Precision luminosity calibration with proton-proton collisions at the CMS experiment

Zimányi School 2024

Attila Rádl

Luminosity

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

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

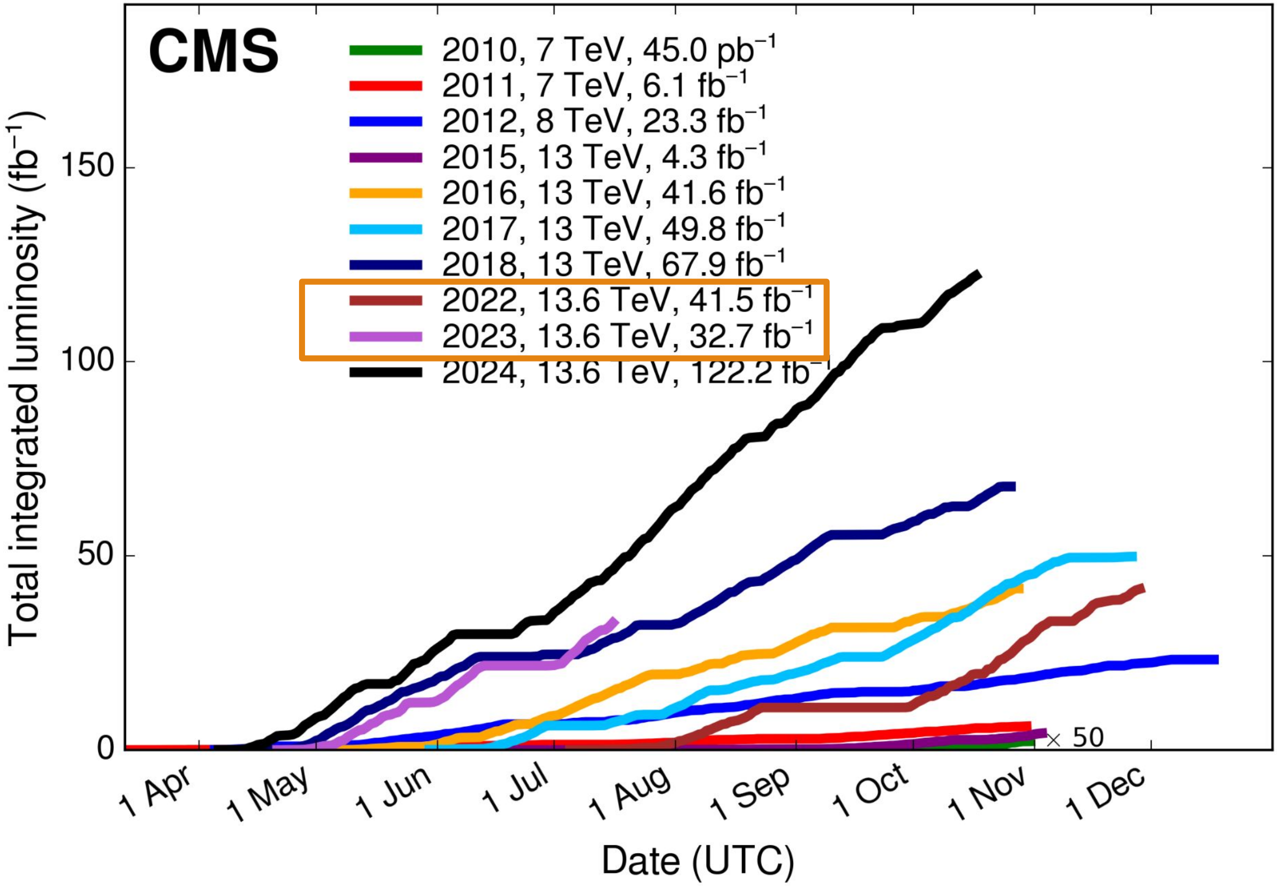
- Time integrated: represents the amount of data recorded

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

- Number of interesting events in a sample

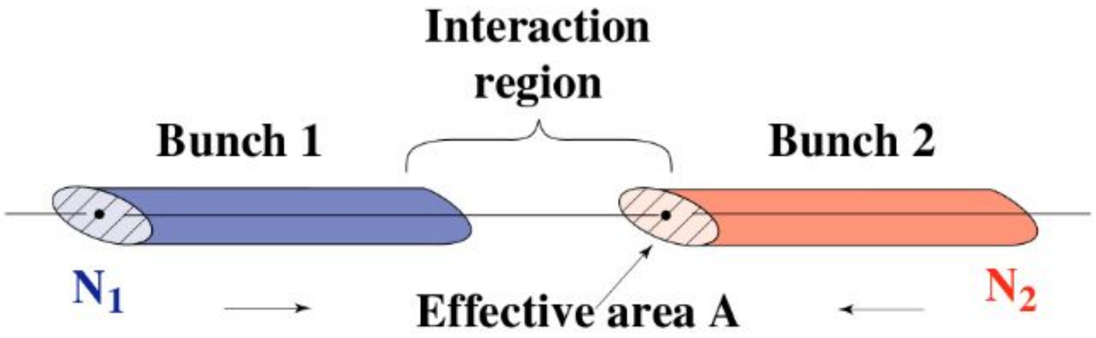
$$N = L\ \sigma_p$$

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



Luminosity for colliding beams

- Precise measurement of absolute luminosity
- Luminosity for two "head-on" colliding bunches
  - Essential properties: proton density function (ρ_i), number of protons in the bunches ($N^i_{1/2}$)
  - Effective area: beam overlap integral



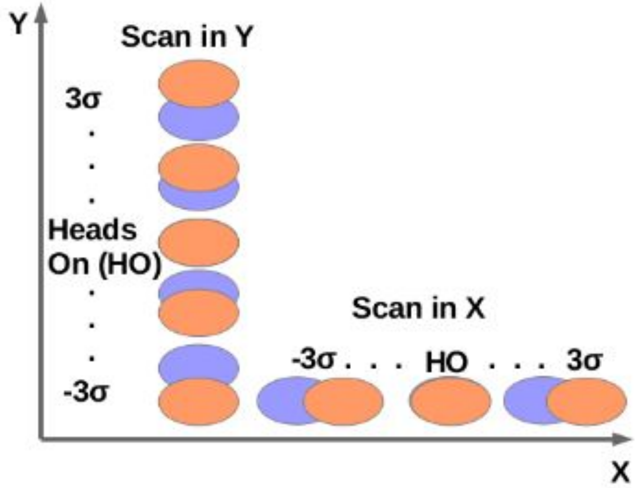
$$\mathcal{L}^i_{\text{inst}} = N^i_1 N^i_2 f \int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y = N^i_1 N^i_2 f \int \rho_{x1}(x)\rho_{x2}(x)\mathrm{d}x \int \rho_{y1}(y)\rho_{y2}(y)\mathrm{d}y$$

Assumption: x-y direction factorization

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

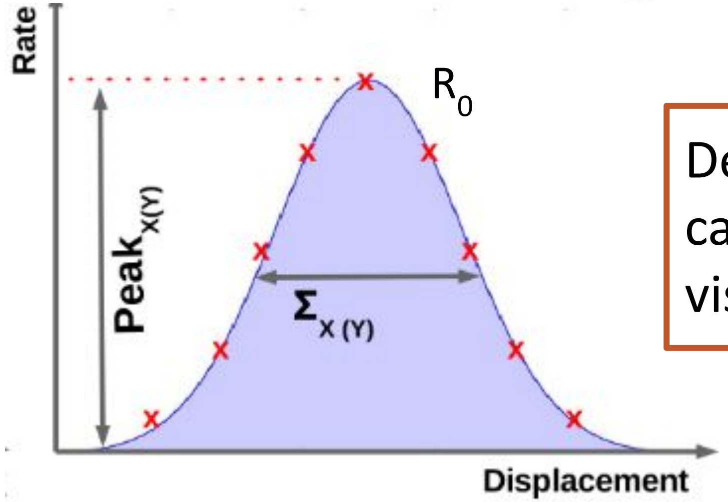
Van der Meer methodology

- 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)

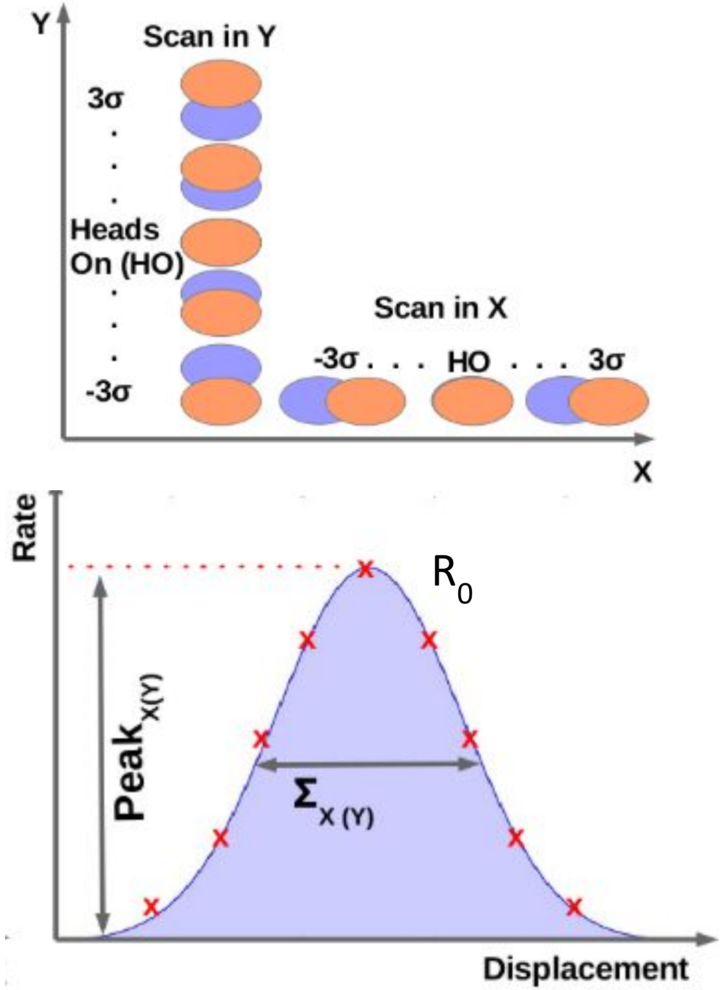


Detector specific calibration constant: visible cross-section

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

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)

