PRECISION LUMINOSITY MEASUREMENT WITH THE CMS DETECTOR

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on behalf of the CMS collaboration

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Outline

- **Luminosity and its measurement**
- **Luminometers in CMS**
- **Van der Meer (vdM) scan method**
- **Corrections and systematic uncertainties**
- **Summary**
- **Useful links**

Introduction

Luminosity of a particle collider

Determines the rate of particle collisions

$$R(t) = \mathrm{d}N/\mathrm{d}t = L(t) \cdot \sigma_{\mathrm{inel}}$$

Why precise measurement of instantaneous and integrated luminosity is needed?

Online:

- provides real-time feed-back on the LHC performance and operation
- provides information for CMS operations such as measurements of trigger rates

Offline:

- crucial component of nearly every physics analysis: $N_{\mathrm{signal}} = L_{\mathrm{int}} \cdot \sigma_{\mathrm{signal\ process}}$
  measuring cross-sections or setting upper limits in searches for BSM processes

Luminosity measurement

Using well-known physics processes

$$L(t) = R_{\text{process}}(t) \,/\, \sigma_{\text{process}}$$

- **Large Electron-Positron (LEP) collider**

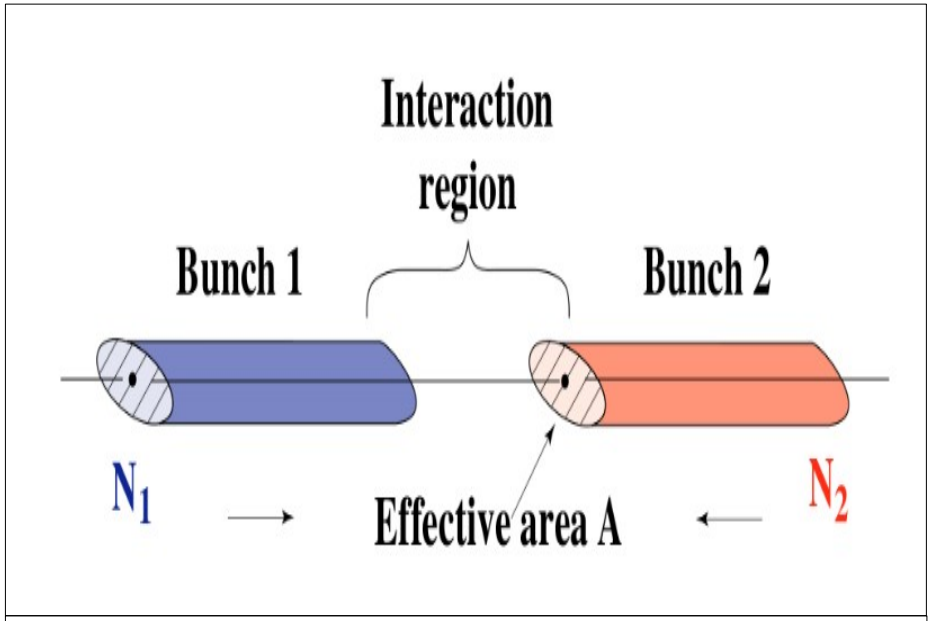
  Bhabha scattering $e^+ e^- \rightarrow e^+ e^-$ used

Large Hadron Collider (LHC)

Z production rate significant
But theory cross-section not very precise

In future measure cross-section in special (low pileup) campaign close in time to vdM calibration

Using machine parameters



$$L = N_1 . N_2 . f . n_b / A_{eff}$$

$$A_{eff} = 2\pi \Sigma_x \Sigma_y$$

Σ_x, Σ_y : beam overlap widths in x and y directions obtained from vdM scans.

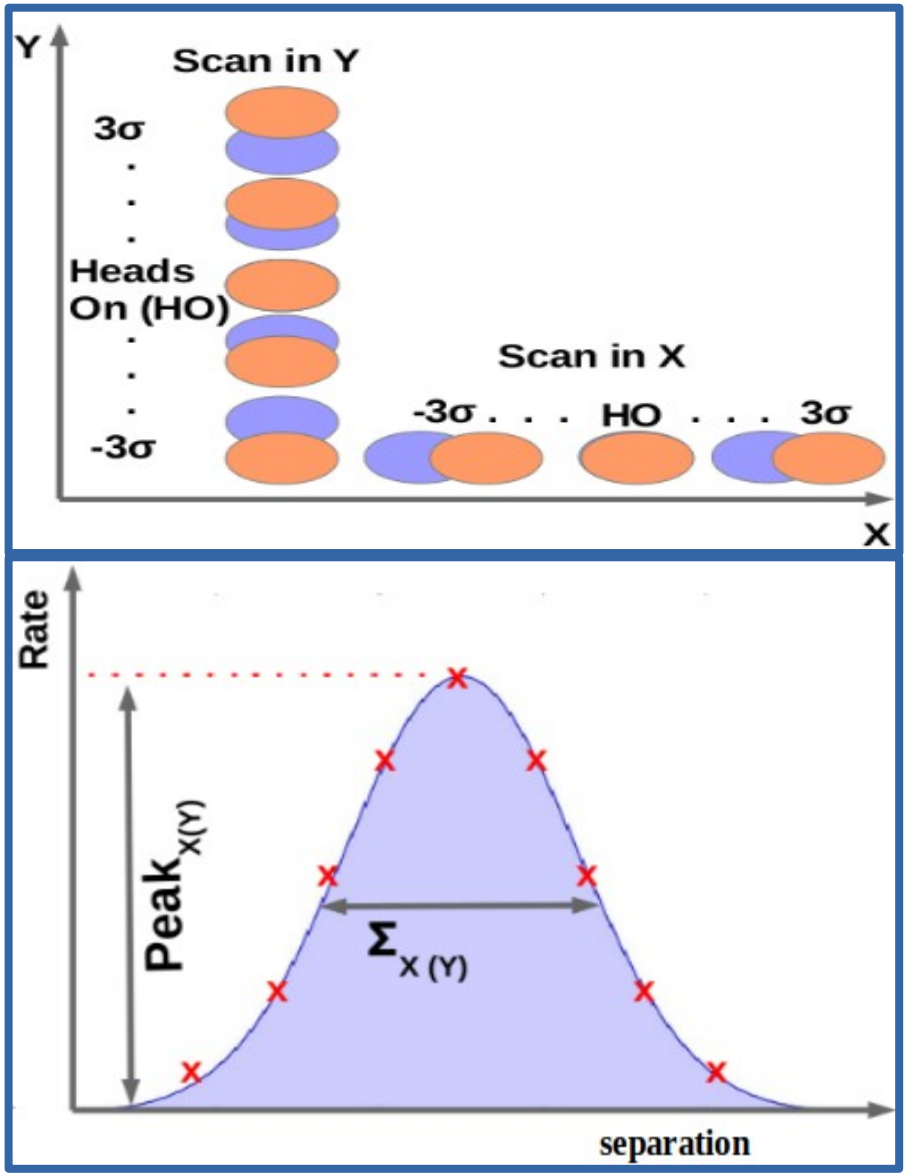
vdM scan

- Performed during special fill with low lumiosity to avoid pileup and large seperation between bunches to avoid train effect.
- Assume bunch proton density function factorizable into independent x- and y- terms:

$$f(x,y) = g(x) * h(y)$$

- Measure rate R as a function of beam separation in x and in y planes by luminometers
- Σ_x, Σ_y and R_{peak} obtained from a (typically Gaussian) fit
- Before performing the fit, raw data subjected to various corrections (see later)
- Detector-dependent calibration constant σ_{vis} measured during special vdM fill, then used during physics fills:

