Precision luminosity measurement at the CMS experiment

Zimányi School 2023

Attila Rádl

Luminosity

- Luminosity: relation between the event rate and the cross section

$$dN/dt = L_{inst}\,\sigma_p$$

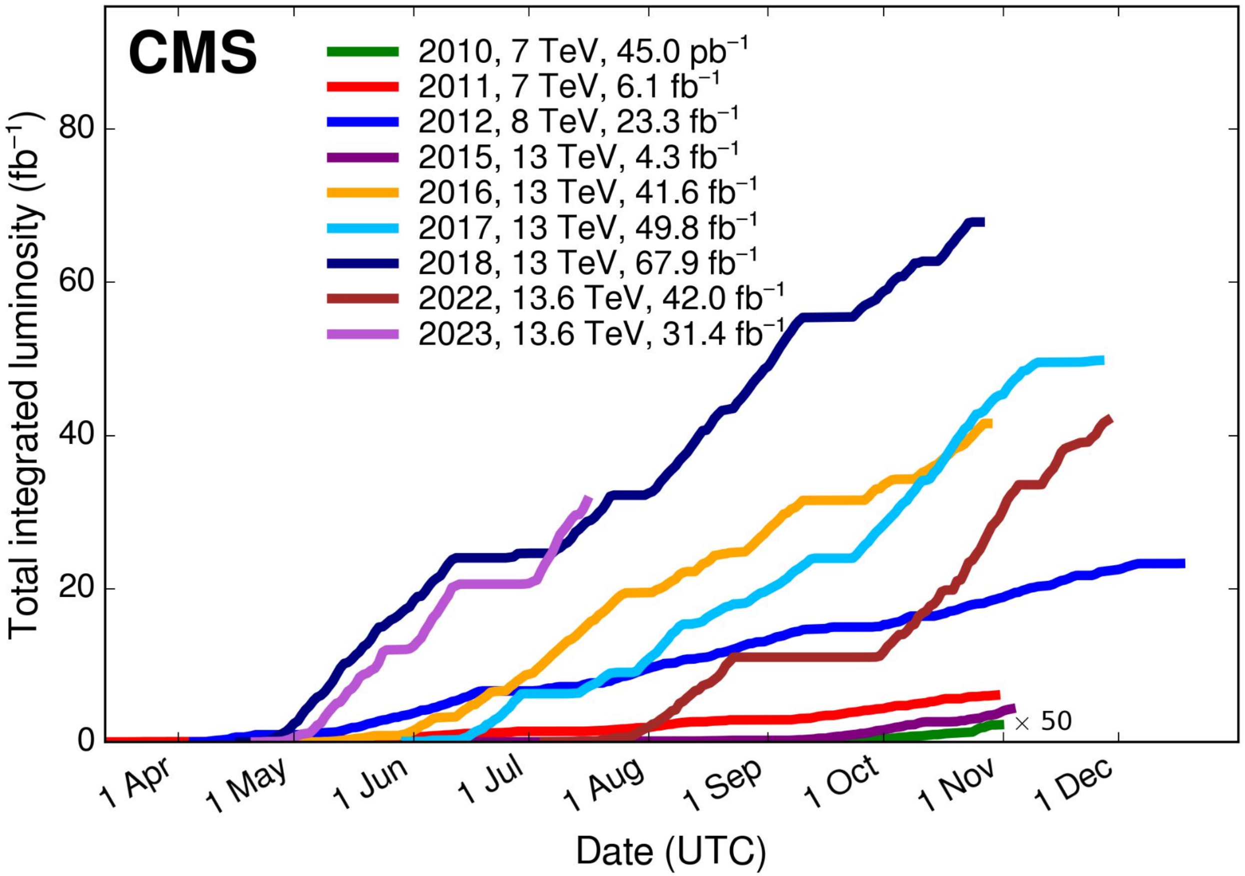
- Time integrated: represents the amount of data recorded

$$L = \int L_{inst}\,dt$$

- Number of interesting events in a sample

$$N = L\,\sigma_p$$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults



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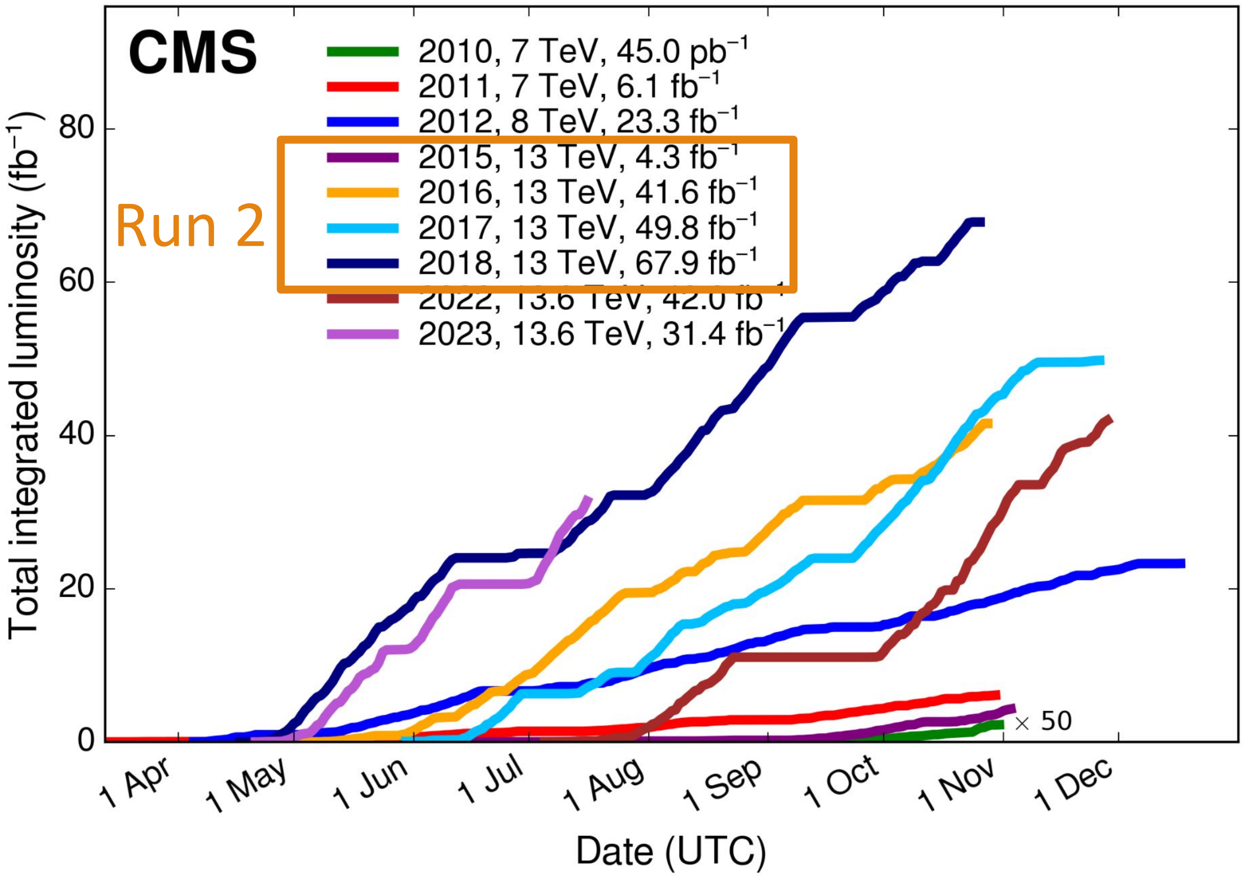
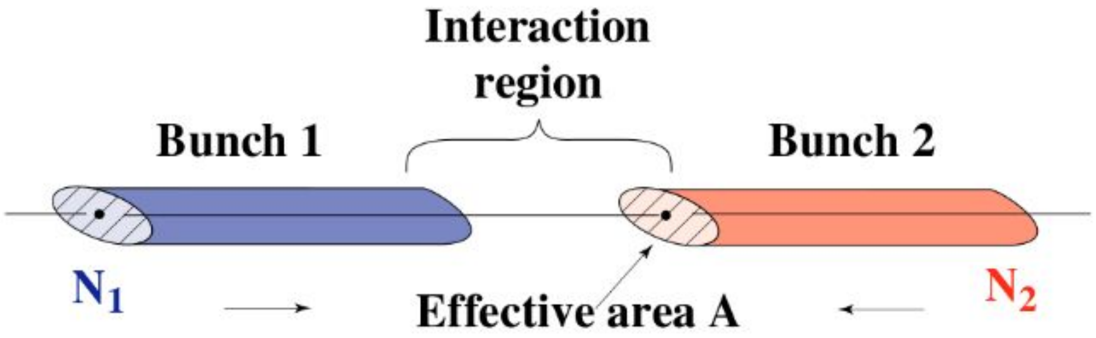


Luminosity for colliding beams

- Precise measurement of absolute luminosity
- Luminosity for two “head-on” colliding bunches
  - Measured properties: proton density function, number of protons in the bunches
  - Effective area: beam overlap integral



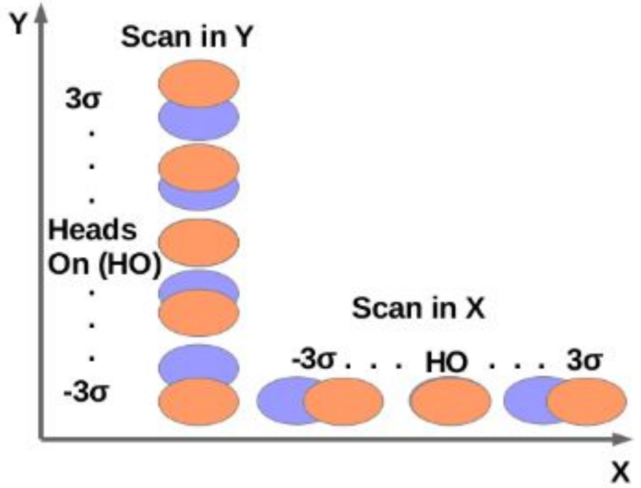
$$\mathcal{L}^i_{\text{inst}} = N^i_1 N^i_2 f \int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y = N^i_1 N^i_2 f \int \rho_{x1}(x)\rho_{x2}(x)\mathrm{d}x \int \rho_{y1}(y)\rho_{y2}(y)\mathrm{d}y$$