Beam overlap widths from VdM scans

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

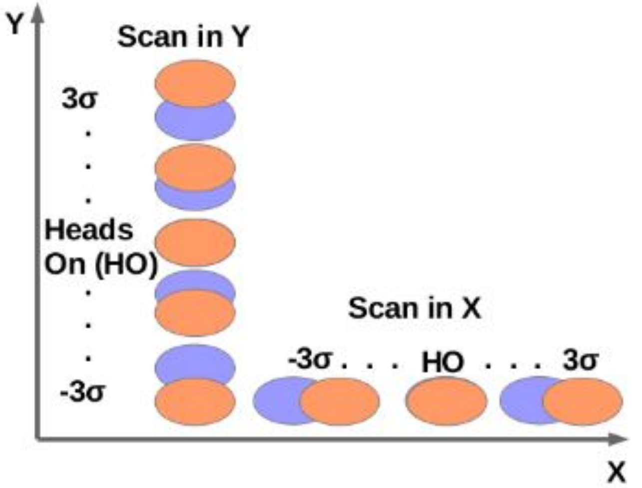
Zero separation rate

LHC orbit revolution frequency:
f = 11245.5 Hz

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

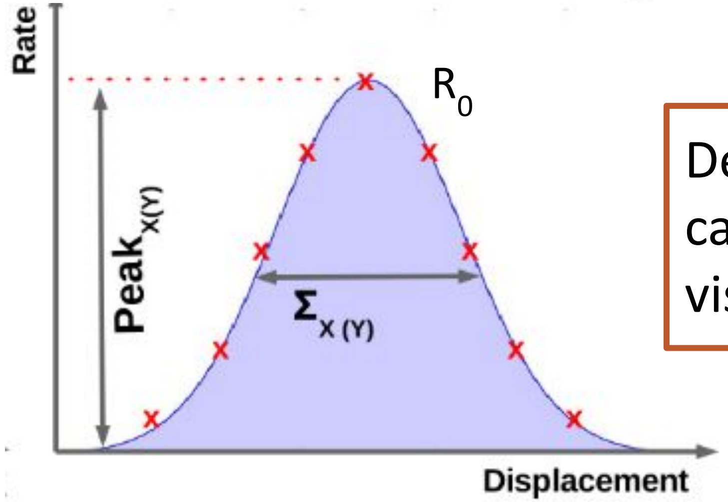
Van der Meer methodology

- 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)



Detector specific calibration constant: visible cross-section

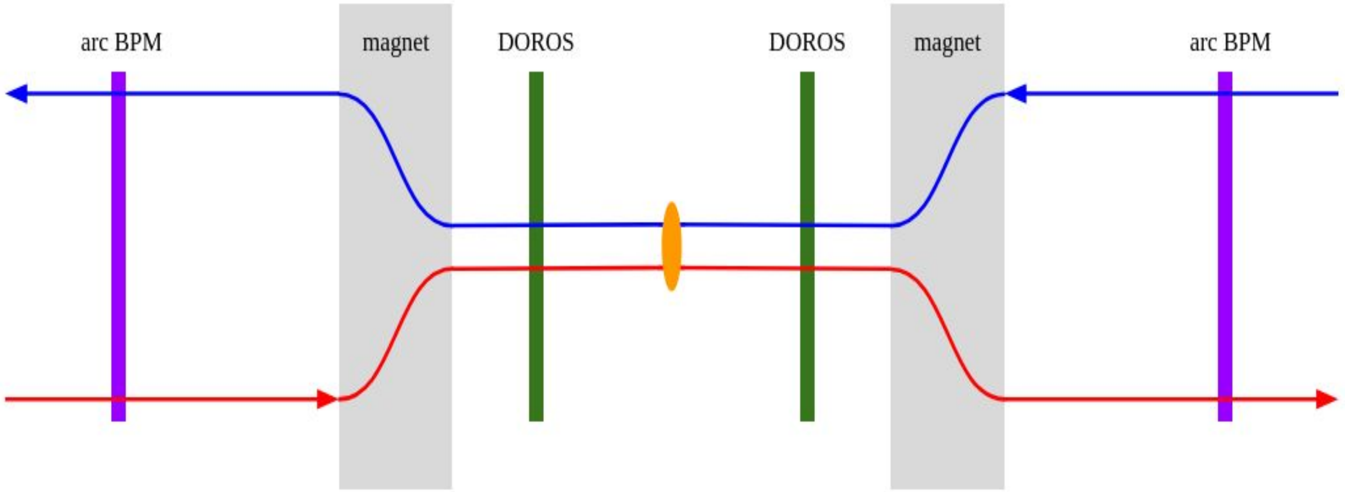
$$\sigma_{\mathrm{vis}} = \frac{2\pi\Sigma_x\Sigma_y R_0}{N_1^i N_2^i f}$$

Expectation: same σ_{vis} for regular conditions

$$R = \mathcal{L}_{\mathrm{inst}}\sigma_{\mathrm{vis}}$$

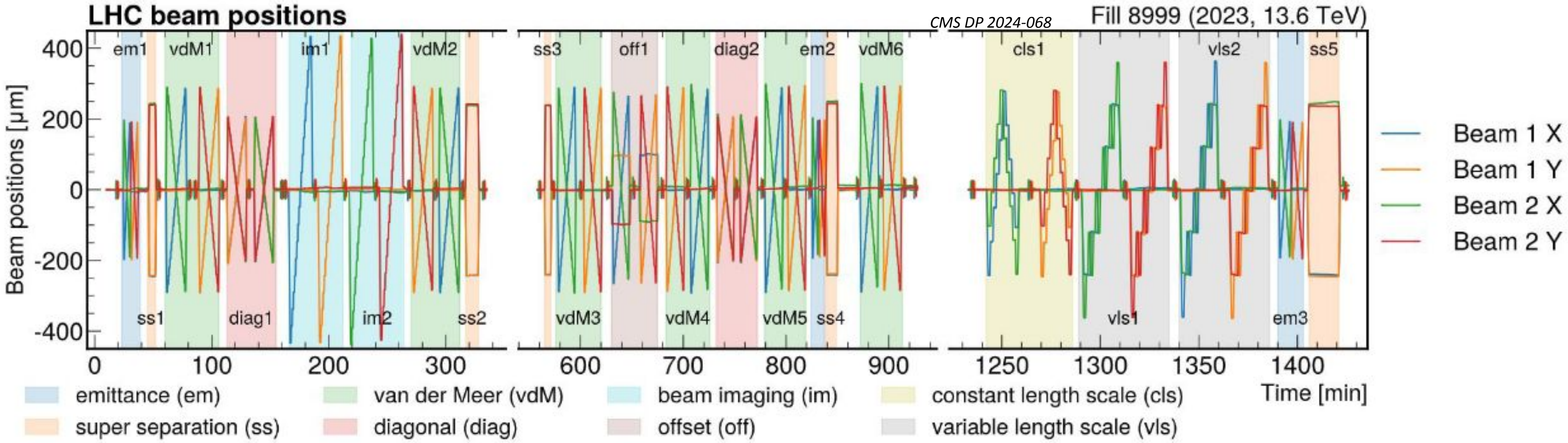
Beam position for the calibration

- Nominal defined by LHC magnet configuration
- Beam position monitors (BPM) to measure the orbit of the circulating beams
  - Based on image charges
  - Orbit integrated position for each second
  - Diode ORbit and OScillation (DOROS) inside the steering magnets
  - Arc BPMs placed outside in LHC arcs
    - Measuring the displacement compared to closed orbit, the positions are extrapolated to the IP using the LHC optics model
  - Average between the measurements of the two sides gives the position at the IP



Orbit during vdM scans

- Several scan types, each scan pair contains two orthogonal scans
- Average position per scan step (measurements performed every second)
    - Uncertainty is the std dev of the position measurements within a scan step
- Horizontal (X) and vertical (Y) positions of the two beams provided by DOROS