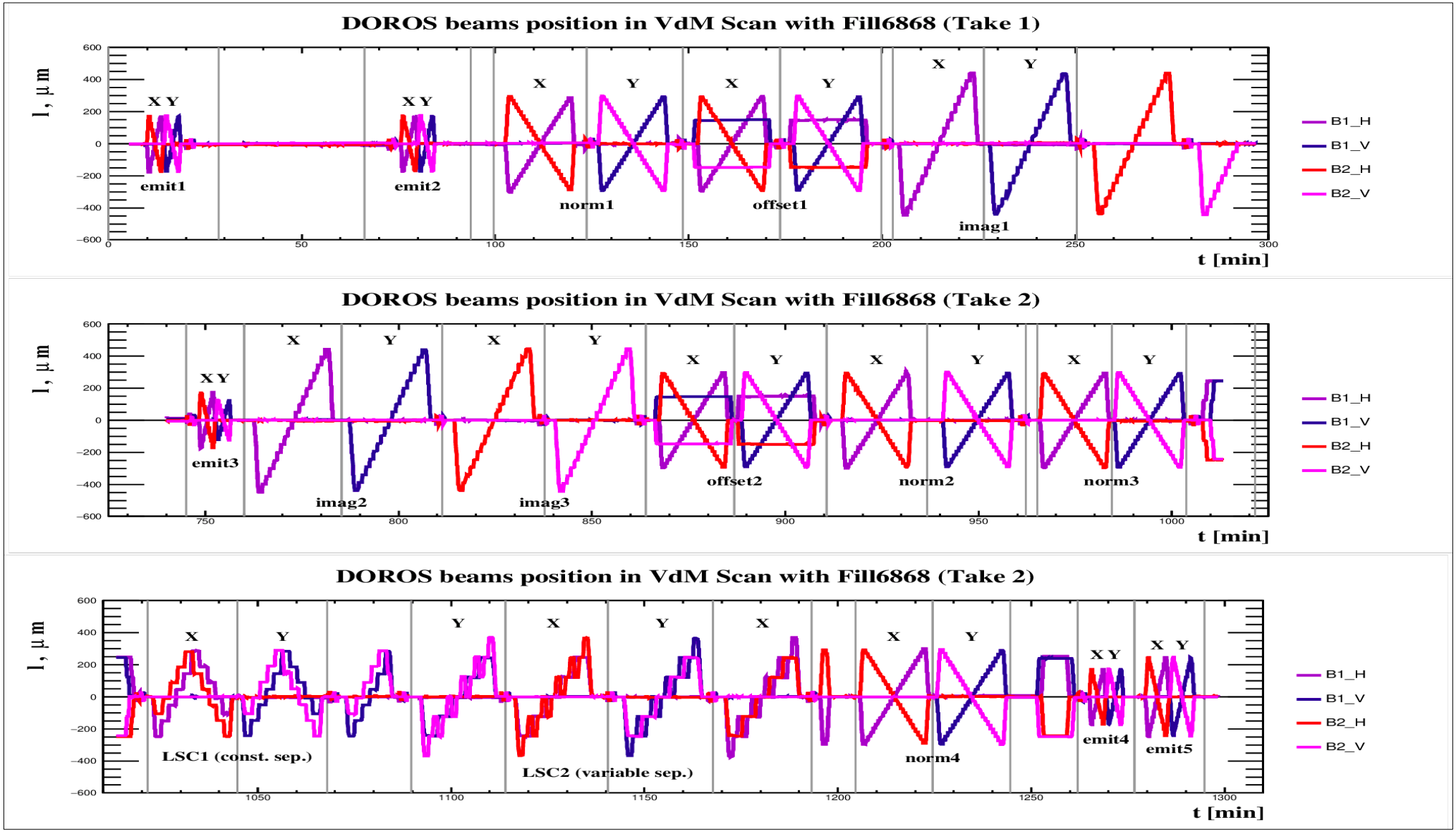
$$L(t) = R_{detector}(t) / \sigma_{vis}$$



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

vdM scan program

2018 vdM fill



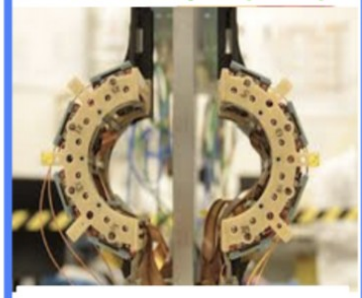
CMS PAS-LUM-18-002

Luminometers at CMS

$$R(t) = \sigma_{\text{vis}} \cdot \mathcal{L}(t)$$

Online measurements

Pixel Luminosity Telescope (PLT)



Event counting

Fast Beam Condition Monitor (BCM1F)

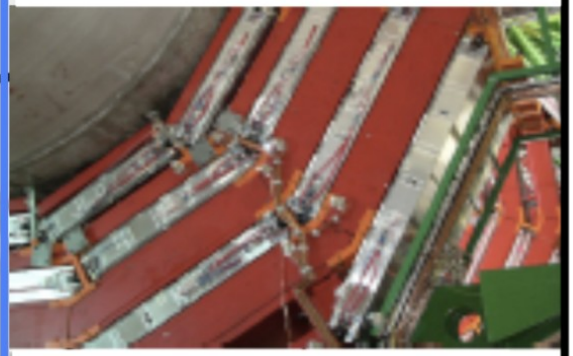
Hit counting

RAMSES

Dose equivalent rate

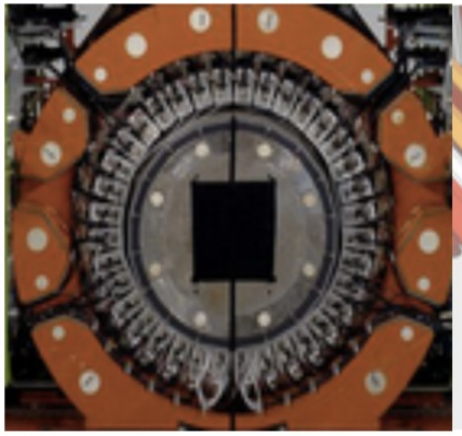
Offline measurements

Muon Drift Tubes (DT)