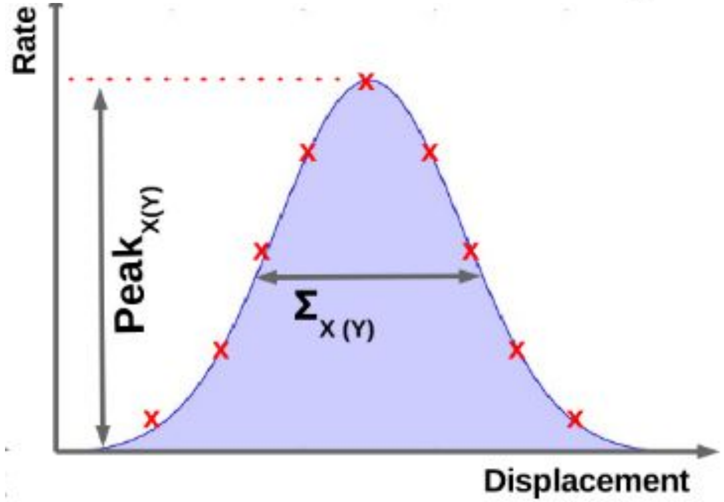
Assumption: x-y direction factorization

No precise, direct measurement for $\rho_i(x)$ → Van der Meer method: beam profile scan

Van der Meer methodology

- Separate the two beams and measure the rate continuously



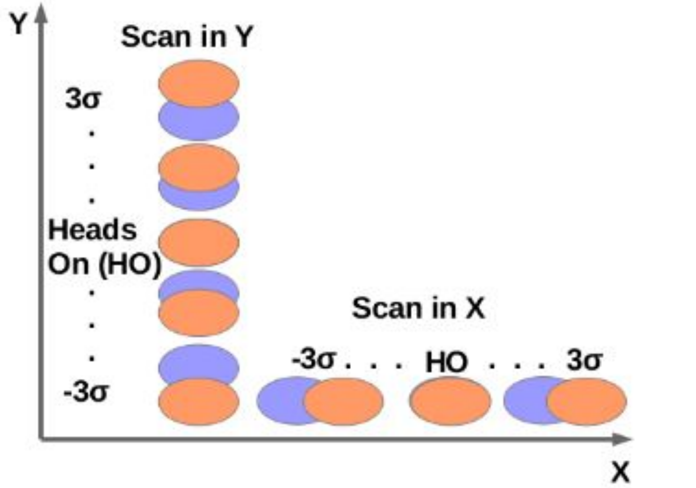


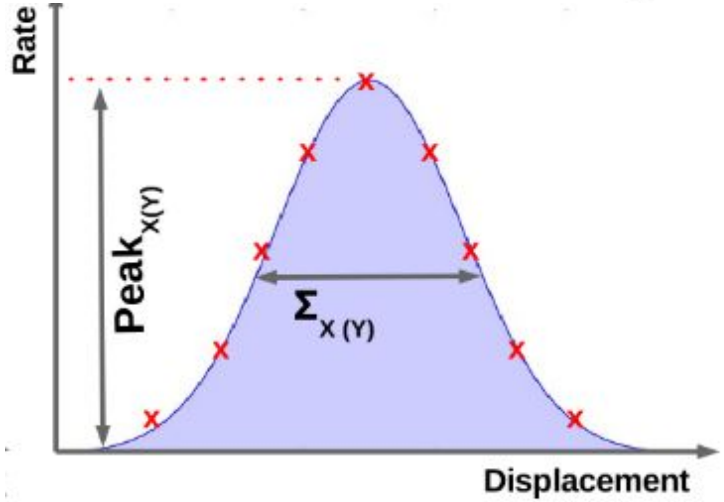
$$\int \rho_{x1}(x)\rho_{x2}(x)\mathrm{d}x = \frac{R_x(0)}{\int R_x(\Delta)\mathrm{d}\Delta} = \sqrt{2\pi}\,\Sigma_x$$

- Event rate from luminometers
- Beam orbit monitoring with Beam Position Monitors (BPM)

Van der Meer methodology

- Separate the two beams and measure the rate continuously





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- Event rate from luminometers
- Beam orbit monitoring with Beam Position Monitors (BPM)

Bunch intensity from beam current measurements $N_1, N_2 \approx 8\times10^{10}$

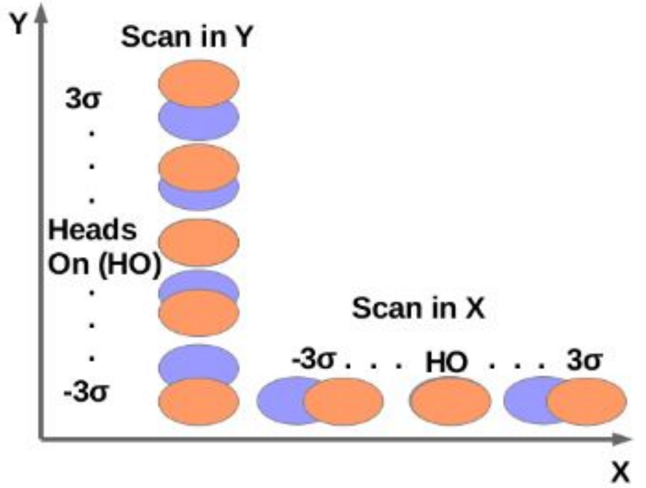
$$\mathcal{L}^i_{\mathrm{inst}} = \frac{N^i_1 N^i_2 f}{2\pi \Sigma_x \Sigma_y}$$

LHC orbit revolution frequency:
f = 11245.5 Hz

Beam overlap widths from VdM scans

Van der Meer methodology

- Separate the two beams and measure the rate continuously



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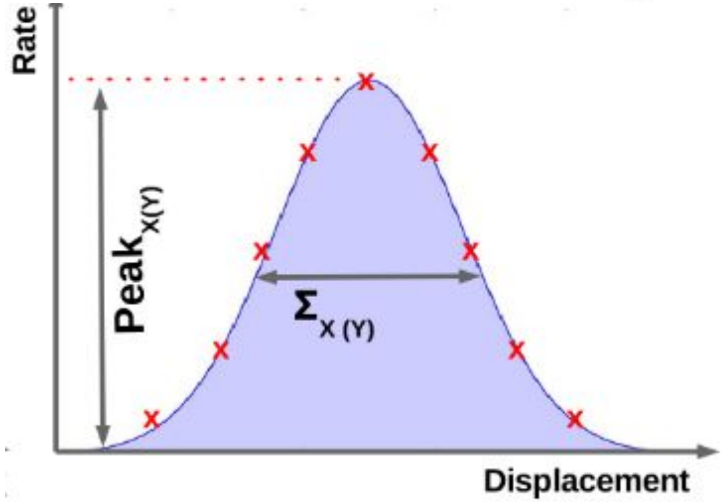
- Event rate from luminometers
- Beam orbit monitoring with Beam Position Monitors (BPM)