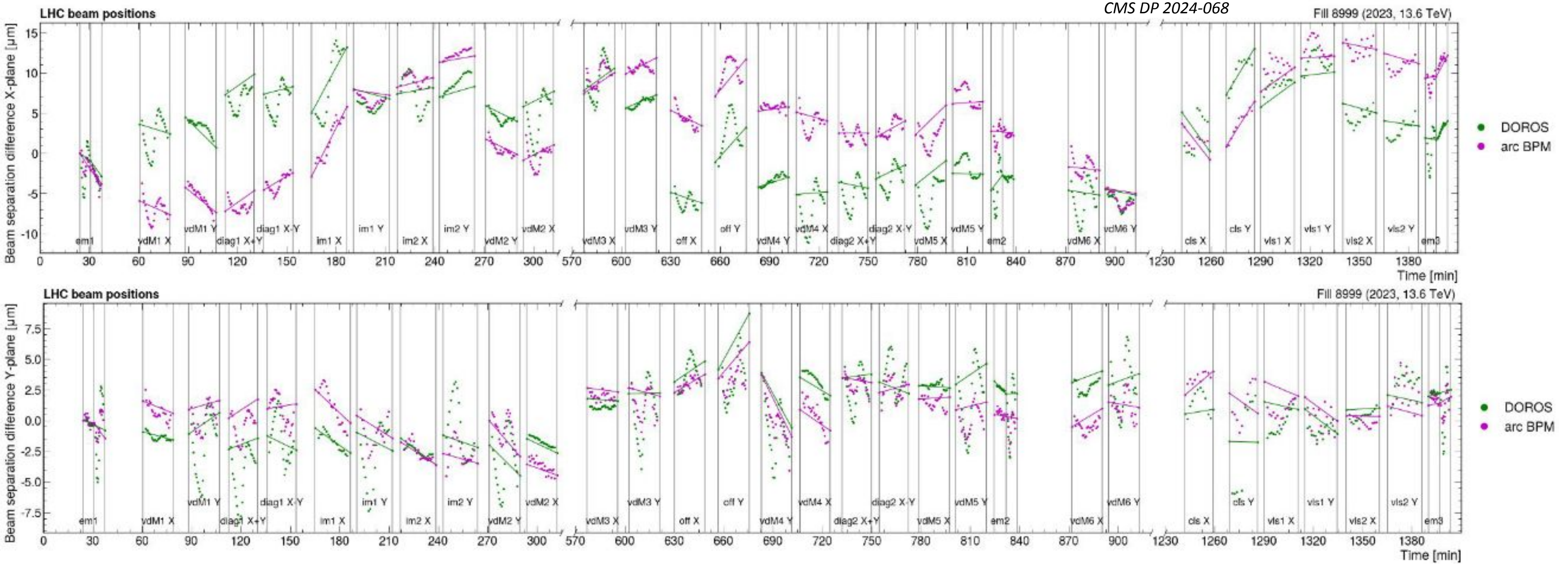
Comparison between measured and nominal

- Difference between measured and LHC nominal beam separations per scan step as a function of time
- Solid lines: measured steps (30s) for head-on periods just before and after the scans
  - Slow orbit drift component applied as a time-dependent correction

Separation: Δ = Beam 1 - Beam 2

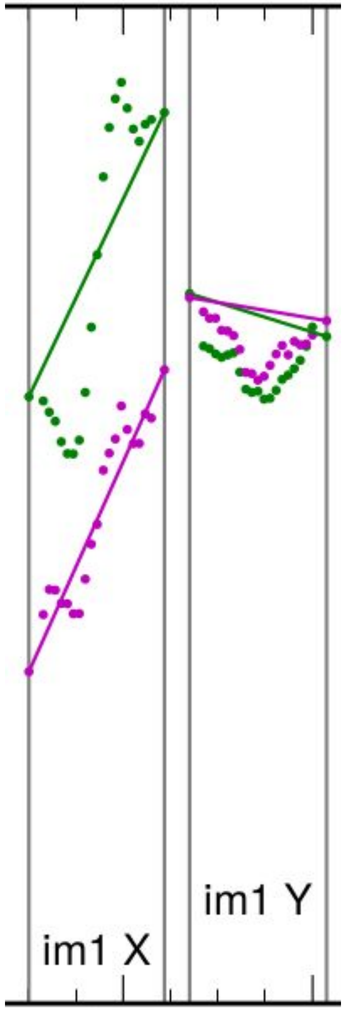
$\Delta Nom_x - \Delta BPM_x$

$\Delta Nom_y - \Delta BPM_y$



BPM calibration

- Assumption: smooth dependence between measured and nominal positions

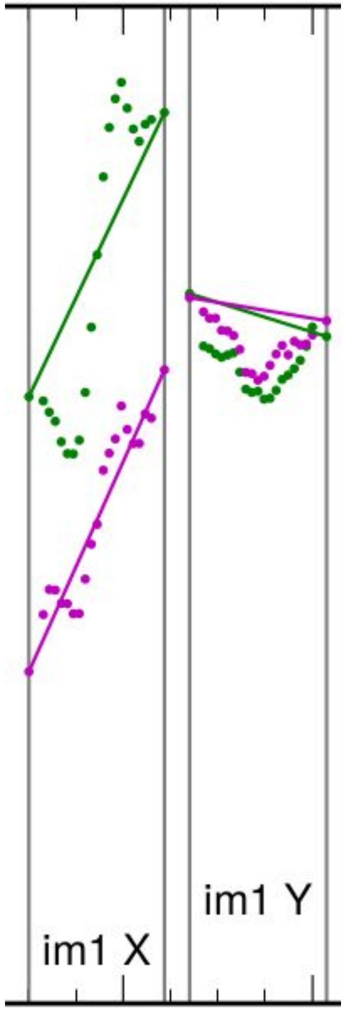


Scanning plane	$\mathbf{BPM_{x/y}}$ - $\mathbf{linOD_{x/y}}$ =
Stationary plane	$\mathbf{BPM_{y/x}}$ - $\mathbf{linOD_{y/x}}$ =

- Two beams fitted separately

BPM calibration

- Assumption: smooth dependence between measured and nominal positions
- Length-scale: $BPM_{x/y} = \alpha \times Nom_{x/y}$, where $\alpha \approx 1$



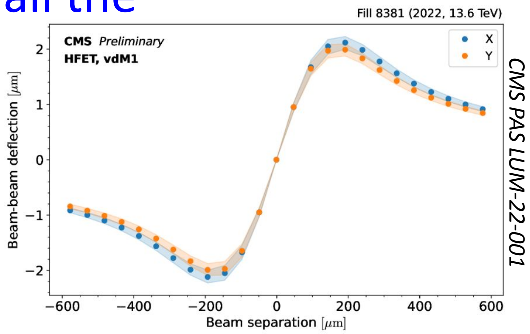
Scanning plane: $\mathbf{BPM_{x/y} - linOD_{x/y} = \alpha \times Nom_{x/y} + const_{x/y}}$

Stationary plane: $\mathbf{BPM_{y/x} - linOD_{y/x} =}$

- Two beams fitted separately

BPM calibration

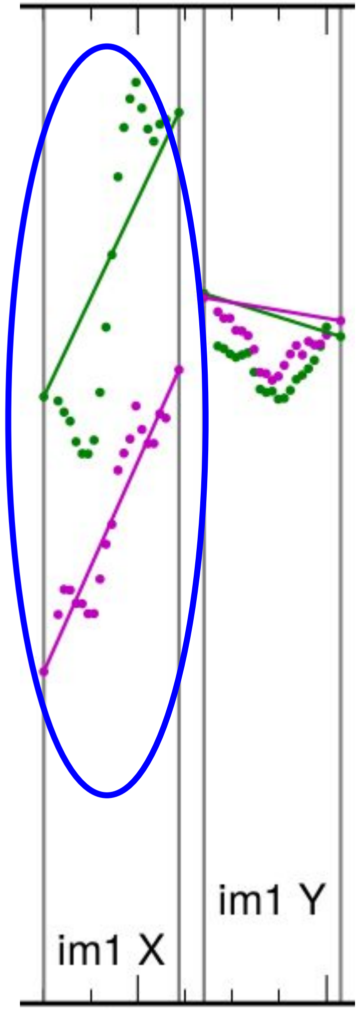
- Assumption: smooth dependence between measured and nominal positions
- Length-scale: $BPM_{x/y} = \alpha \times Nom_{x/y}$, where $\alpha \approx 1$
- Repulsion: beam-beam deflection depends on the nominal separation $BB(\Delta Nom)$
  - Fitted magnitude (β) to ensure the compatibility (ideally $\beta \approx 1$, if all the bunches are colliding)



Scanning plane: $BPM_{x/y} - linOD_{x/y} = \alpha \times Nom_{x/y} + \beta \times BB_{x/y}(\Delta Nom_{x/y}) + const_{x/y}$

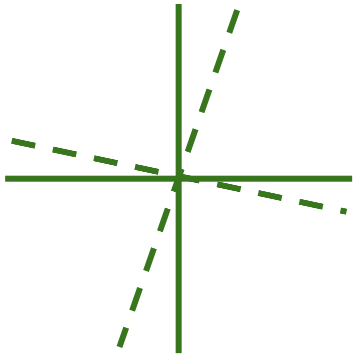
Stationary plane: $BPM_{y/x} - linOD_{y/x} =$

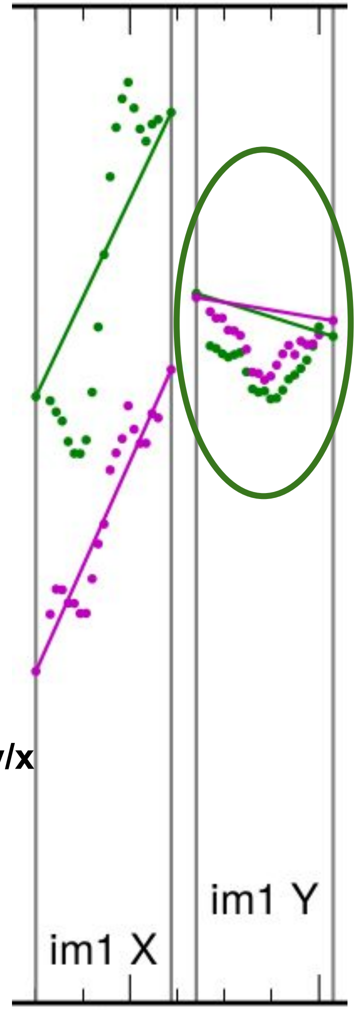
- Two beams fitted separately



BPM calibration

- Assumption: smooth dependence between measured and nominal positions
- Length-scale: $BPM_{x/y} = \alpha \times Nom_{x/y}$, where $\alpha \approx 1$
- Repulsion: beam-beam deflection depends on the nominal separation BB(ΔNom)
  - Fitted magnitude (β) to ensure the compatibility (ideally $\beta \approx 1$, if all the bunches are colliding)
- Factor to address misalignment between measured and nominal plane (γ)
  - The coordinate systems may not be perfectly aligned (ideally $\gamma \approx 0$)