Rate of muon tracklet trigger primitives

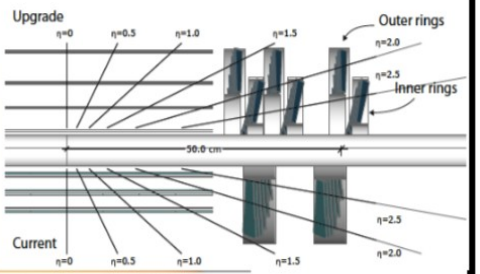
Hadron Forward Calorimeter (HF)



HFOC: hit counting

HFET: sum E_T

Silicon Pixel Detector



Pixel Cluster Counting (PCC)

Primary CMS luminometer:

2015-2016: PCC
2017: HFET (PCC)
2018: HFOC (PCC)

Si Pixel + Strip
Vertex Counting

Corrections and systematic uncertainties

- Normalization uncertainties affect absolute luminosity calibration in the vdM scan procedure
- Integration uncertainties arise from detector operations over the course of the year, as well as from the transfer of calibration from special vdM fill conditions to physics

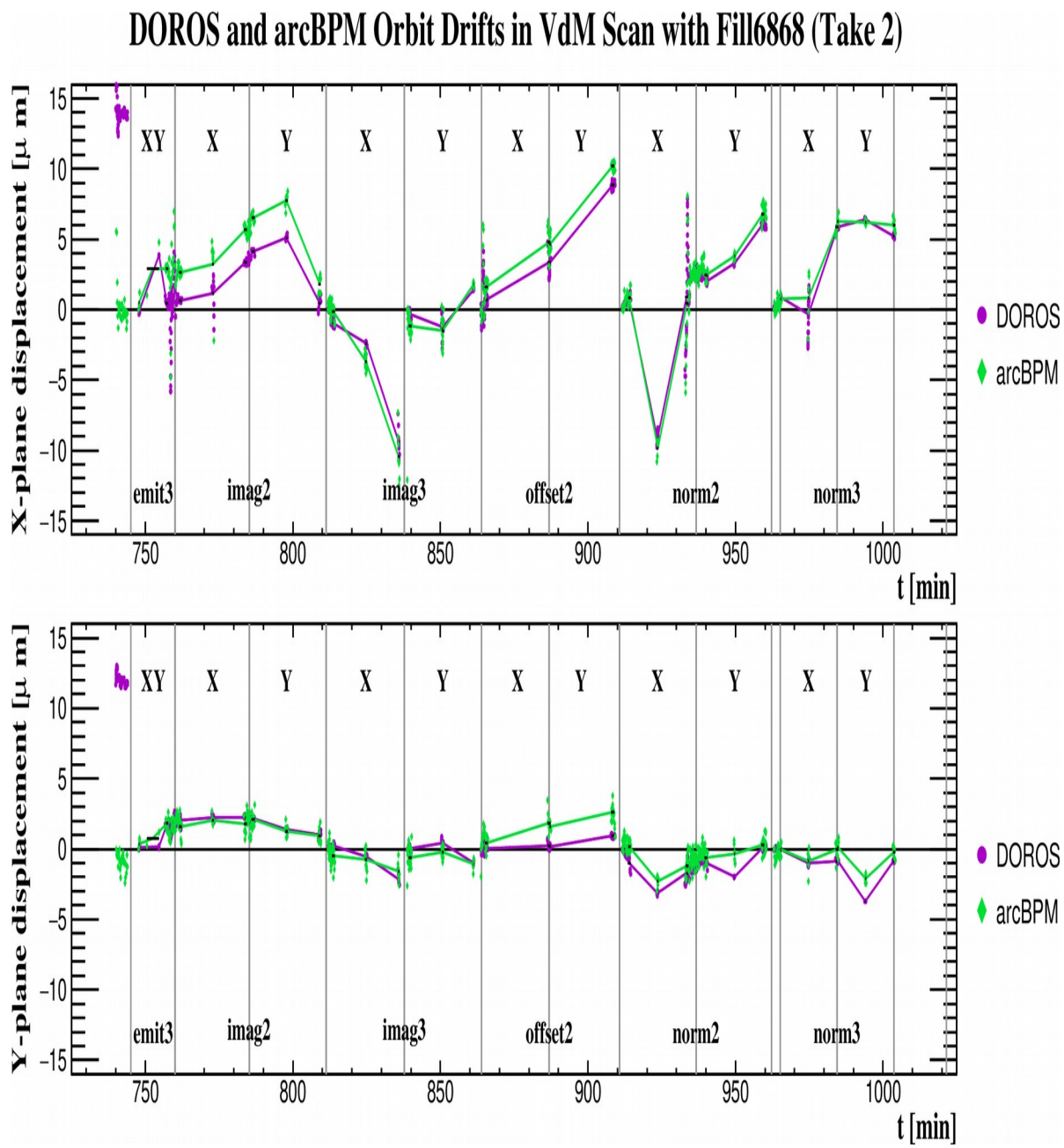
	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—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

CMS PAS-LUM-18-002

Orbit drift

- Potential movement of LHC orbit during the vdM fill
- 2 beam position monitor (BPM) systems: DOROS BPM and arc BPMs
- Orbit drift during the 2018 VdM scans is quite small, less than 10 μm .
- Used to correct all vdM and other special scans (eg. for length scale calibration)

(0.2 ± 0.1) %



Length scale calibration (procedure)

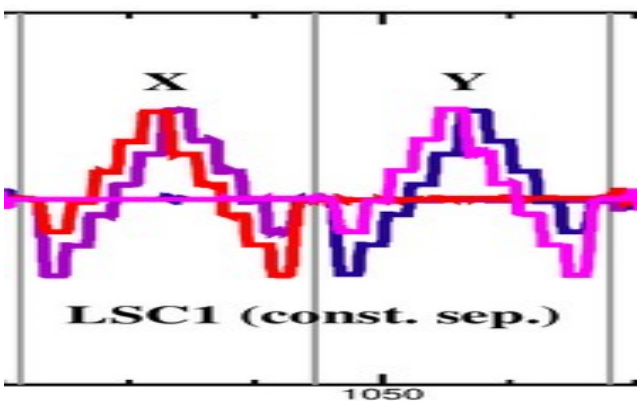
Possible differences between the actual and nominal beam separations during the scans
Measured using two different methods → combined for correction and systematics evaluation