Expectation: same σ_{vis} for regular conditions

Calibration constant: visible cross-section

$$\sigma_{\mathrm{vis}} = \frac{2\pi\Sigma_x\Sigma_y R_0}{N_1^i N_2^i f}$$

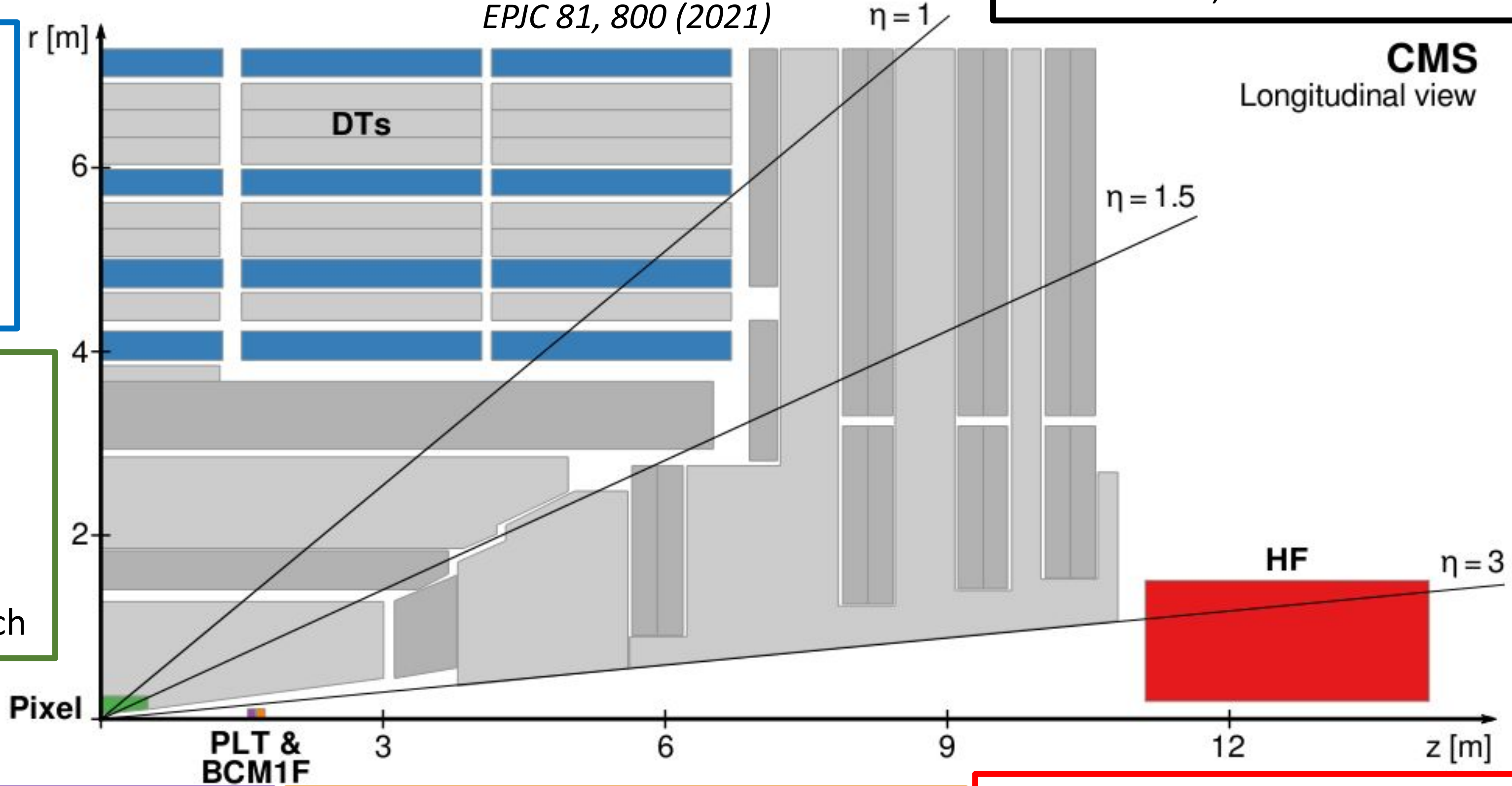
Luminometers at the CMS

RAMSES on the HF platform:
- Radiation monitoring system
- Also used for lumi estimation
- Real-time, cross-calibrated

Muon barrel drift tubes:
- Counting muon track stubs
- Real-time, cross-calibrated

Pixel detector:
- Pixel cluster counting (PCC)
  - Occupancy of the detector
  - bunch-by-bunch

EPJC 81, 800 (2021)



Pixel Luminosity Telescope (PLT):
- Pixel planes in a telescope arrangement
- Counting coincidences
- Real-time, bunch-by-bunch lumi

Fast Beam Condition Monitor (BCM1F):
- Hit counting
- Machine induced background measurements
- Real-time, bunch-by-bunch lumi

Hadron Forward Calorimeter (HF):
- Dedicated backend for lumi (real-time, bunch-by-bunch)
- Two algorithms
  - ΣE_t (HFET)
  - Tower occupancy (HFOC)

Beam instrumentation devices used for the calibration:

Beam position monitors (BPM) to measure the orbit of the circulating beams
- Diode ORbit and OScillation (DOROS) detectors
- Arc BPM detectors

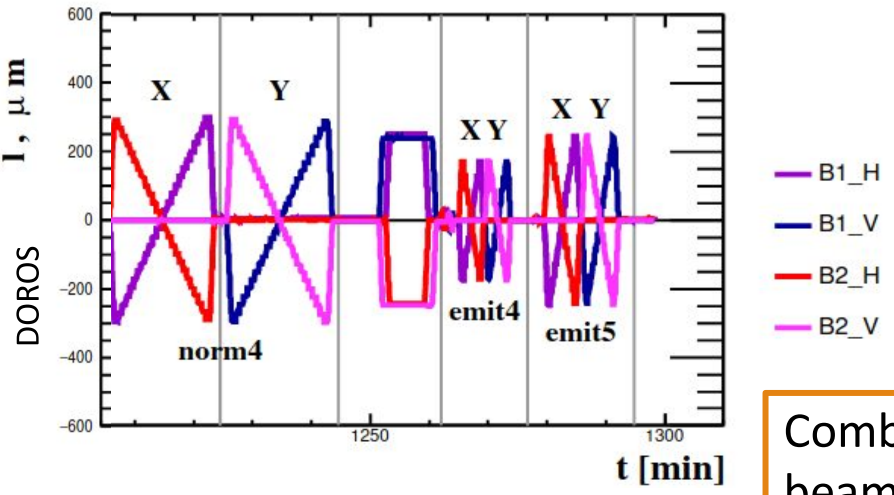
Beam current detectors
- DC Current Transformers (DDCT)
- Fast Beam Current Transformers (FBCT)

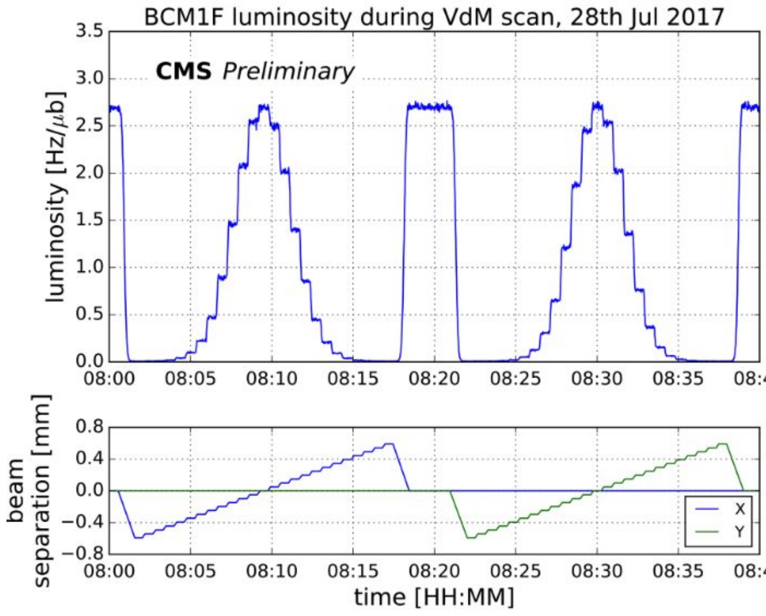
Measuring ghost and satellites
- LHC Longitudinal Density Monitor (LDM)
- LHCb Beam-Gas Imaging (BGI) using VELO

VdM calibration

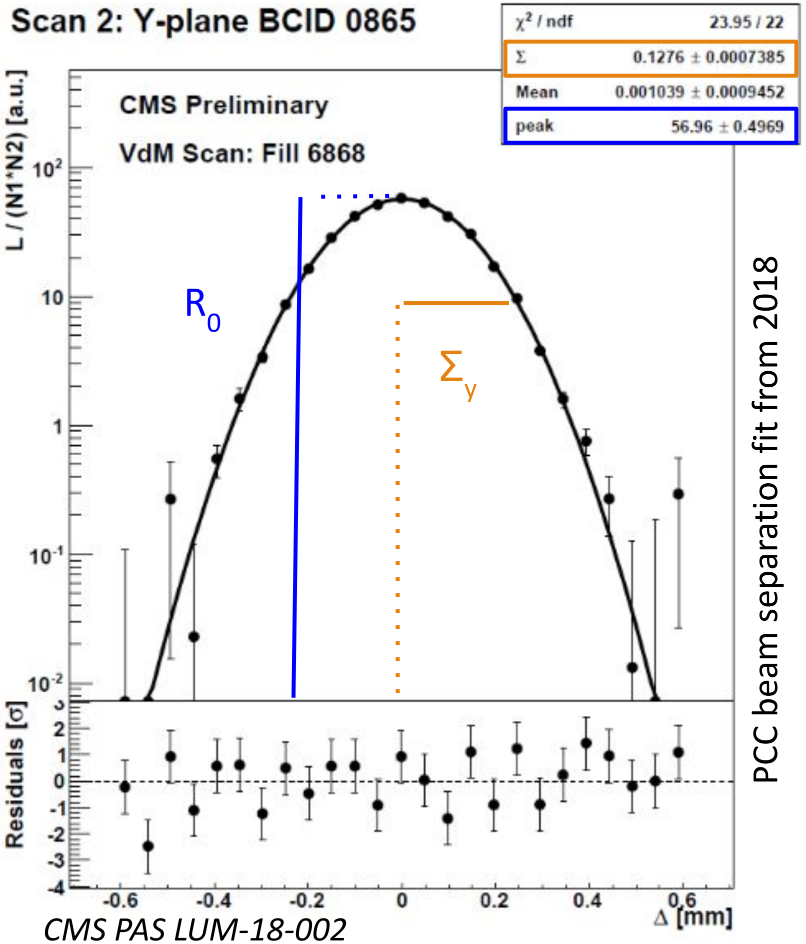
- Collision rates measured as a function of the beam separation
  - Rates from luminometers
  - Orbit from beam position monitors

CMS PAS LUM-18-002





CMS-DP-2018-062



CMS PAS LUM-18-002

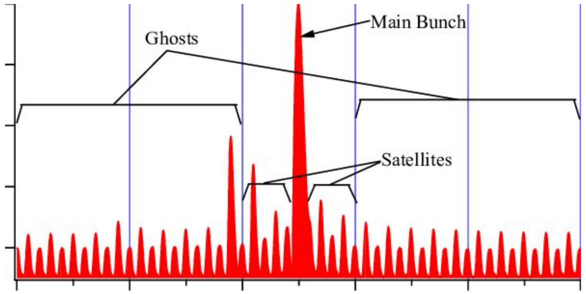
PCC beam separation fit from 2018

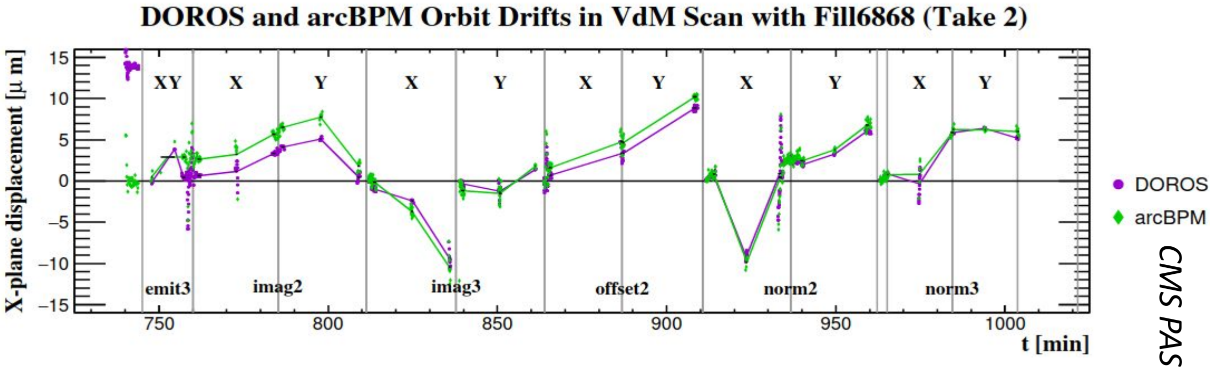
Combination of the two measurements: beam separation fit for $\Sigma_{x,y}$ and R_0