Scanning plane	$BPM_{x/y} - linOD_{x/y} = \alpha \times Nom_{x/y} + \beta \times BB_{x/y}(\Delta Nom_{x/y}) + const_{x/y}$
Stationary plane	$BPM_{y/x} - linOD_{y/x} = \gamma \times Nom_{x/y} + (\gamma/\alpha \times \beta) \times BB_{x/y}(\Delta Nom_{x/y}) + const_{y/x}$

- Two beams fitted separately

Fit parameters

- Expectation: α and β parameters are stable over long time periods
  - Several fitting procedures based on globally fitted parameters

<table>
<tr><th>name</th><th>α</th><th>β</th><th>γ</th><th>$\text{const}_{\text{scanning}}$</th><th>$\text{const}_{\text{stationary}}$</th></tr>
<tr><td>separate</td><td>per scan</td><td>per scan</td><td rowspan="4">per scan</td><td rowspan="4">per scan</td><td rowspan="4">per scan</td></tr>
<tr><td>global length scale</td><td>global</td><td>per scan</td></tr>
<tr><td>global beam-beam amplitude</td><td>per scan</td><td>global</td></tr>
<tr><td>global length scale and beam-beam amplitude</td><td>global</td><td>global</td></tr>
</table>

Scanning plane

$$\mathrm{BPM}_{x/y} - \mathrm{linOD}_{x/y} = \alpha \times \mathrm{Nom}_{x/y} + \beta \times \mathrm{BB}_{x/y}(\Delta \mathrm{Nom}_{x/y}) + \mathrm{const}_{x/y}$$

Stationary plane

$$\mathrm{BPM}_{y/x} - \mathrm{linOD}_{y/x} = \gamma \times \mathrm{Nom}_{x/y} + (\gamma/\alpha \times \beta) \times \mathrm{BB}_{x/y}(\Delta \mathrm{Nom}_{x/y}) + \mathrm{const}_{y/x}$$

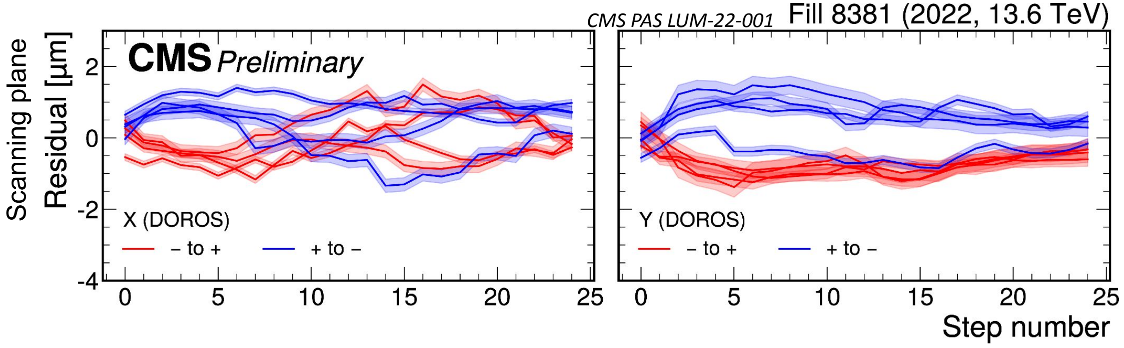
Fitted positions

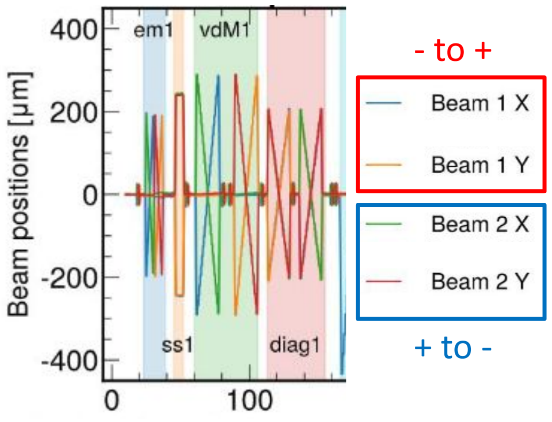
- Two beams fitted separately

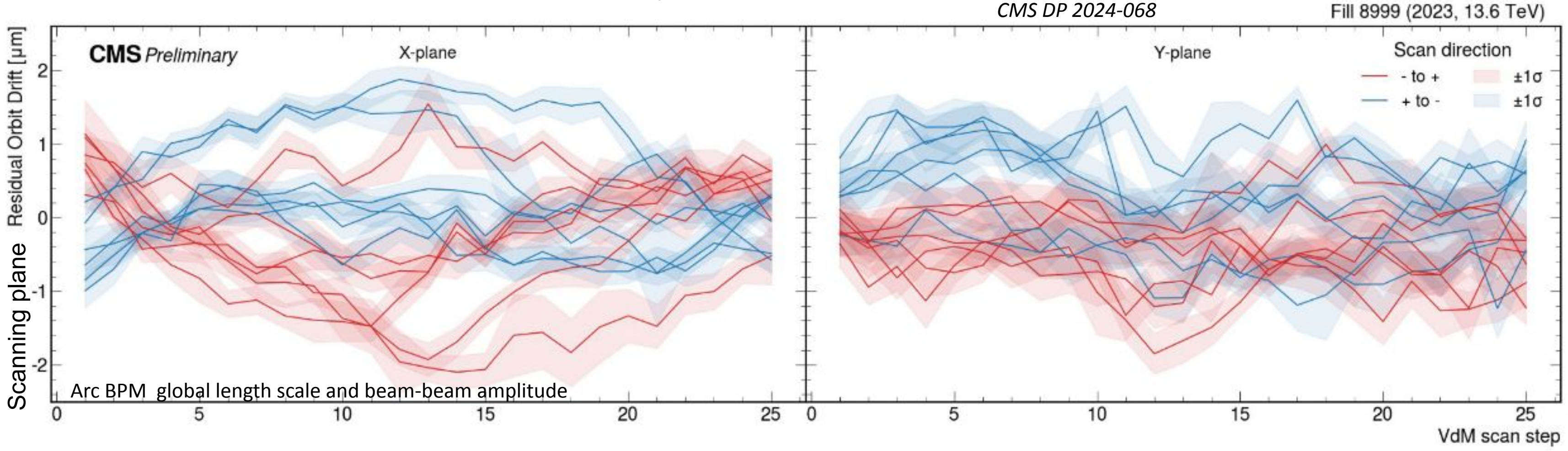
Residual beam positions

Residual orbit drift = BPM - linOD - Fitted

- Difference between the measurements that are cleaned from linear orbit drift and the fitted model
- Fitted constants $const_{x/y}$ are not subtracted
  - Considered as part of the magnetic hysteresis effect
- Residuals are added to the nominal positions to address the residual movement of the beams
- Calibration constant (σ_{vis}) is calculated for each fit strategy
  - Central corrections from the fits with the best scan-to-scan consistency







Preliminary uncertainties in Run 3

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 sources	Preliminary uncertainty in 2022 (%)	Preliminary uncertainty in 2023 (%)
Normalization	Beam current	0.2	0.2
	Ghosts and satellites	0.2	0.1
	Orbit drift	0.1	0.02
	Residual beam positions	0.3	0.16
	Beam-beam effects	0.4	0.34
	Length scale	0.1	0.2
	Factorization bias	0.8	0.67
	Scan-to-scan variation	0.28	0.5
	Bunch-to-bunch variation	0.1	0.06
	Cross-detector consistency	0.4	0.16
Integration	HFET OOT pileup corrections	0.2	
	Cross-detector stability	0.5	0.71
	Cross-detector linearity	0.5	0.59
	Total uncertainty	**1.4**	**1.28**

Derived from CMS-PAS-LUM-22-001, CMS DP-2024/068

Preliminary uncertainties in Run 3

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 sources	Preliminary uncertainty in 2022 (%)	Preliminary uncertainty in 2023 (%)
Norm			
	Orbit drift	0.1	0.02
	Residual beam positions	0.3	0.16
		0.4	0.34
		0.1	0.2
		0.8	0.67
		0.28	0.5
			0.06
	Cross-detector consistency	0.4	0.16
Integration	HFET OOT pileup corrections	0.2	
	Cross-detector stability	0.5	0.71
	Cross-detector linearity	0.5	0.59
	Total uncertainty	**1.4**	**1.28**

Residual beam positions uncertainty is correlated over the years

Systematic	Uncertainty in 2016 (%)
Linear orbit drift	0.1
Residual orbit drift	0.5

EPJC 81, 800 (2021)

