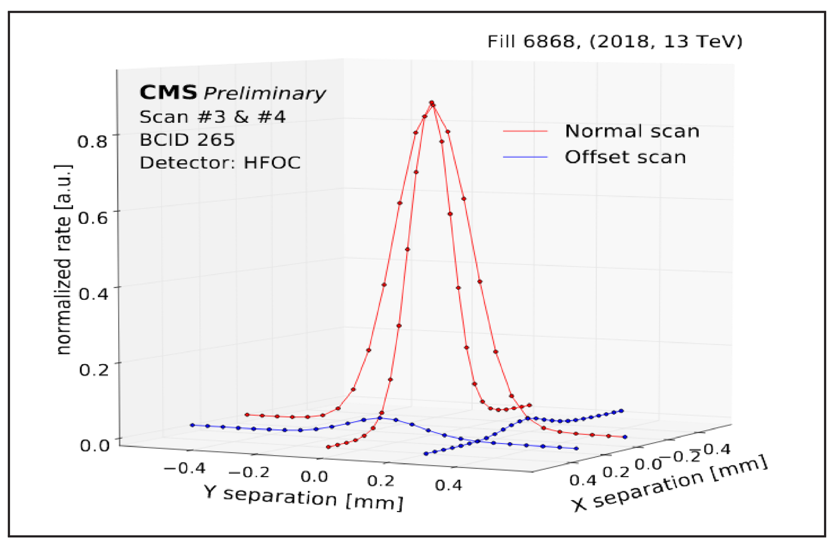
Bias from x-y factorization assumption

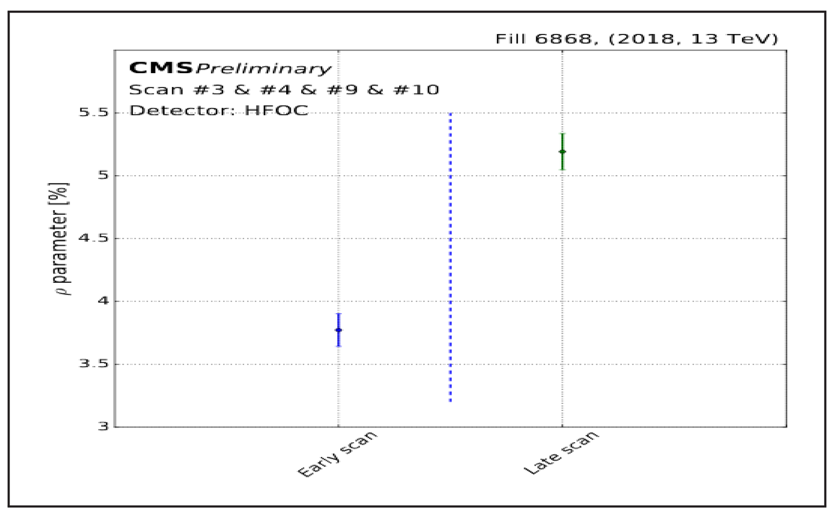
The assumption that the bunch proton density function is factorizable into independent x and y terms can lead to a biased estimate of the beam overlap integral. This effect is measured using two methods.

Beam-imaging scan: One beam kept fixed at nominal position and its shape scanned by the other beam in 19 steps from $+4.5\sigma_b$ to $-4.5\sigma_b$ separation. The reconstructed vertex positions are fitted to derive the two-dimensional (2D) proton density function for both beams.

Offset scan: A vdM scan where the two beams are separated by $\pm$ 1.5 σ_b in the nonscanning direction to sample the tails of the beam overlap integral.

Pairs of x and y vdM and offset scans taken right after each other are fit simultaneously to determine the 2D beam overlap integral with various functional forms manifesting correlation to measure directly σ_{vis}. The bias from the factorization assumption is then derived by comparision to the standard vdM results.





x-y correlation is found to increase during the fill. The derived correction is small compared to the assigned conservative uncertainty of 2% , as estimated from the "beam-imaging" scans.

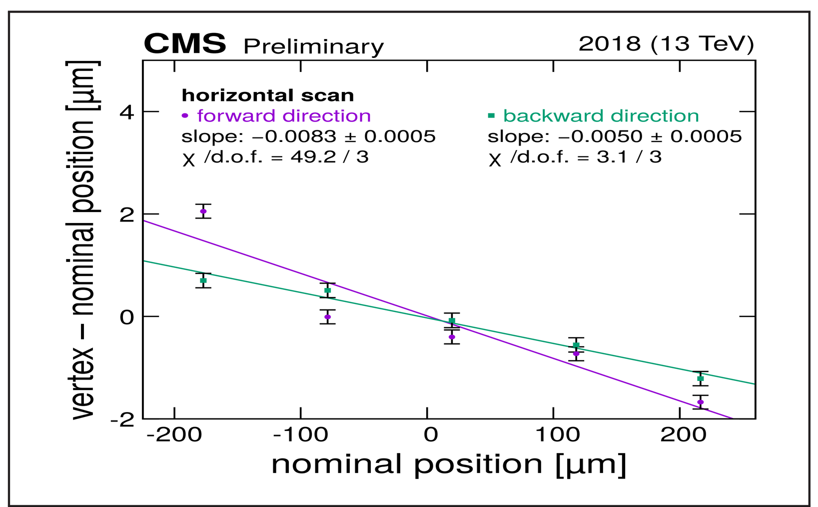
Length scale calibration

To correct possible differences between the actual and nominal beam separations during the scans. The calibration constant is measured using two different methods:

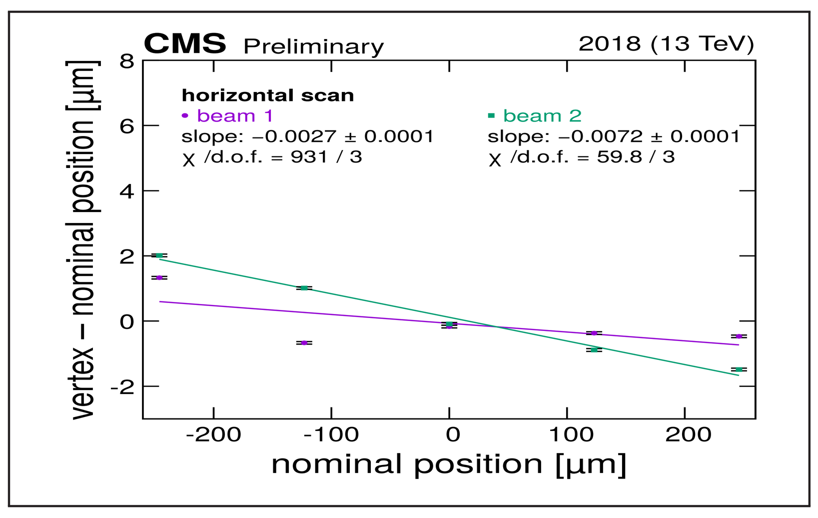
Constant separation scan: Beams are separated by $1.4\sigma_b$ (where σ_b is the beam size) and moved together in steps of $1\sigma_b$ along the positive then negative directions in x and y.

Variable separation scan: Each beam is moved from $-2.5\sigma_b$ to $+2.5\sigma_b$ in 5 steps along the positive horizontal and then vertical directions. In each step, a 3-point miniscan is performed with the other beam at relative positions of $-1.25\sigma_b$, 0 and $+1.25\sigma_b$.

The CMS tracker is used to reconstruct the position of interaction vertices defining the luminous region and the resulting mean position is plotted against the nominal (orbit drift corrected) separation. The length scale correction is extracted by a linear fit.



Constant separation LSC scan in x



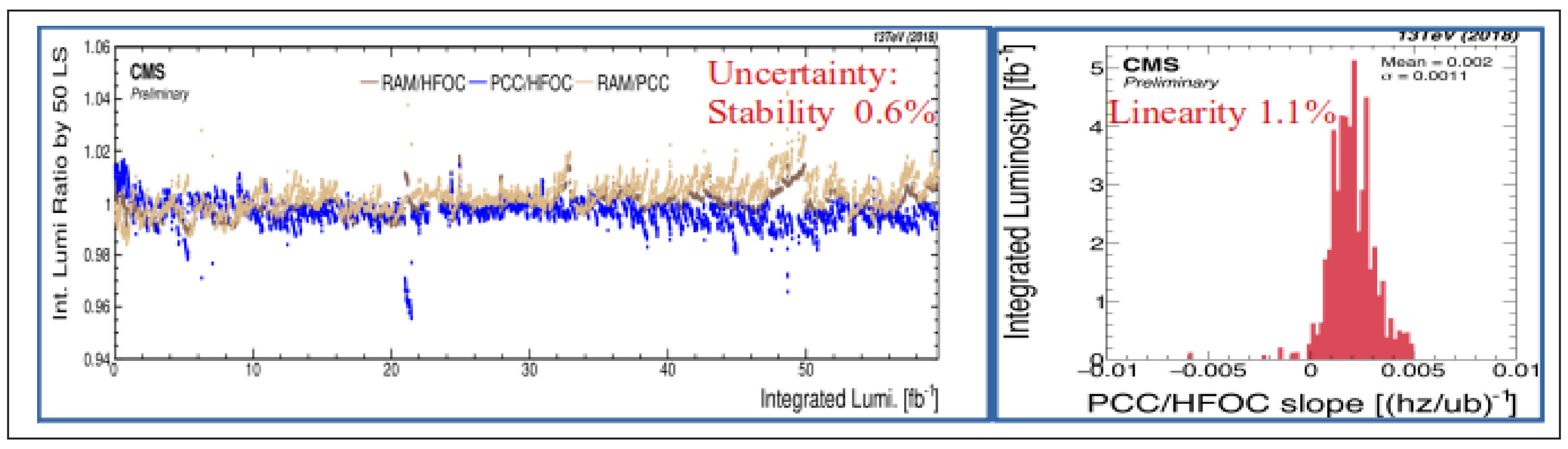
Variable separation LSC scan in x

The final correction and uncertainty in σ_{vis} due to the length scale is evaluated by combining the two independent results: -0.8 $\pm$ 0.2%.