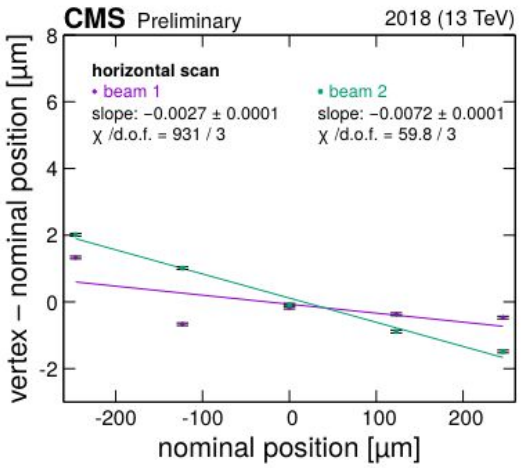
VdM (normalization) corrections I

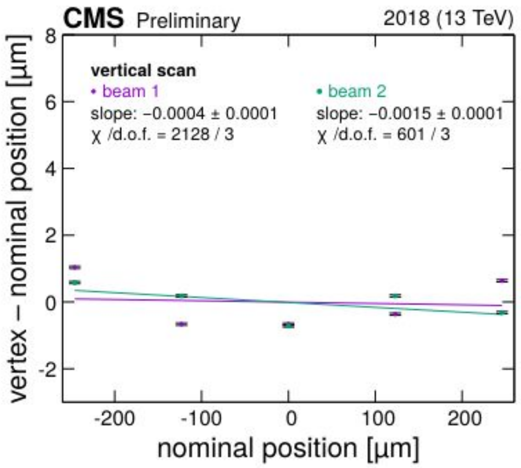
- Charge current per bunch, corrected for ghosts and satellites
- Background subtraction (luminometer specific): intrinsic noise measured for empty bunch crossings or using super separation scans (6 σ_b separation in both directions)
- Linear and residual orbit drift corrections: from interpolation between measured head-on positions and positions per step during scans
- Length scale: correction of the nominal beam positions to use the CMS length scale extracted from vertex positions

CERN-ATS-Note-2012-029









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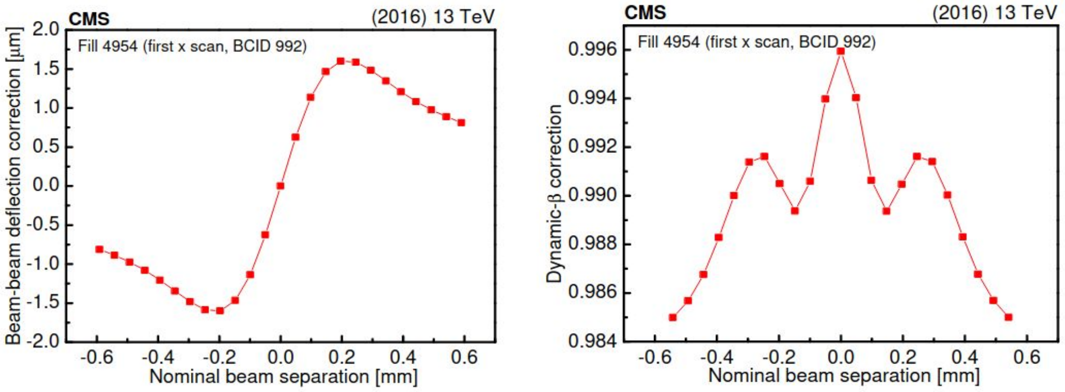
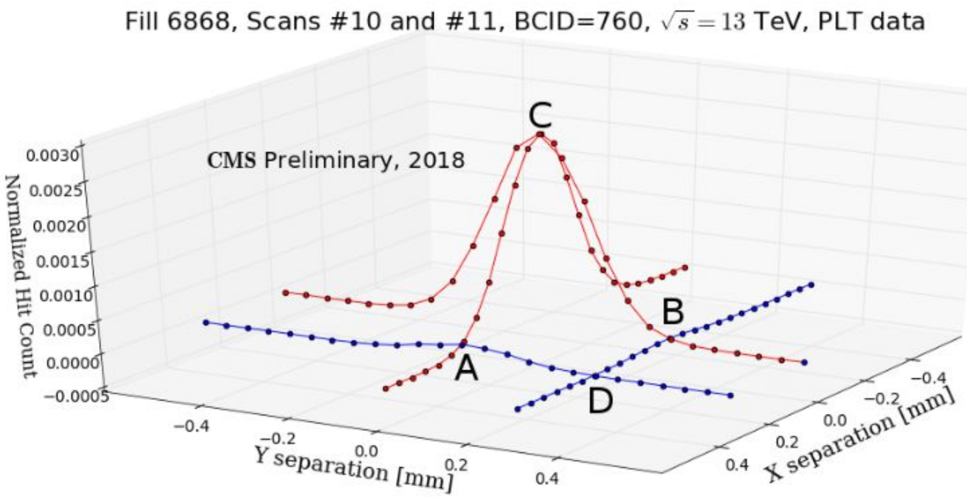
VdM (normalization) corrections II

- Beam-beam effects: electromagnetic interaction between the two beams leads to a deflection from the nominal position and an optical distortion effect on the bunch shapes (dynamic-beta)



EPJC 81, 800 (2021)

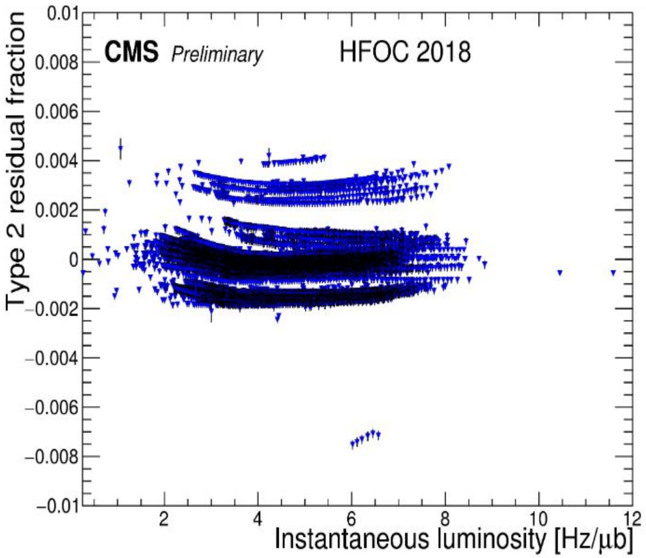
- Non-factorizable x and y bunch proton density function, calculated from specific separation scans (imaging, offset and diagonal) or by studying the luminous region parameters in standard VdM scans



CMS PAS LUM-18-002

Corrections for data-taking (integration)

- Out-of-time corrections: packed trains of filled bunches arriving during data-taking
  - type-1: effect on the next bunch crossing
  - type-2: late hits, nuclear excitations, etc
    - exponential time development
- Efficiency corrections: reduced response due to irradiation, ageing or other detector specific effects.
- Absolute calibration form short, vdM-like emittance scans recorded during physics runs since 2017



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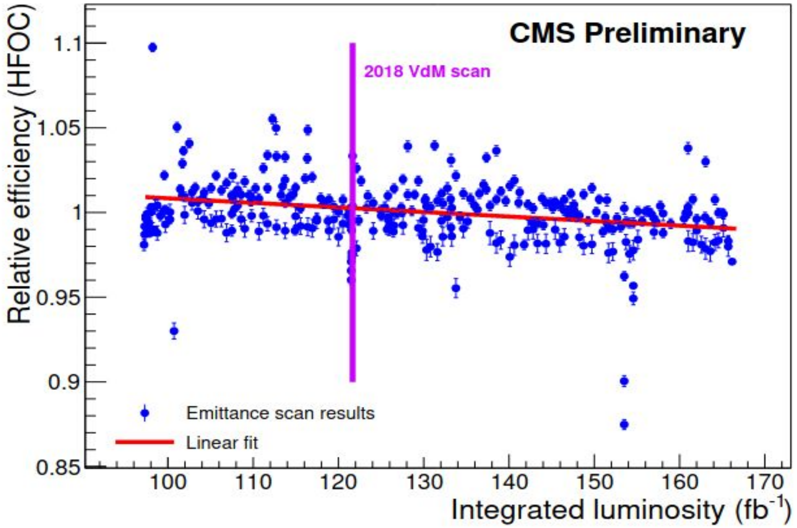