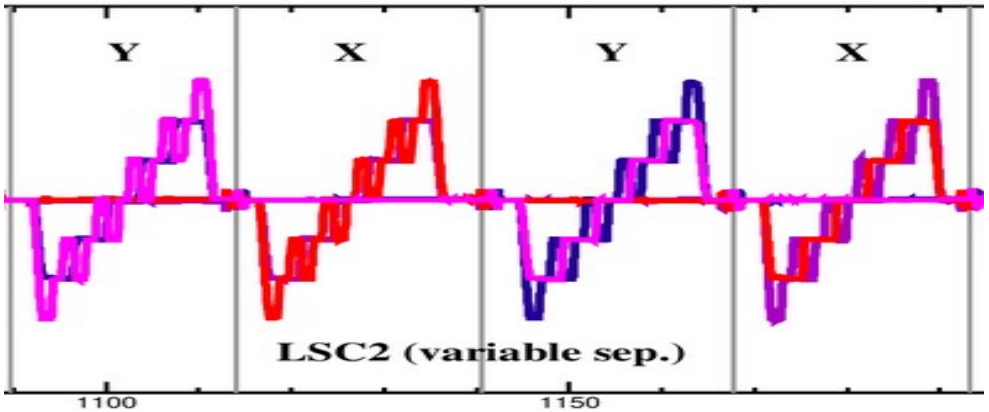
Constant separation scan

- Beams separated by $1.4\sigma_b$
- Moved together in steps of $1\sigma_b$ across and back
- 2 scans in total: in 2 transverse directions

Variable separation scan

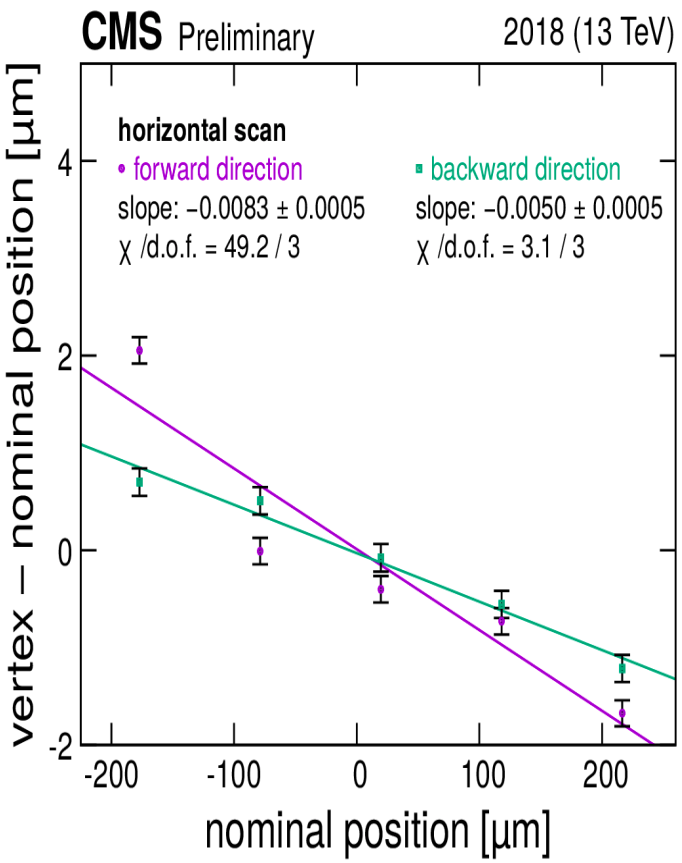
- One beam moved from $-2.5\sigma_b$ to $+2.5\sigma_b$ in 5 steps
- In each step, a 3-point miniscan performed with the other beam at relative positions of $-1.25\sigma_b$, 0 and $+1.25\sigma_b$
- 4 scans in total: in 2 transverse directions around both beams

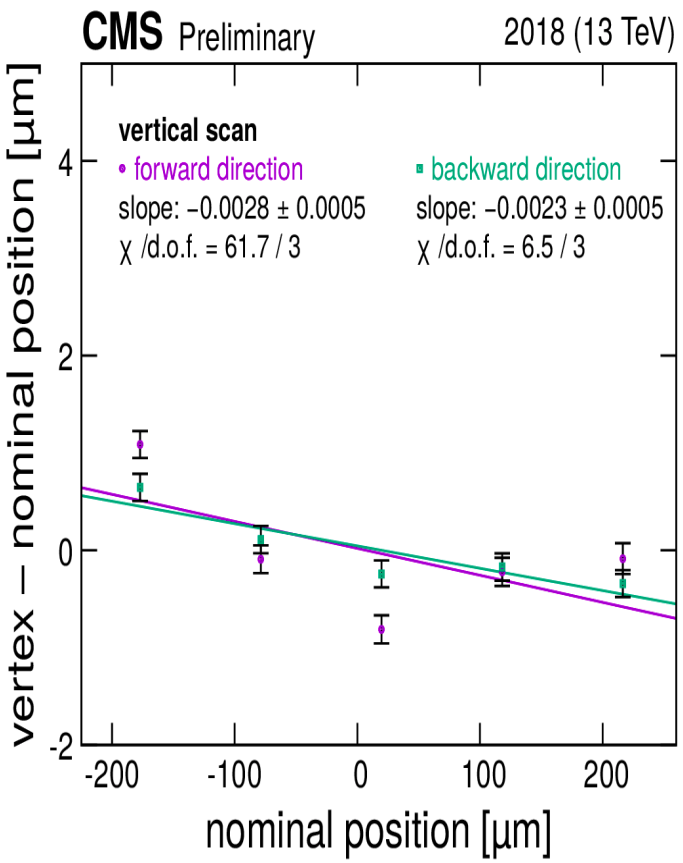




Length scale calibration (correction and uncertainty)

- CMS tracker used to reconstruct the position of interaction vertices defining the luminous region
- Resulting mean position is plotted against the nominal (orbit drift corrected) separation
- Linear fit applied to extract the length scale correction and its uncertainty





Constant separation scan

(-0.8 ± 0.2) %

Bias from of x-y factorization assumption

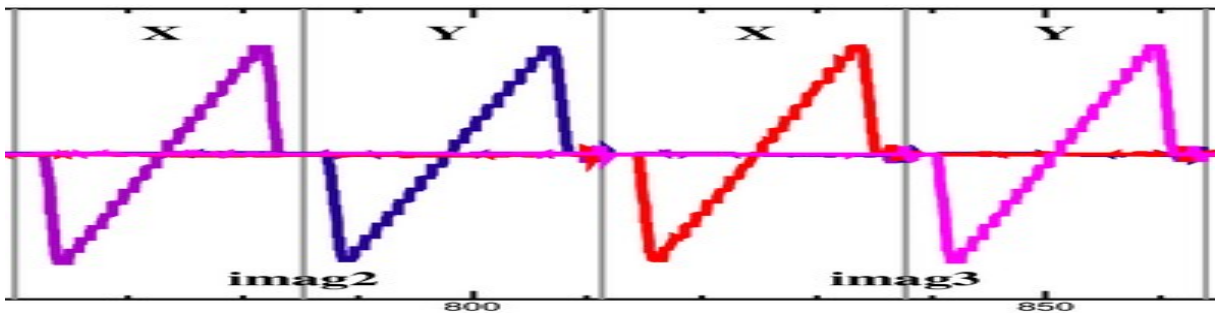
Bunch proton density function not strictly factorizable into independent x- and y-terms:

$$f(x,y) \neq g(x) * h(y)$$

Measured using two alternative scans ⟶ Beam-imaging scan and Offset scan

Beam-imaging scans

- One beam kept fixed at its nominal position and its shape scanned by the other beam in 19 steps from $+4.5\sigma_b$ to $-4.5\sigma_b$ separation