Integration uncertainty: luminometer stability and linearity

During the course of the data-taking years, individual luminometers are affected by operational issues and radiation damage that can be monitored by short vdM-like ("emittance") scans in normal physics conditions, performed at the start and end of fills. They provide data with different single bunch instantaneous luminosity (SBIL), thus linearity response can also be measured and corrected for.

After corrections, the various luminometer measurements are compared to measure stability and residual nonlinearity. The luminosity ratio of luminometer pairs plotted as a function of SBIL and fitted by a linear function gives the relative nonlinearity.

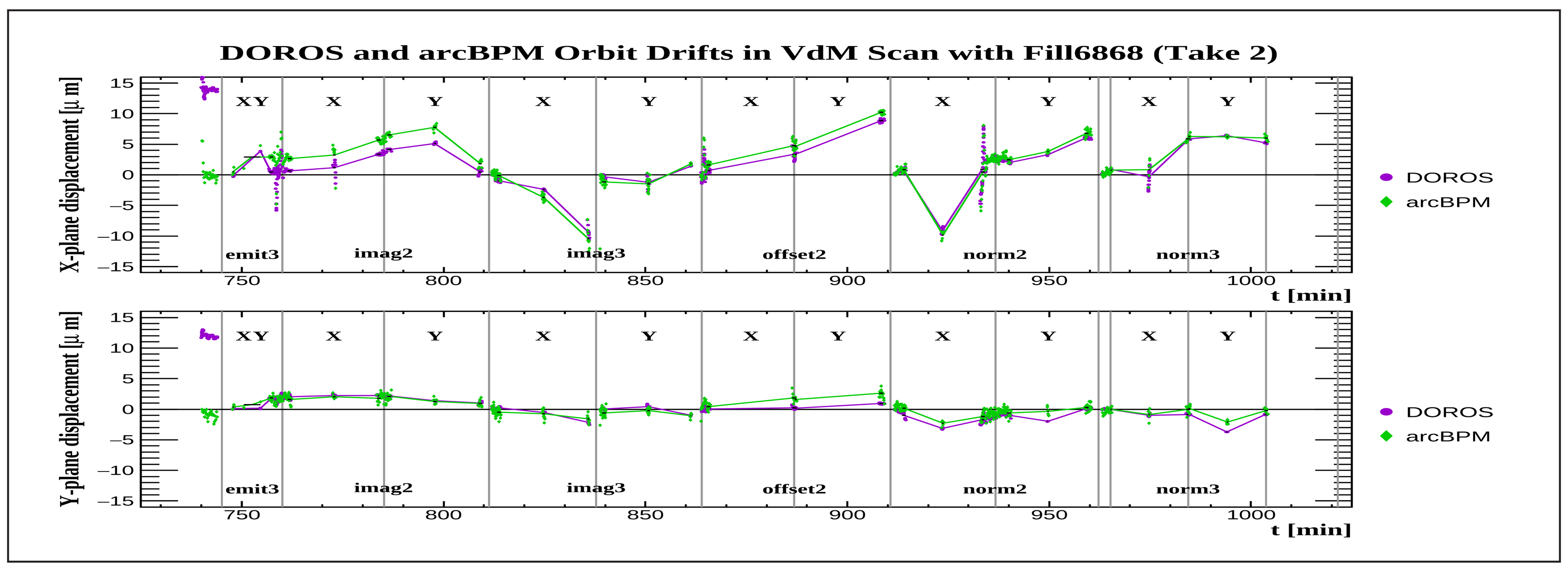


Orbit drift correction

To correct for the potential movement of the LHC orbit during the VdM scans using the data from two beam position monitoring (BPM) systems, DOROS and (LHC) arc BPMs.

Beam position measurements at head-on collisions are taken before, in the middle and after each scan, and a slow linear drift between these points is assumed to derive the corrections for the scan points with non-zero separation.

During the 2018 VdM scans, the orbit drift was small, less than 10 and 5 μm in the x and y directions, respectively, leading to a correction and uncertainty in σ_{vis} of 0.2 $\pm$ 0.1 %.



Luminosity uncertainty

The total uncertainty in proton-proton collisions in 2018 is 2.5% (similar to previous years) and dominated by the uncertainty from x-y factorization and luminometer linearity. When the full Run 2 data set of 2015–2018 is combined, it is reduced to 1.8%.

To reach the target precision of 1% at the HL-LHC, all sources of uncertainties must be controlled at the subpercent level. Developments are thus ongoing both to improve the measurement techniques and the luminometer instrumentation.

	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	—	0.5
	Background subtraction	0 to 0.8	0.1
Integration	Afterglow (HFOC)	0 to 4	$0.1\oplus0.4$
	Cross-detector stability	—	0.6
	Linearity	—	1.1
	CMS deadtime	—	<0.1
	Total		2.5