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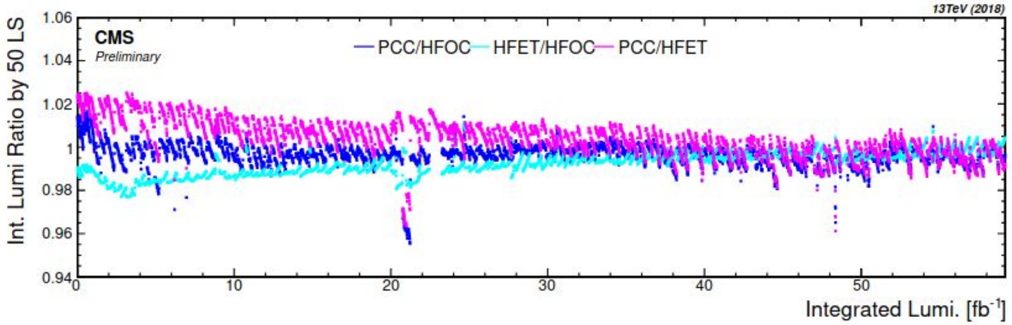
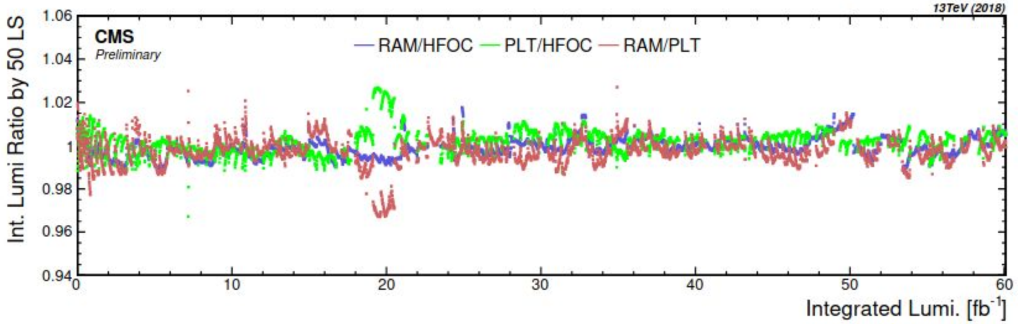
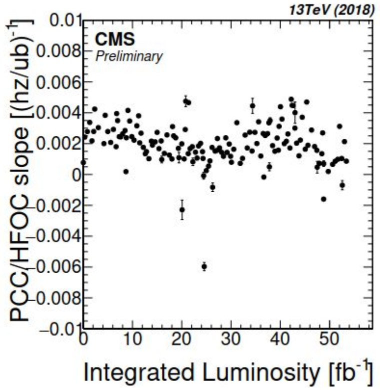
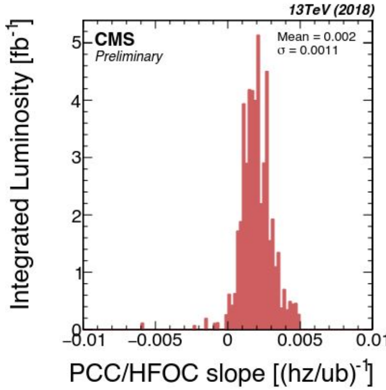
Luminosity under physics conditions

CMS PAS LUM-18-002



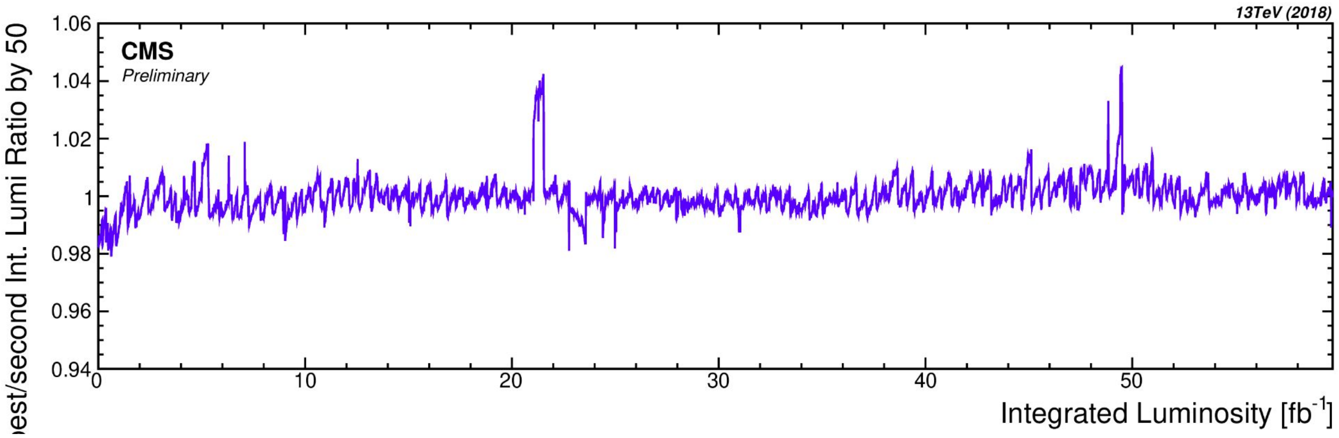






CMS PAS LUM-18-002

- Final selection of the primary luminometer (HFOC in 2018), its data is used for luminosity estimations.
- Uncertainty comes from the comparison of well-performing, stable luminometers.



CMS PAS LUM-18-002

long-term comparison of the measured luminosities by various independently calibrated luminometers

Uncertainties in Run 2

Uncertainty on the σ_{vis} estimations (VdM)

Coming from the extrapolation of the calibration to high pileup conditions, and from the stability of the measurements

	Systematic	Uncertainty in 2016 (%)	Preliminary uncertainty in 2017 (%)	Preliminary uncertainty in 2018 (%)
Normalization	Length scale	0.3	0.3	0.2
	Linear orbit drift	0.1	0.2	0.1
	Residual orbit drift	0.5	0.2	0.1
	x-y nonfactorization	0.5	0.8	2.0
	Beam-beam deflection Dynamic-β	0.5	0.6	0.2
	Beam current calibration	0.2	0.3	0.2
	Ghosts and satellites	0.1	0.1	0.1
	Scan to scan variation	0.3	0.9	0.3
	Bunch to bunch variation		0.1	0.1
	Cross-detector consistency		0.6	0.5
	Background (detector specific)		0.1	0.1
Integration	Out-of-time effects (detector specific)	0.3⊕0.3	0.2⊕0.3	0.2⊕0.4
	Cross-detector stability	0.5	0.5	0.6
	Linearity	0.3	1.5	1.1
	CMS deadtime	< 0.1	0.5	<0.1
	Total uncertainty	**1.2**	**2.3**	**2.5**

Derived from EPJC 81, 800 (2021), LUM-17-004, LUM-18-002

Overview

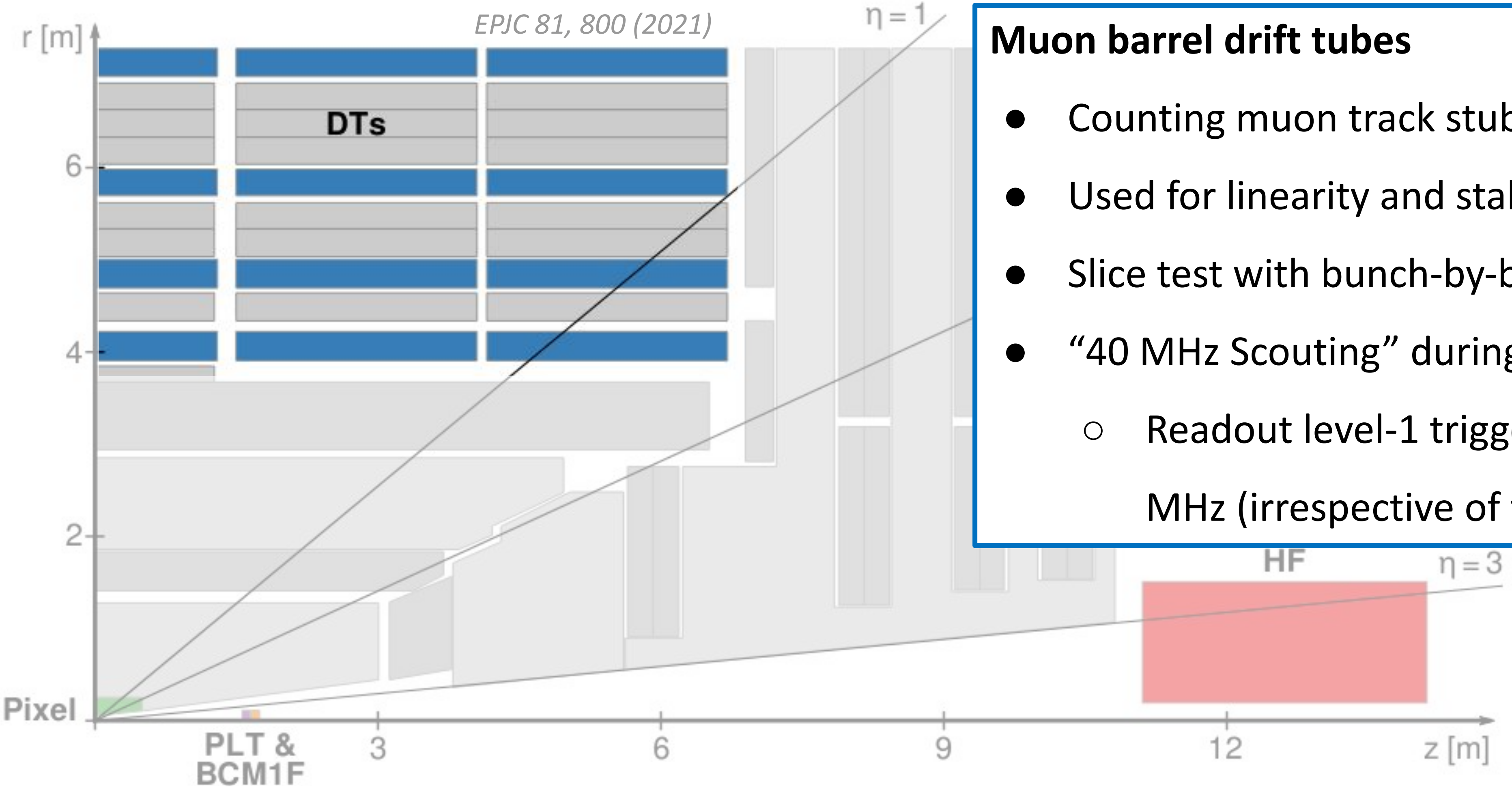
- Precise luminosity measurements during Run 2
  - Reaching 1.2% precision in 2016 pp@13 TeV
  - Combined 1.6% preliminary precision for Run 2
- Expectations for Run-3: continue understanding the dominant sources of systematics to achieve more precise luminosity calculations with partially rebuilt / upgraded detectors
  - Opportunity to test some of the Phase-2 (HL-LHC) systems: muon barrel stubs and “40 MHz Scouting” (muon candidates, potentially calorimeter observables), semi-online pixel cluster counting