Significant improvement compared to 2016

Derived from CMS-PAS-LUM-22-001, CMS DP-2024/068

Overview

- Preliminary luminosity results for Run 3 (2022, 2023)
  - Total estimated uncertainty is close to 1% for both data-taking periods
  - Significantly lower than the Run 2 preliminary results (around 2.5%)
  - Final 2016 uncertainty (1.2%) comparable with our preliminary results in Run 3
- Precise beam position measurements are crucial for the calibration
  - Linear and residual orbit drift corrections are applied on the nominal LHC beam positions
  - The corresponding uncertainty has small impact compared to some of the other sources since the new method is introduced

This work was supported by the National Research, Development and Innovation Office of Hungary (K 143460, K 146913, K 146914, 2021-4.1.2-NEMZ_KI-2024-00036)

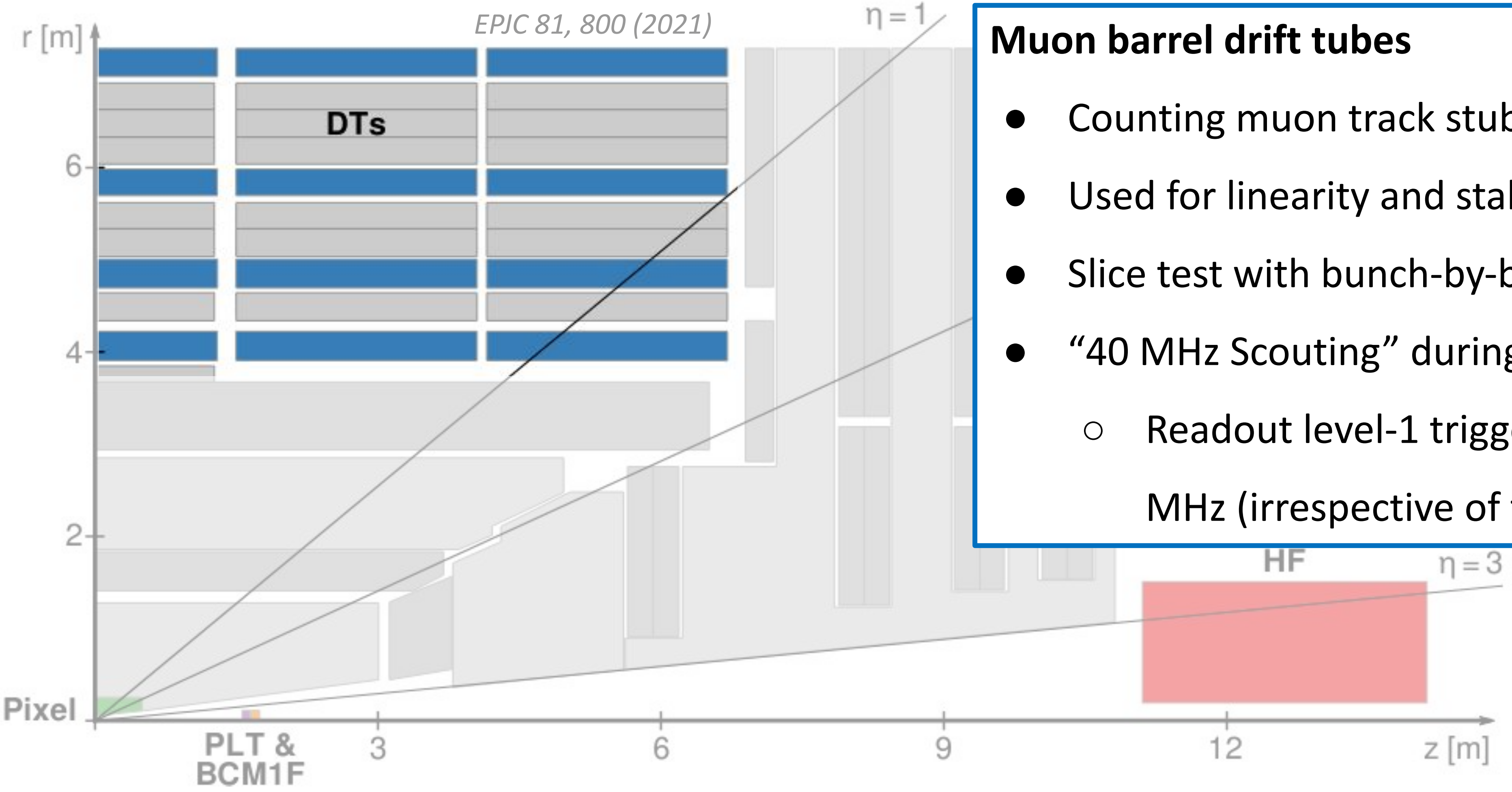
Backup

References

- CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3”, CERN-EP-2023-136
- CMS Collaboration, “Luminosity measurement in proton-proton collisions at 13.6 TeV in 2022 at CMS”, CMS PAS LUM-22-001
- CMS Collaboration, “Measurement of the offline integrated luminosity for the CMS proton-proton collision dataset recorded in 2023”, CMS DP 2024-068
- 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)

Luminometers at the CMS

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



Muon barrel drift tubes

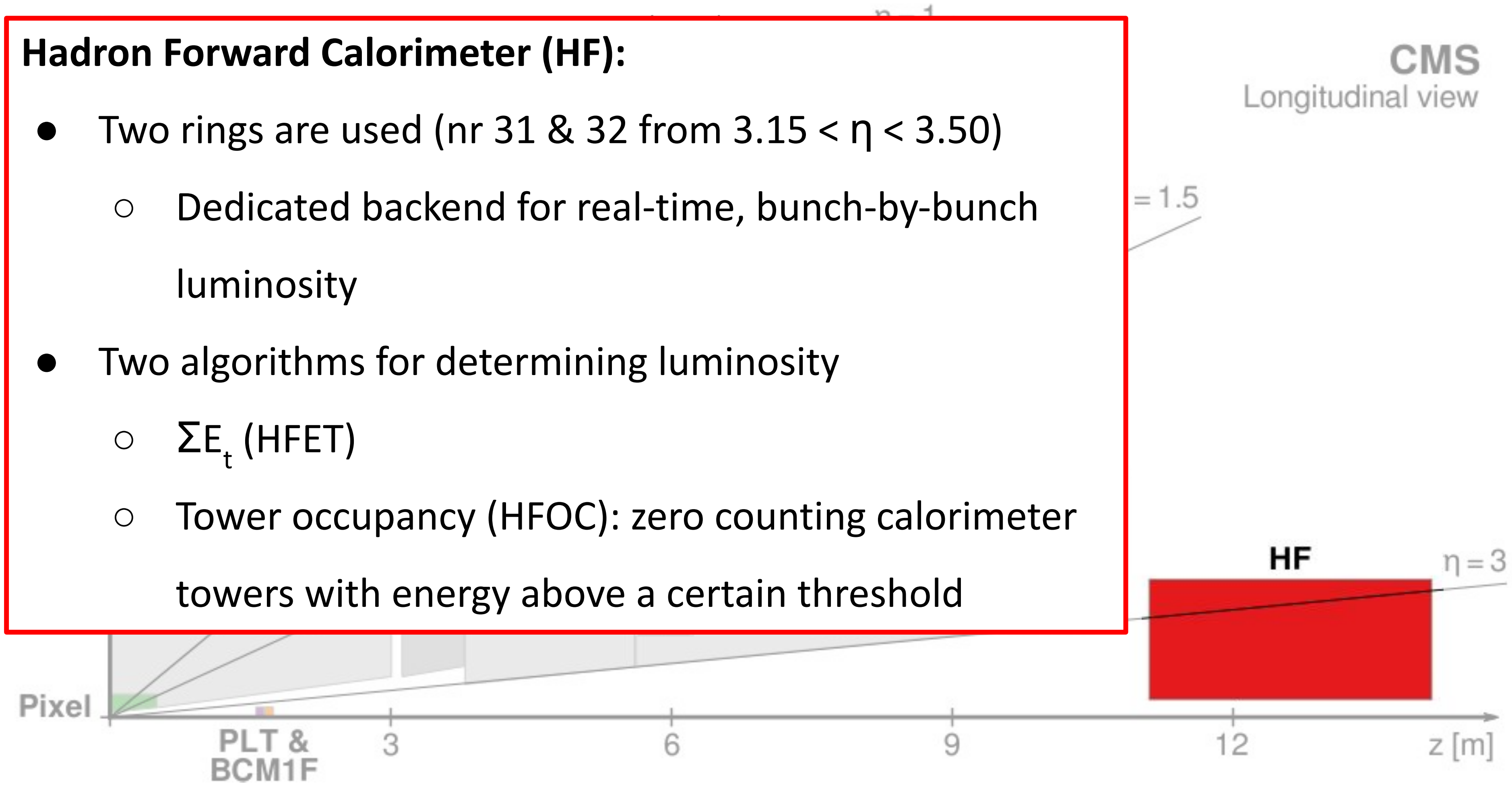
- Counting muon track stubs
- Used for linearity and stability cross-checks
- Slice test with bunch-by-bunch resolution
- “40 MHz Scouting” during Run 3
  - Readout level-1 trigger objects with 40 MHz (irrespective of trigger decision)