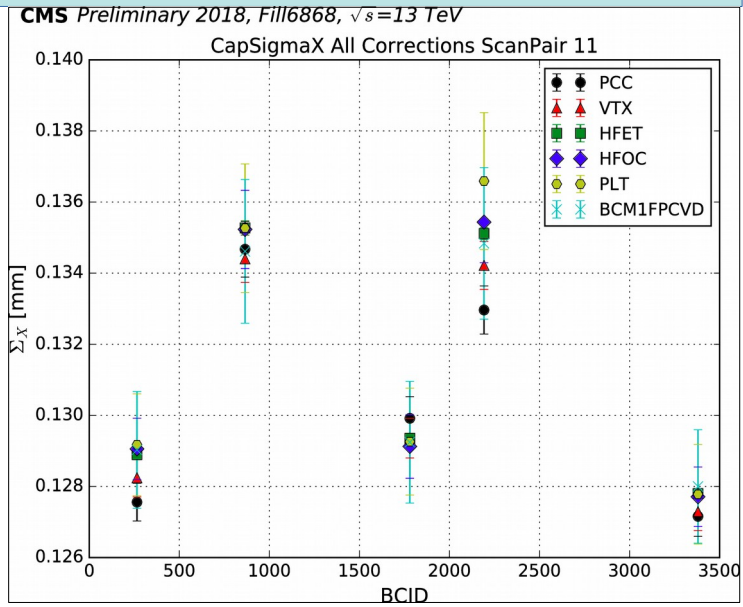


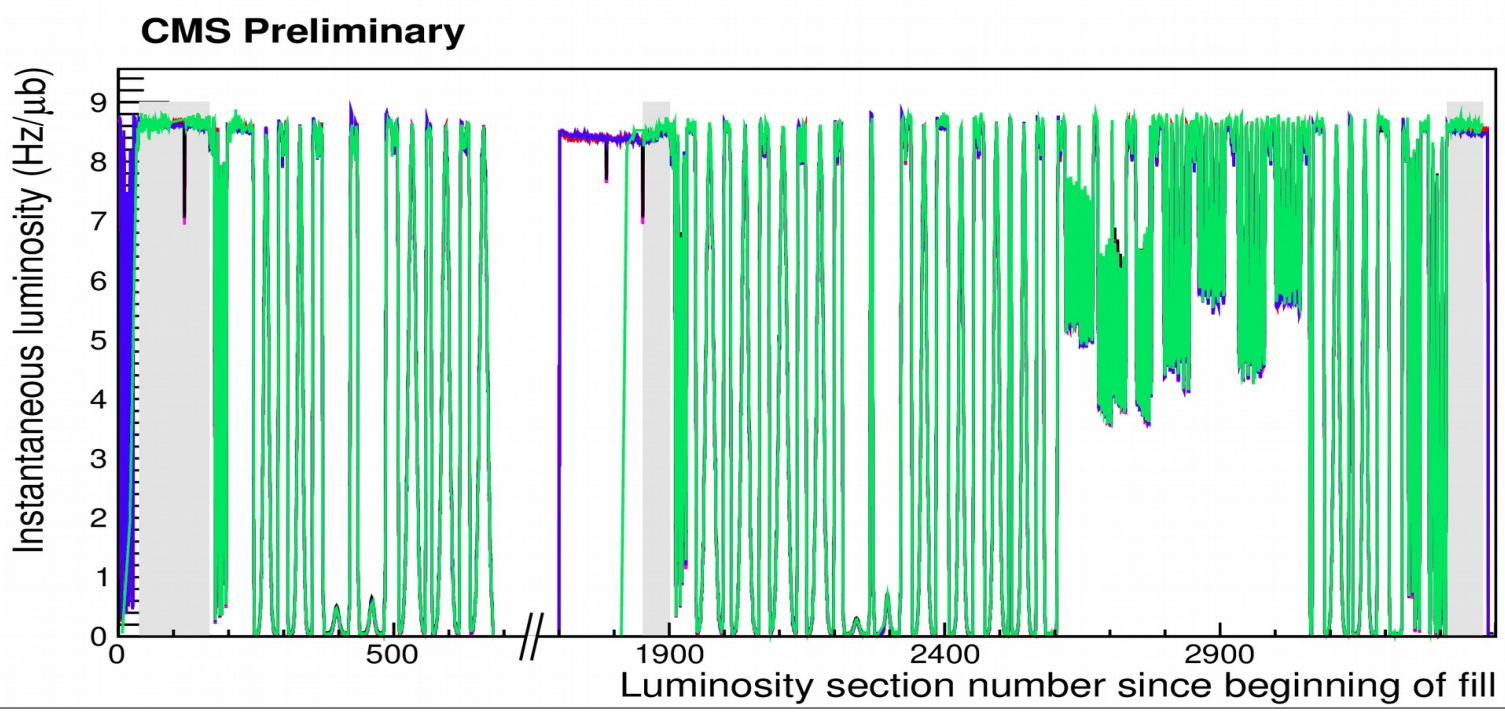
- Resulting distribution of measured vertex positions fitted to derive the 2D proton density function for both beams
- Compare overlap integral calculated by the convolution of the 2D proton density functions to the product of $2\pi\ \Sigma_x \cdot \Sigma_y$ from traditional vdM fits
- In 2018, best fit shows significant remaining residuals, resulting in large systematic uncertainty

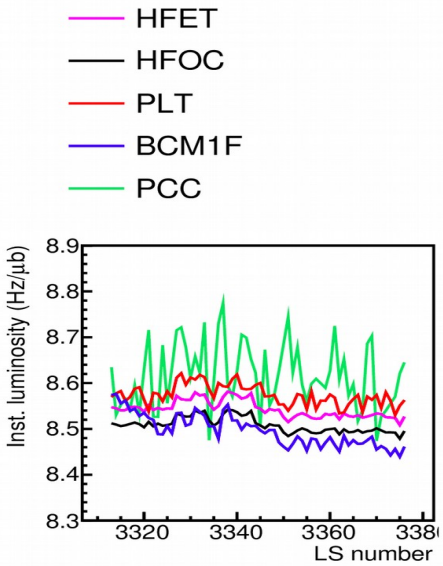
No correction but overall systematic uncertainty of 2.0%