References

- CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3”, *CERN-EP-2023-136*
- CMS Collaboration, “CMS Luminosity Measurement for the 2017 Data-Taking Period at 13 TeV”, *CMS PAS LUM-17-004*
- CMS Collaboration, “CMS Luminosity Measurement for the 2018 Data-Taking Period at 13 TeV”, *CMS PAS LUM-18-002*
- CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at 13 TeV in 2015 and 2016 at CMS”, *EPJC 81, 800 (2021)*
- CMS Collaboration, “BCM1F and Luminosity calibration”, *CMS-DP-2018-062*
- CMS Collaboration, “The Pixel Luminosity Telescope: A detector for luminosity measurements at CMS using silicon pixel sensors”, *CMS-DP-2021-020*

Luminometers at the CMS

- Requirement: linear signal-luminosity dependency or measuring and correcting non-linearity



Muon barrel drift tubes

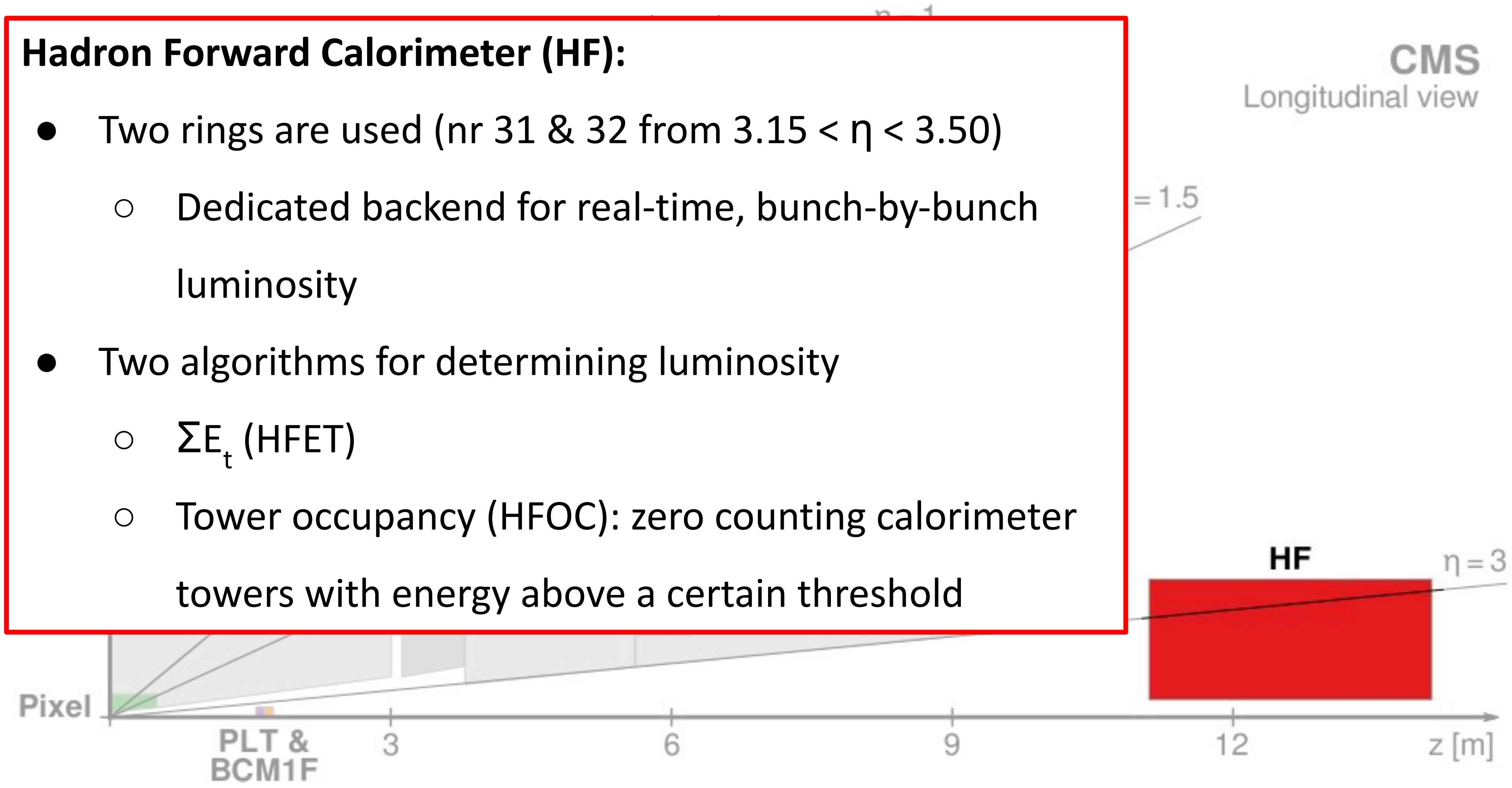
- Counting muon track stubs
- Used for linearity and stability cross-checks
- Slice test with bunch-by-bunch resolution
- “40 MHz Scouting” during Run 3
  - Readout level-1 trigger objects with 40 MHz (irrespective of trigger decision)

Luminometers at the CMS

- Requirement: linear signal-luminosity dependency or measuring and correcting non-linearity

Hadron Forward Calorimeter (HF):

- Two rings are used (nr 31 & 32 from 3.15 < η < 3.50)
  - Dedicated backend for real-time, bunch-by-bunch luminosity
- Two algorithms for determining luminosity
  - ΣE_t (HFET)
  - Tower occupancy (HFOC): zero counting calorimeter towers with energy above a certain threshold



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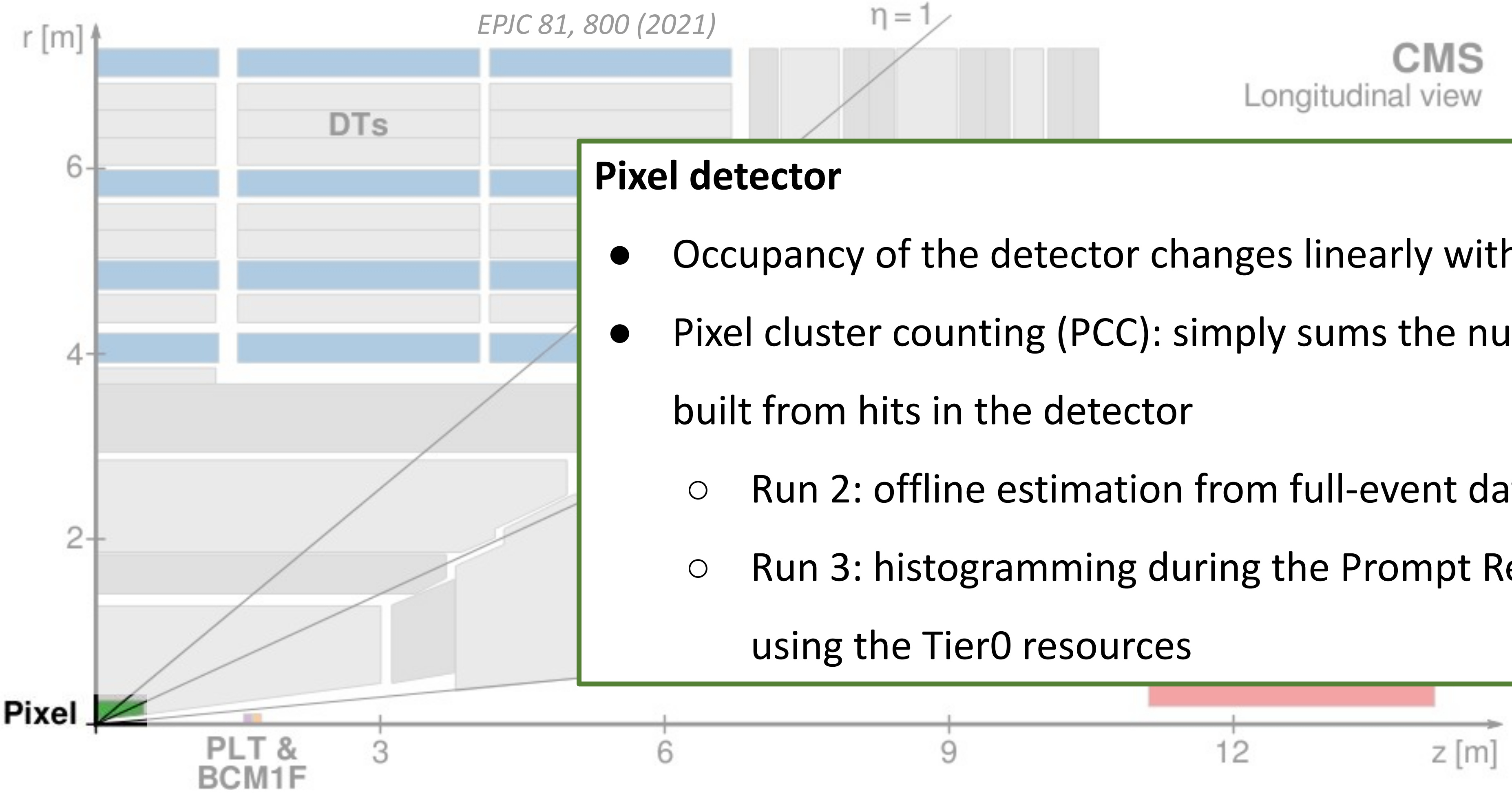
EPJC 81, 800 (2021)