Luminometers at the CMS

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

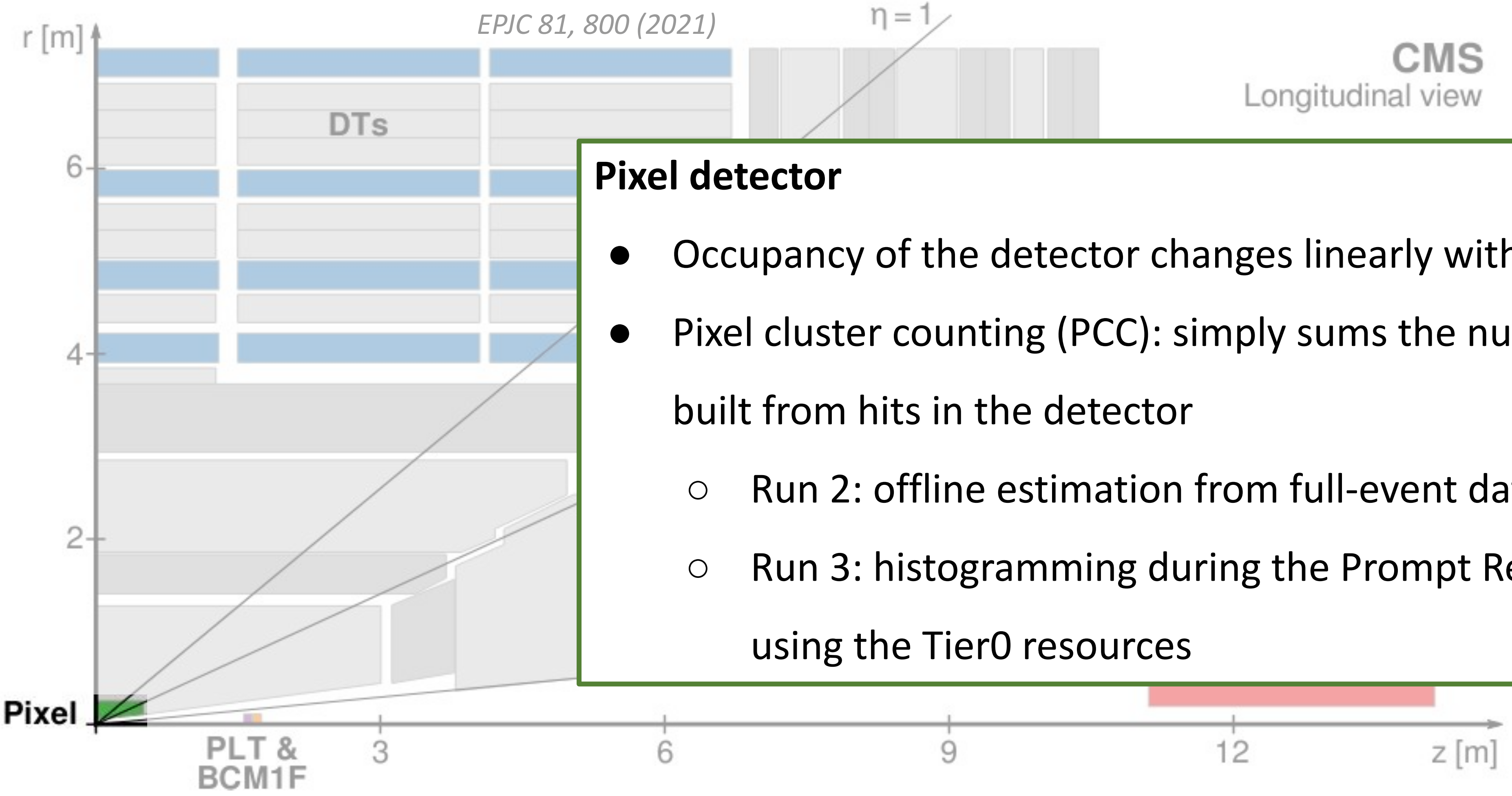
Hadron Forward Calorimeter (HF):

- 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



Luminometers at the CMS

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

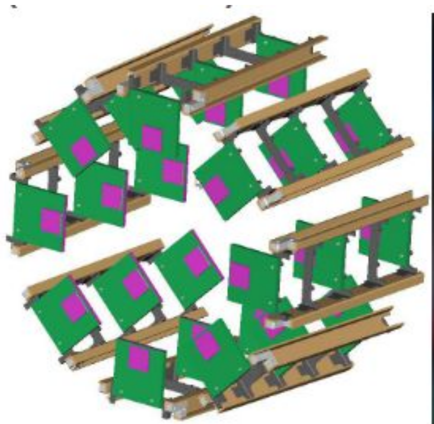


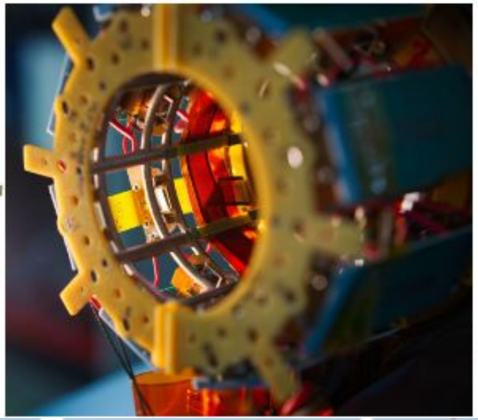
Pixel detector

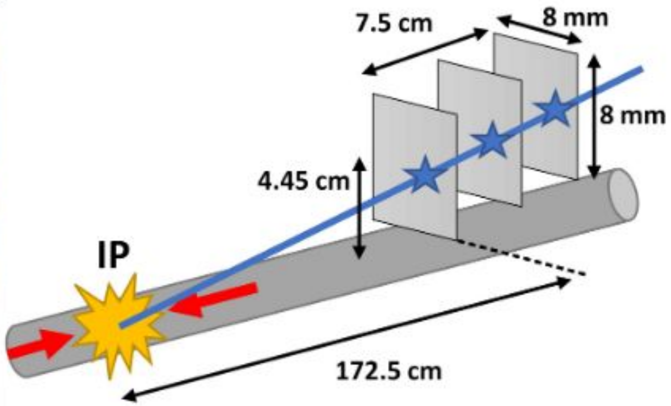
- Occupancy of the detector changes linearly with the luminosity
- Pixel cluster counting (PCC): simply sums the number of clusters built from hits in the detector
  - Run 2: offline estimation from full-event data
  - Run 3: histogramming during the Prompt Reconstruction using the Tier0 resources