Consistency of vdM calibration

- $\Sigma_{x,y}$ characterize beam overlap:
  should be same for all luminometers
- σ_{vis} depends on luminometer and applied method:
  should be stable over bunches and scans
- Small variations observed:
  scan to scan 0.32% and bunch to bunch 0.06%
- Total integrated luminosity in stable periods of vdM fill should be same for all luminometers
  any difference seen covers unknown systematic effects



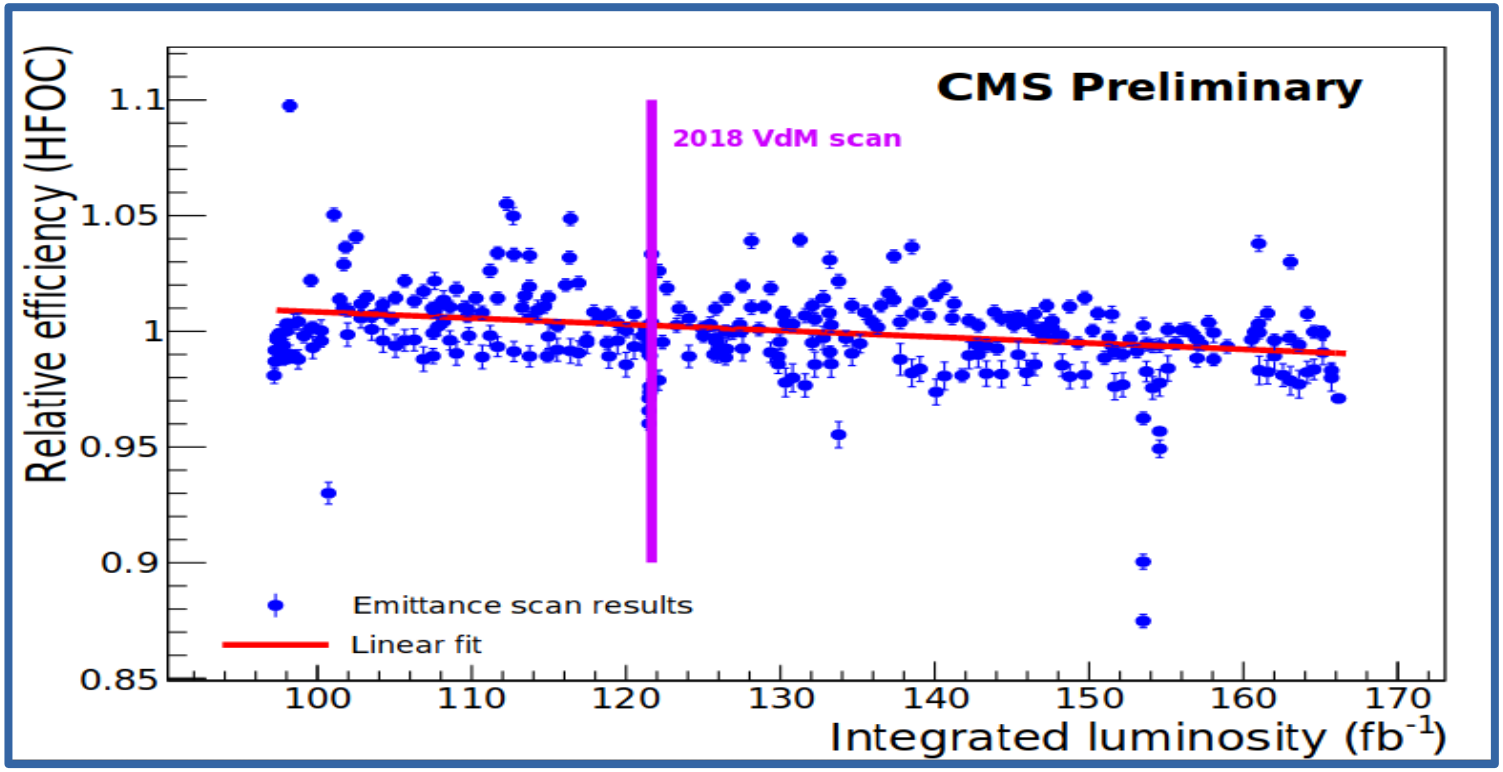




Uncertainty: 0.5 %

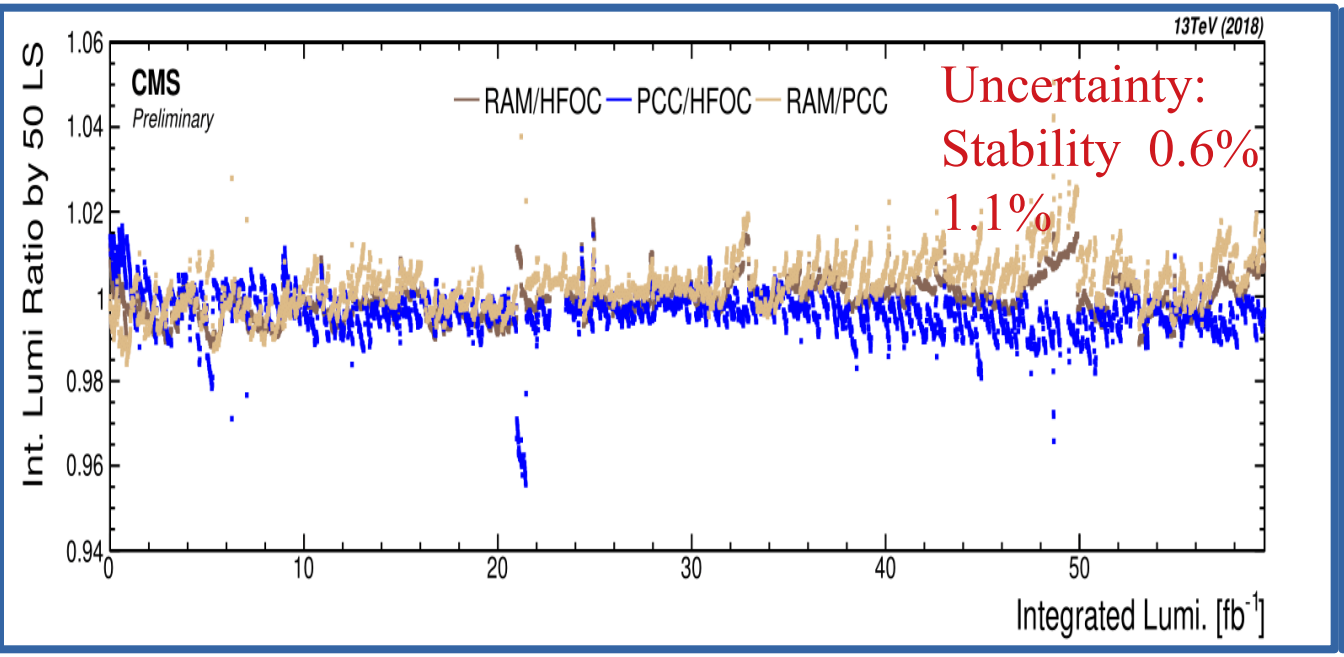
Stability and linearity of detectors

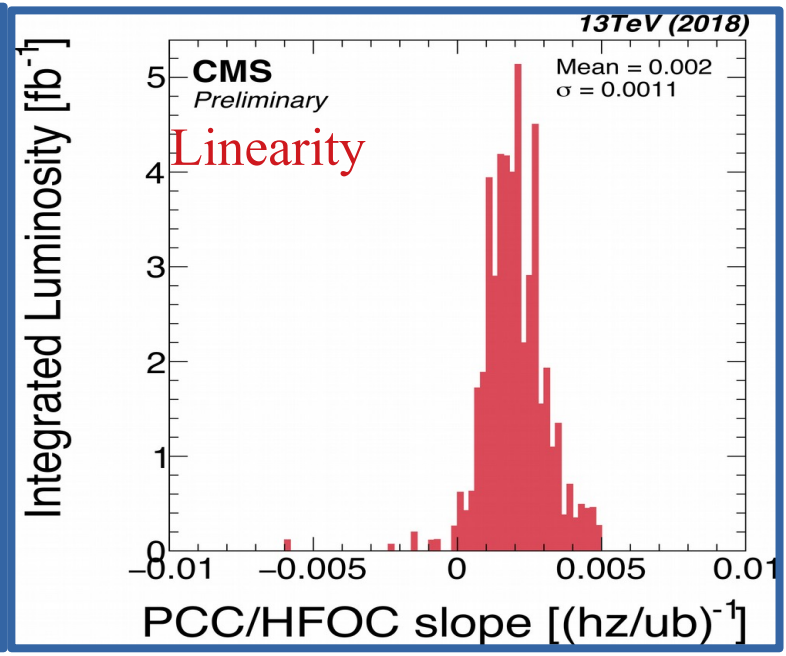
- Emittance scans (mini VdM scans in normal physics conditions) used to monitor performance of individual luminometers
  - Provides estimate of σ_{vis} in each fill ⟶ detector performance (e.g. efficiency) can be monitored
  - Performed at start and end of fill providing data with different Single Bunch Instantaneous Luminosity (SBIL) ⟶ linearity response can be measured and corrected for



Stability and linearity of detectors

- After corrections, different luminometer measurements compared for stability and residual non-linearity
- For given fill, luminosity ratio of pairs of luminometers plotted as a function of SBIL linear fit to ratio ⟶ slope taken as relative nonlinearity for studied luminometers
- Extracted slopes histogrammed weighted by luminosity ⟶ mean and RMS determines systematics
- Uncertainty from largest mean slope among all individual detector pairs (for PCC/HFOC in 2018)





Summary

- Total uncertainty of preliminary luminosity calibration in 2018 is 2.5% (similar to previous years)
  - Dominated by uncertainty from x-y factorization and luminometer linearity
- When 2015-2018 data combined, uncertainty is reduced to 1.8%
- Significant improvement expected for final calibration
- Target precision for HL-LHC is 1% arXiv:1902.10229
- Lot of work on measurement techniques and instrumentation under way TDR-19-003

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Useful links

- Pixel Luminosity Telescope
- Fast Beam Condition Monitor