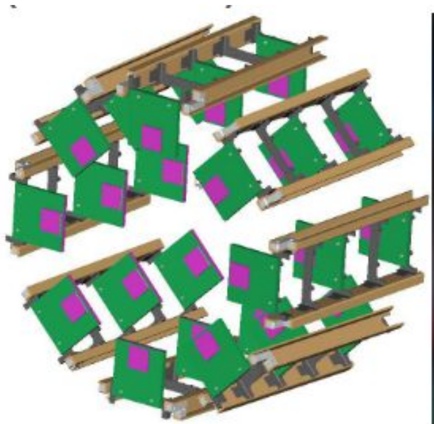


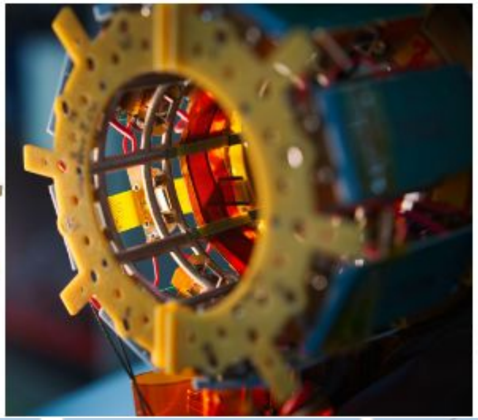
Pixel detector

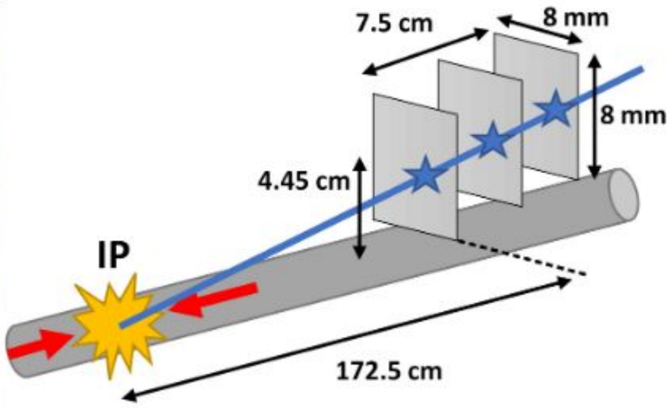
- Occupancy of the detector changes linearly with the luminosity
- Pixel cluster counting (PCC): simply sums the number of clusters built from hits in the detector
  - Run 2: offline estimation from full-event data
  - Run 3: histogramming during the Prompt Reconstruction using the Tier0 resources

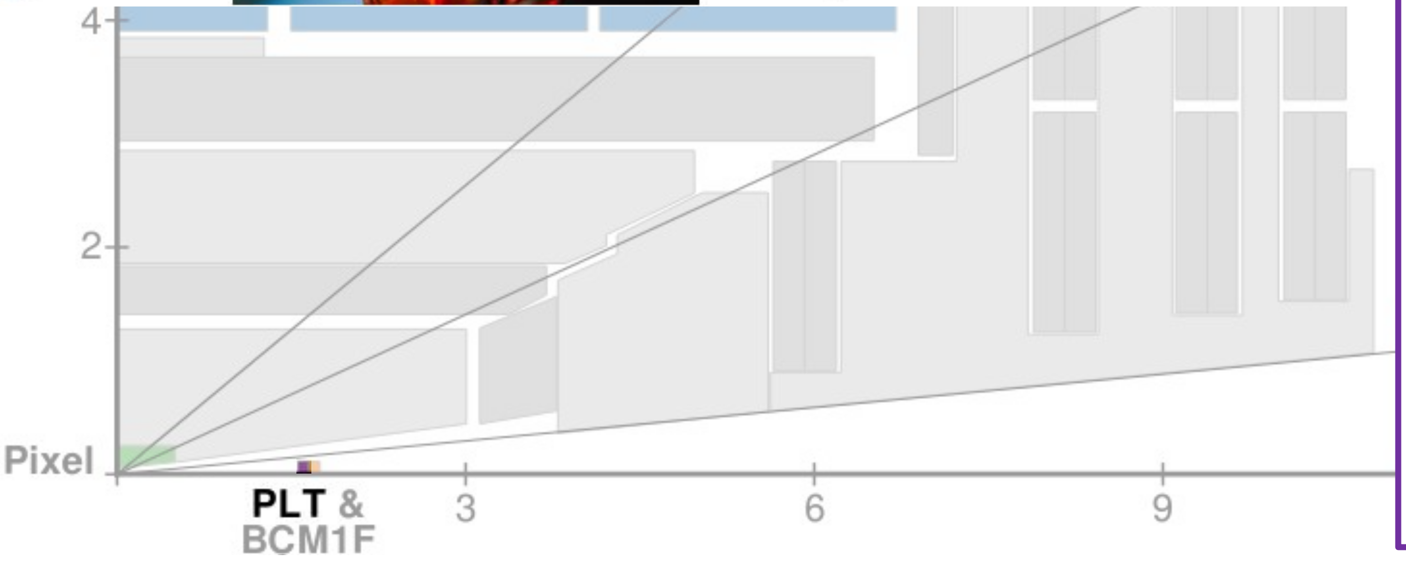
Luminometers at the CMS

- Requirement: linear signal-luminosity dependency or measuring and correcting non-linearity







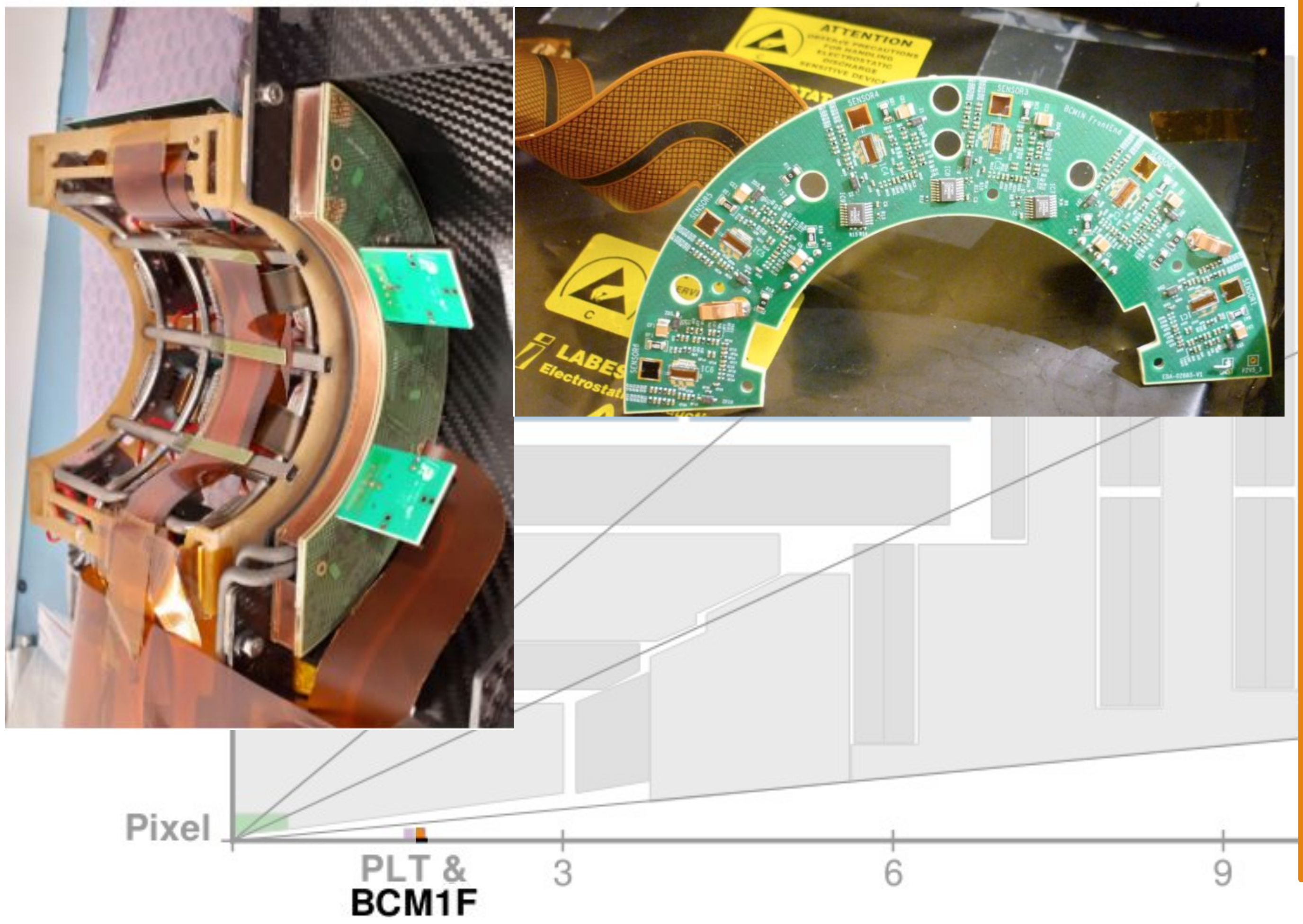


Pixel Luminosity Telescope (PLT)

- Pixel planes in a telescope arrangement
  - Phase-0 pixel sensors
  - Run 3: rebuilt PLT, one telescope equipped with Phase-2 sensor prototypes
- Counting triple-coincidences
- Real-time, bunch-by-bunch luminosity calculations

Luminometers at the CMS

- Requirement: linear signal-luminosity dependency or measuring and correcting non-linearity