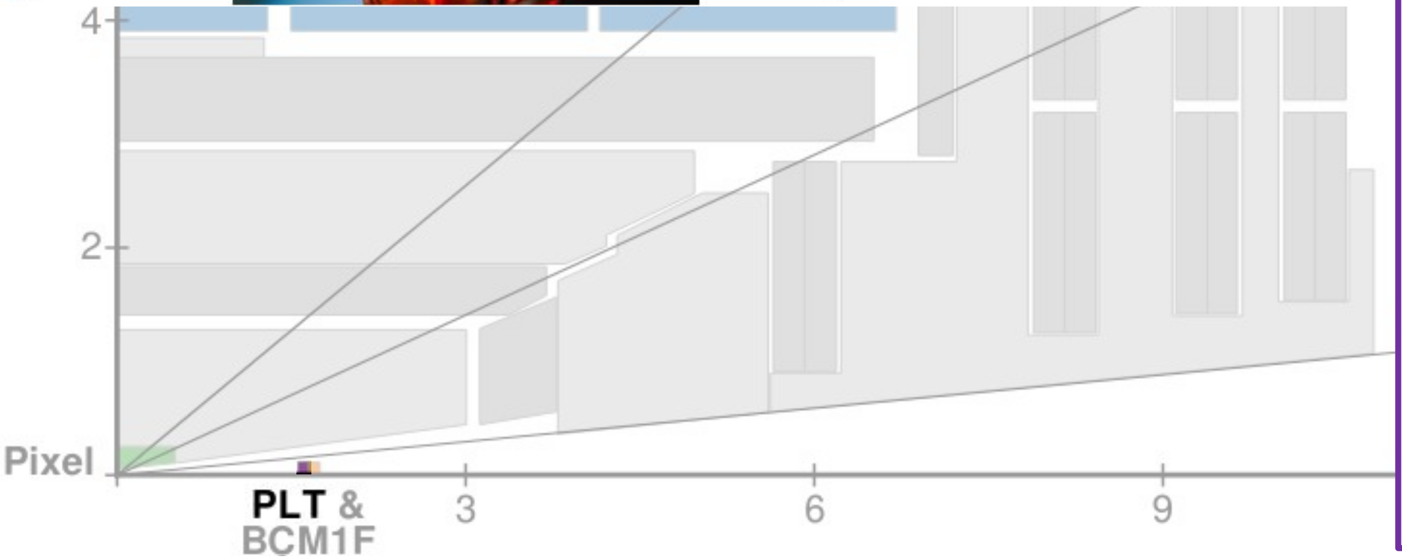
Luminometers at the CMS

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







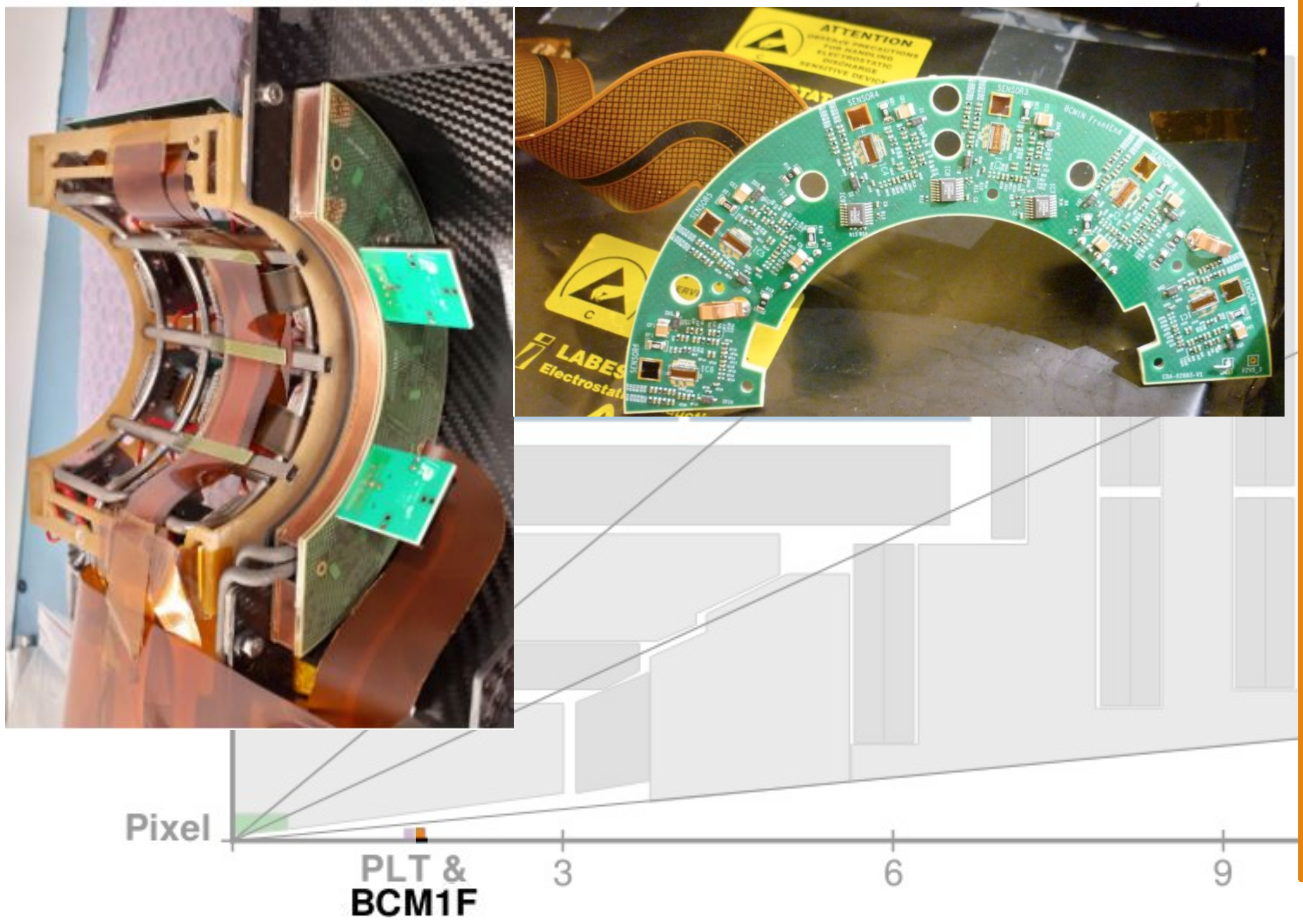


Pixel Luminosity Telescope (PLT)

- 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



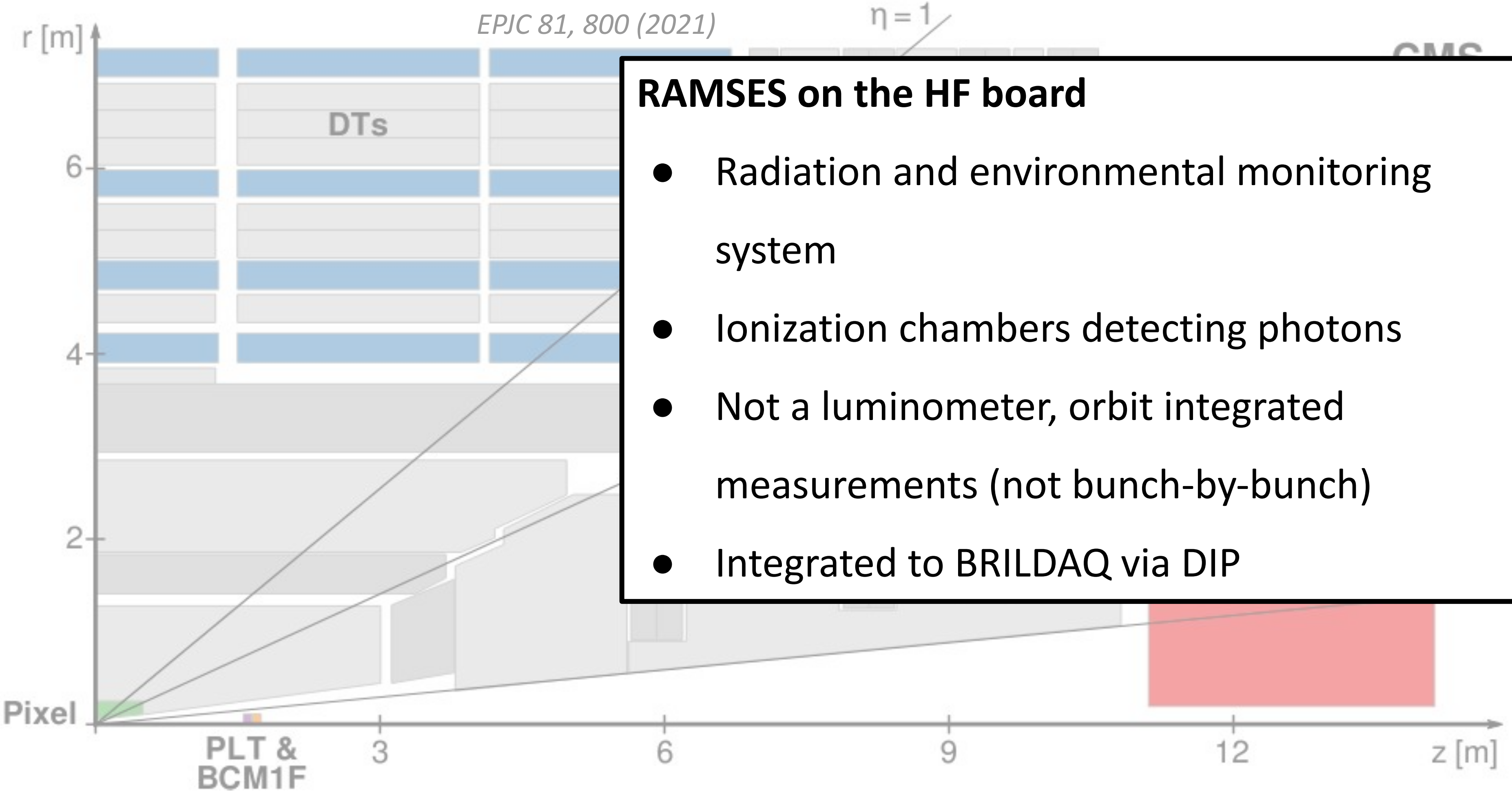
Fast Beam Condition Monitor (BCM1F):

- 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)

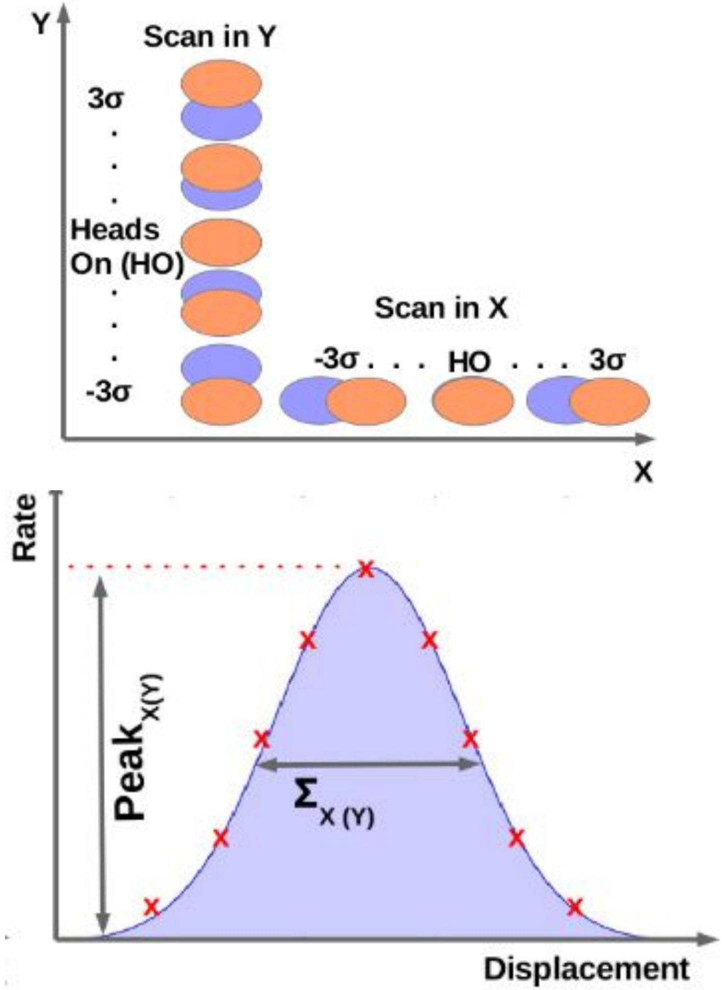


RAMSES on the HF board

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

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)