- Bias from of x-y factorization assumption
- CMS luminosity measurement
- CMS luminosity measurement2
- CMS Luminosity Preliminary Results

BACKUP

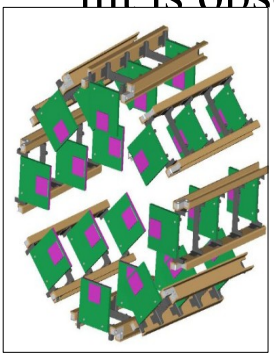
Luminometers at CMS (I)

Beam Radiation Instrumentation and Luminosity (BRIL) project using eight systems were used to monitor and measure luminosity at CMS.

1- The Pixel Luminosity Telescope (PLT)

- 1.8 m away from the interaction point
- 48 sensors arranged into 16 "telescopes"

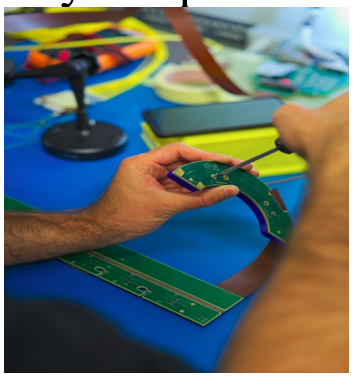
  eight at either end of CMS
- 3 individual sensors for each telescope (7.5 cm long and 5 cm away from beam pipe)
- rate of "triple coincidences", where a hit is observed in all three planes

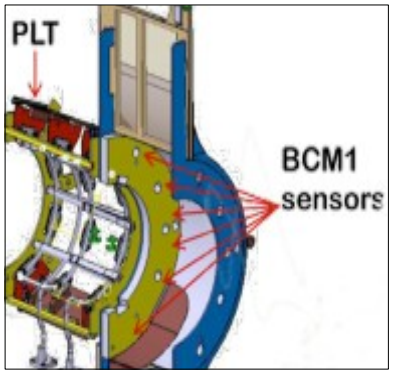


two dedicated luminosity measurement systems

2- Fast Beam Conditions Monitor (BCM1F)

- 1.8 m from the center of CMS
- 10 silicon sensors, 10 polycrystalline diamond (pCVD) sensors, and 4 single-crystal diamond (sCVD) sensors.
- measures both luminosity and machine-induced background (MIB)
- fast readout with 6.25 ns time resolution
- only the pCVD sensors are used





Luminometers at CMS (II)

Beam Radiation Instrumentation and Luminosity (BRIL) project using eight systems were used to monitor and measure luminosity at CMS.

3,4- hadronic forward calorimeter (HF)

- primary online luminosity measurement for CMS
- dedicated readout system installed in the HF calorimeter
- Two algorithms are available
  - the fraction of occupied towers (HFOC)
  - sum of the transverse energy E_T (HFET)

1,2,3,4 are online and use BRILDAQ operates independently of the main CMS readout

5- the pixel cluster counting method (PCC)

- primary offline luminosity measurement for CMS
- rate of pixel clusters in the CMS pixel detector
- Provides a measurement
  - Good statistical precision
  - Good stability over time

6- the vertex counting method (VTX)

- Using CMS tracking system
- Counting reconstructed pp collisions
- reliable method for low pileup luminosity estimates
- the background to this measurement is negligible
- provides excellent profiles of beam shape overlaps.