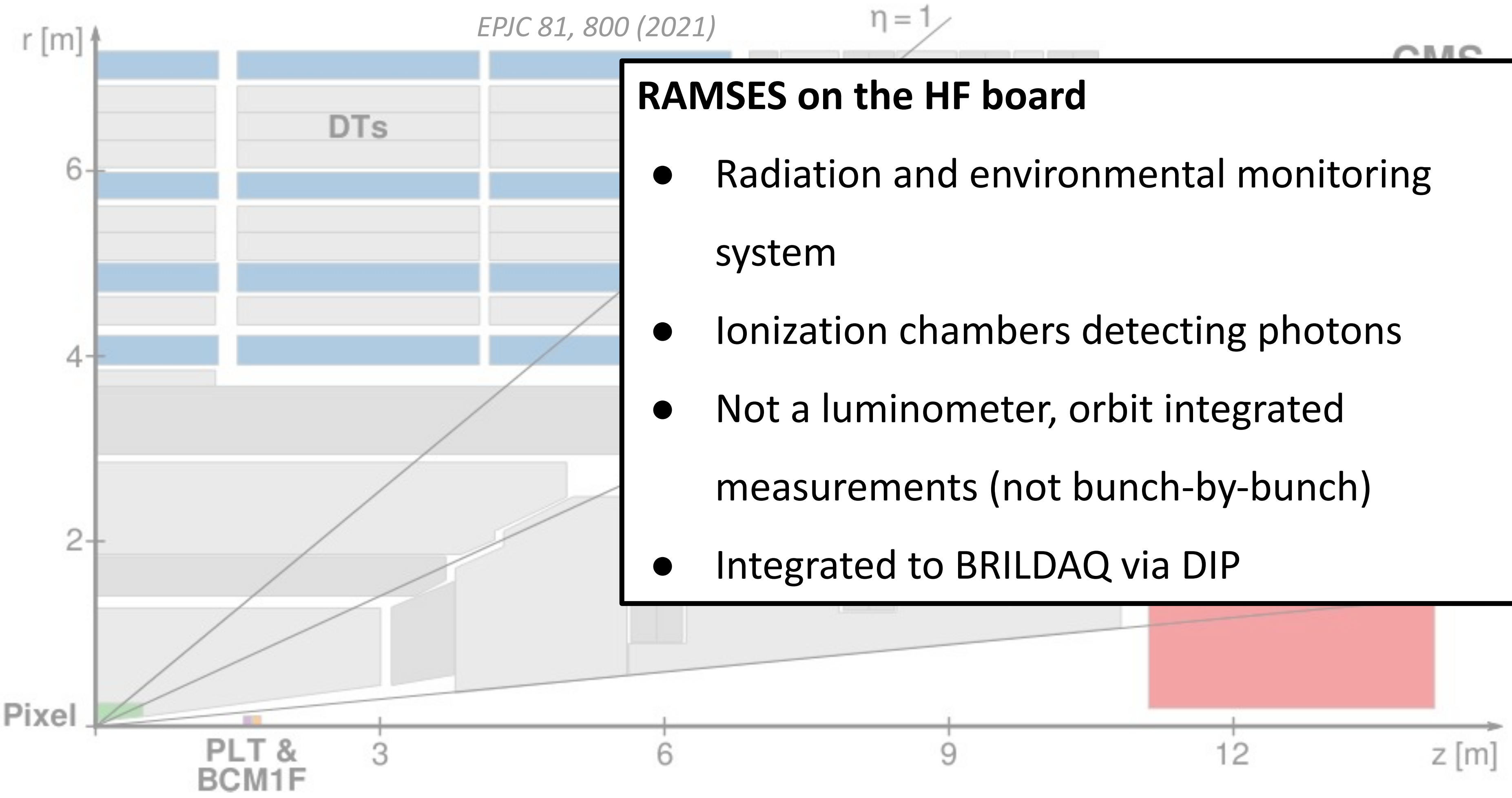
Fast Beam Condition Monitor (BCM1F):

- Silicon and diamond sensors mounted on a C-shape holder (48 altogether)
  - Run 3: fully equipped with silicon sensors. Active cooling and Phase-2 prototypes
- Zero counting
- Machine induced background measurements
- Real-time, bunch-by-bunch lumi

Luminometers at the CMS

- Requirement: linear signal-luminosity dependency or measuring and correcting non-linearity

EPJC 81, 800 (2021)

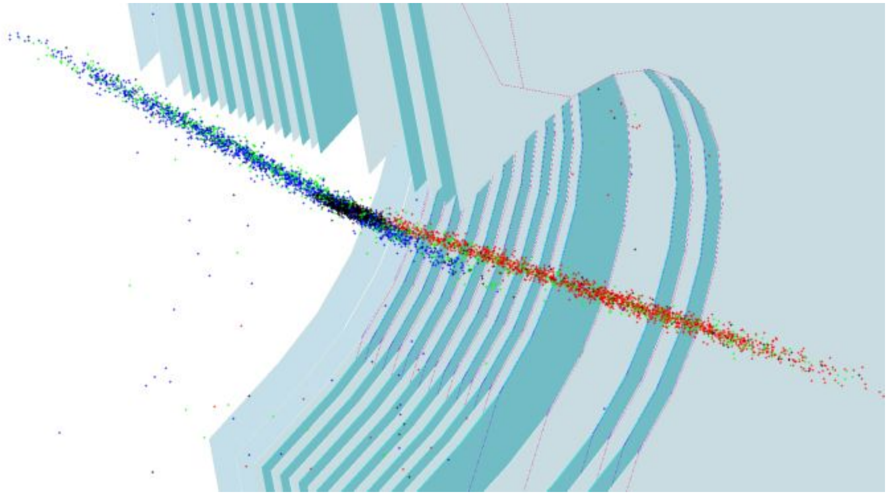


RAMSES on the HF board

- Radiation and environmental monitoring system
- Ionization chambers detecting photons
- Not a luminometer, orbit integrated measurements (not bunch-by-bunch)
- Integrated to BRILDAQ via DIP

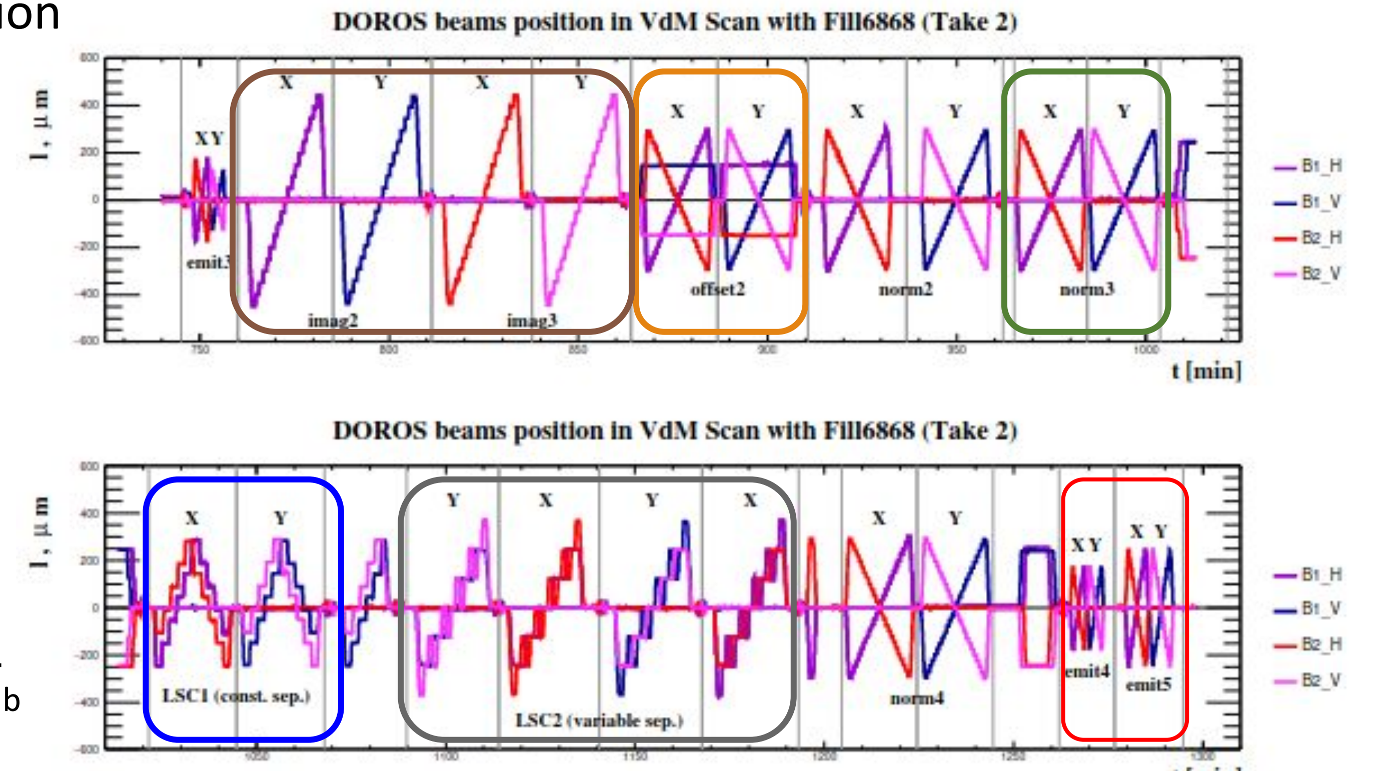
Beam quality and position monitors

- Beam position monitors (BPM) to measure the orbit of the circulating beams, based on image charges
  - Diode ORbit and OScillation (DOROS) detectors
  - Arc BPM detectors
- Beam current detectors
  - DC Current Transformers (DDCT)
  - Fast Beam Current Transformers (FBCT)
- Measuring ghost and satellites
  - LHC Longitudinal Density Monitor (LDM)
  - LHCb Beam-Gas Imaging (BGI) using VELO



VdM fill at CMS

- Emittance scan
  - ±2 σ_b maximal displacement in each direction
- Ordinary VdM scan
  - ±3 σ_b maximal displacement in each direction
- Offset scan
  - VdM, but ±1.5 σ_b transverse displacement
- Beam imaging scan
  - ±4.5 σ_b maximal displacement with one scanning beam
- Constant length-scale
  - 1.4 σ_b separation kept for several positions
- Variable length-scale
  - Mini-scans with 3 steps (-1.25 σ_b, 0, 1.25 σ_b separation) for several positions



CMS PAS LUM-18-002