Luminometers at CMS (III)

Beam Radiation Instrumentation and Luminosity (BRIL) project using eight systems were used to monitor and measure luminosity at CMS.

7- the drift tube luminosity (DT)

- rate of muon track stubs in the muon barrel track finder
- does not provide bunch-by-bunch measurements
- rate in DT is too low , cross-calibrated to another detector.
- stable and linear during the course of the year
- provides a complementary offline reference measurement.

8- Radiation Monitoring System for the Environment and Safety (RAMSES) detector

- part of the LHC environmental protection and monitoring systems
- sensor is a cylindrical plastic ionization chamber
- does not provide bunch-by-bunch measurements
- less affected
  - instability caused by radiation damage
  - nonlinearity caused by high rates over the course of the 2018 run

5,6,7 are use CMSDAQ readout

- *Luminometer measures the rate of the observed quantity R(t)*
- *R(t) is proportional to the instantaneous luminosity, ∫ (t)*
- *with a proportionality constant* σ_{vis}

$$R(t) = \sigma_{\text{vis}} \cdot \mathcal{L}(t)$$

- σ_{vis} *can be calibrated in dedicated fills with van der Meer (vdM) scans*

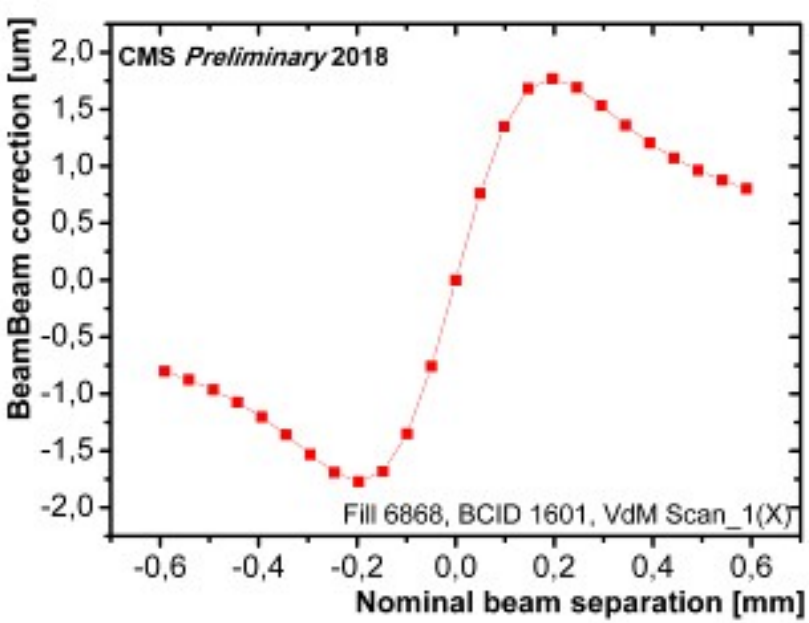
Beam-beam effects

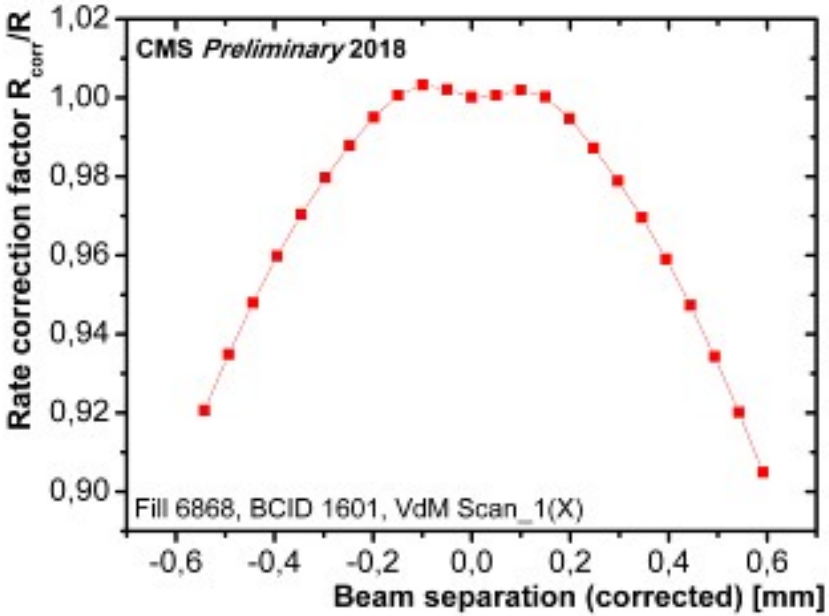
beam beam deflection

- electrical repulsion of the beams
- increases the lateral separation
- calculated from this ref B-B deflection

Dynamic-β* effect

- each beam has a defocusing effect on the other
- calculated using reference beam transport simulations Dynamic-β





1.0 ± 0.2%

Bunch current normalization

bunch current measurement

- Fast Beam Current Transformers (FBCT), bunch-by-bunch granularity.
- DC Current transformers (DCCT) measures the total beam current
- − 0.9% for beam 1 and − 1.4% for beam 2
- uncertainty is 0.2%

$(+0.4 \pm 0.1)\%$

satellite and ghost charges

- satellite charge in the colliding bunch crossing but not in the colliding RF bucket
- ghost charge not in any nominally filled bunch slot.
- Calculated by LHC longitudinal density monitors stallite-ghost
- ghost contribution is 0.13% for beam 1 and 0.16% for beam 2
- satellites account for 0.04% and 0.05%, respectively
- 0.1% uncertainty

Results

- σ_{vis} is differs for the different luminometers

Luminometer	Measured σ_{vis}
BCM1F	210.3 μb
HFET	2503.6 μb
HFOC	805.9 μb
PLT	261.8 μb
PCC	5982 mb
VTX	29.12 mb

- integrated luminosity during stable periods in the VdM fill

Luminometer	Integrated luminosity (nb^{-1})
BCM1F	41.91
HFET	42.16
HFOC	41.99
PCC	42.31
PLT	42.22

Detector-specific effects

- BCM1F and PLT, radiation damage to the sensors,
- HFET and HFOC was similarly affected due to gain loss in the PMTs and fibers in HF
- PCC was affected by operational issues
- measured using emittance scans in normal physics conditions
- These scans are typically performed at the beginning of the fill and at the end
- additional offline corrections are applied to emittance scan data:
  - Increasing leading bunches current
  - peak position correction
- linearity response of a detector measured using different SBIL.