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

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

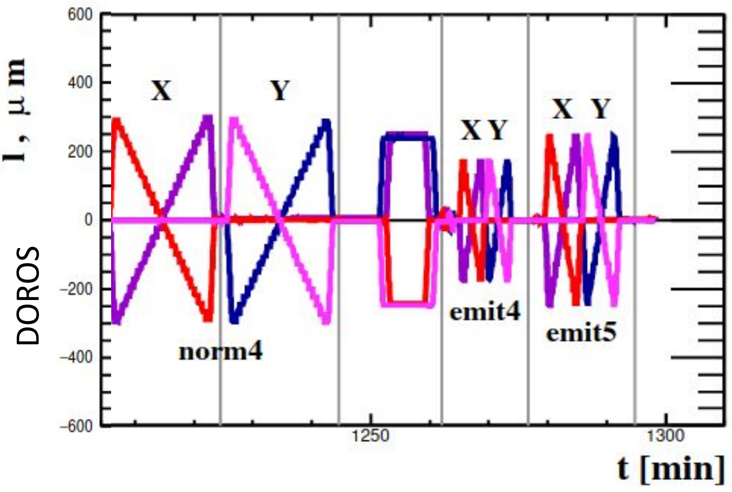
LHC orbit revolution frequency:
f = 11245.5 Hz

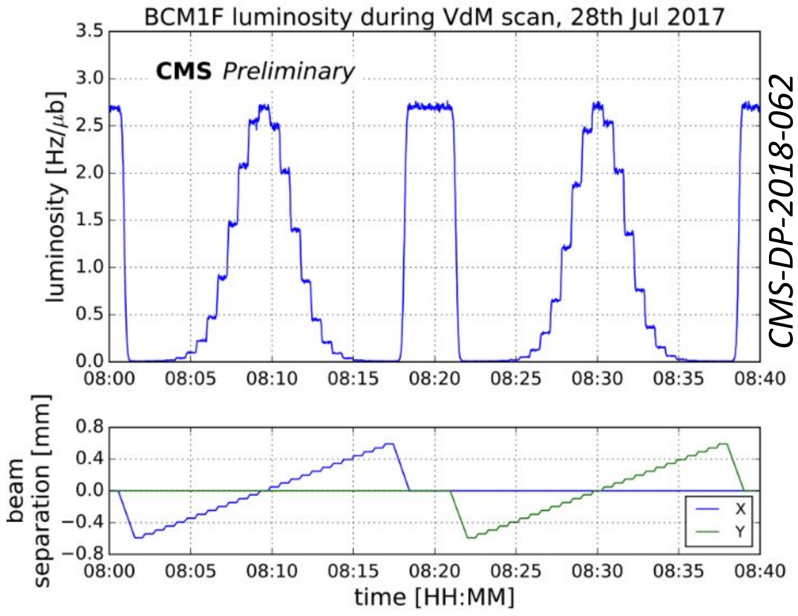
Beam overlap widths from VdM scans

VdM calibration

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

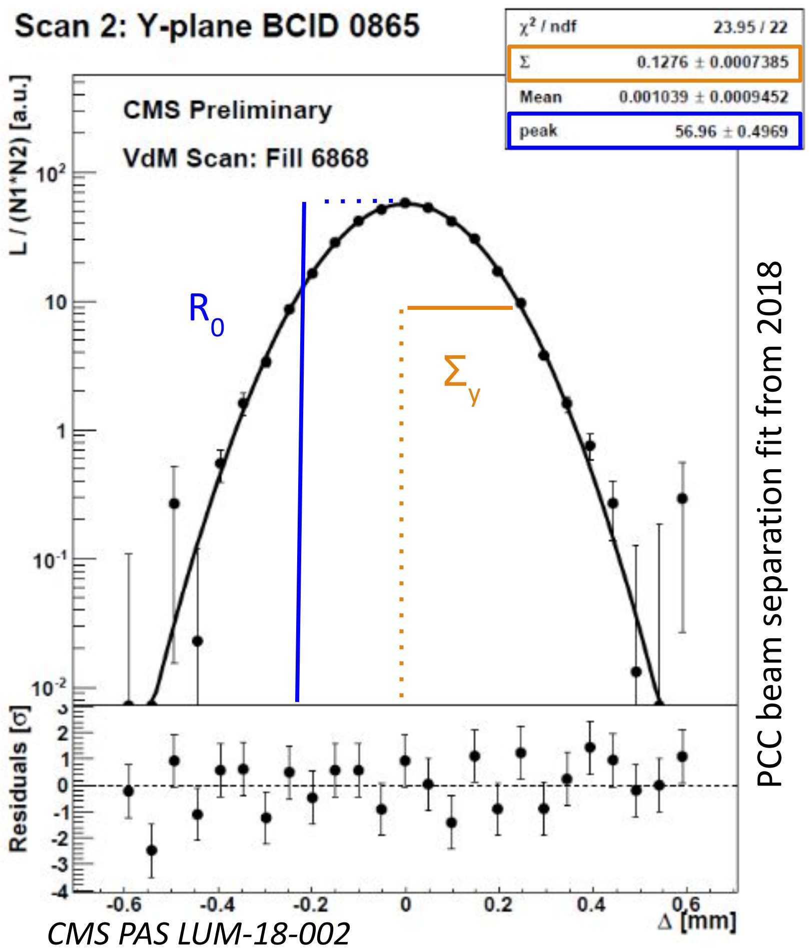
CMS PAS LUM-18-002





CMS-DP-2018-062

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



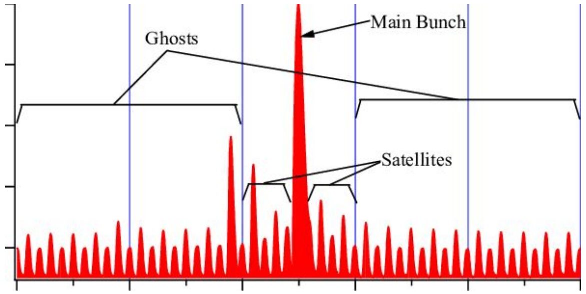
CMS PAS LUM-18-002

PCC beam separation fit from 2018

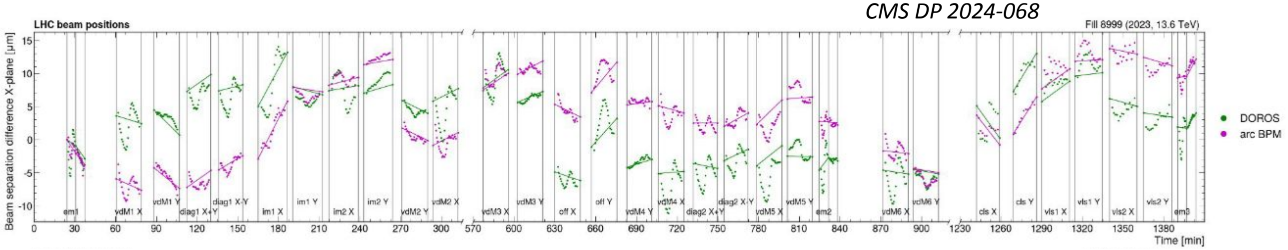
VdM (normalization) corrections I

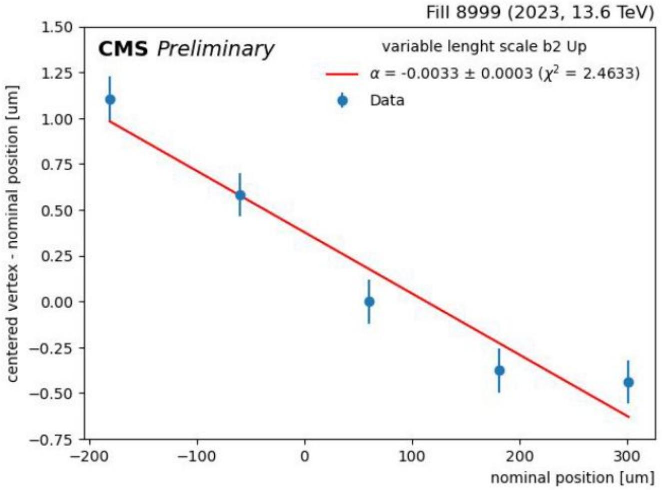
- Charge current per bunch, corrected for ghosts and satellites
- Background subtraction (luminometer specific): intrinsic noise measured for empty bunch crossings or using super separation scans (6 σ_b separation in both directions)
- Linear and residual orbit drift corrections: from interpolation between 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



CMS DP 2024-068

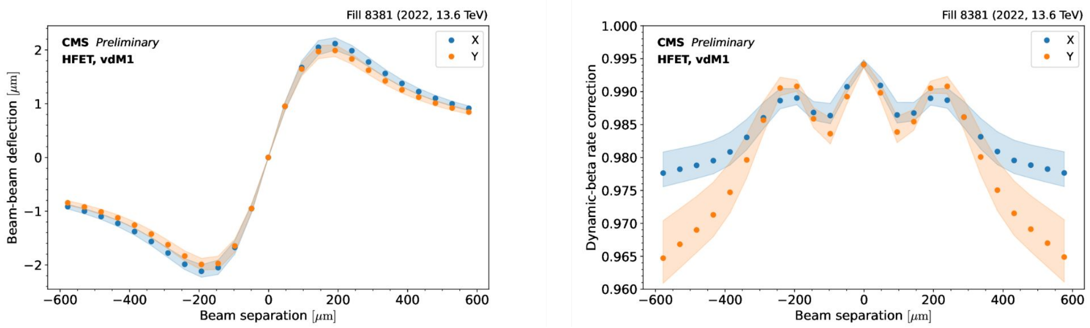




CMS DP 2024-068

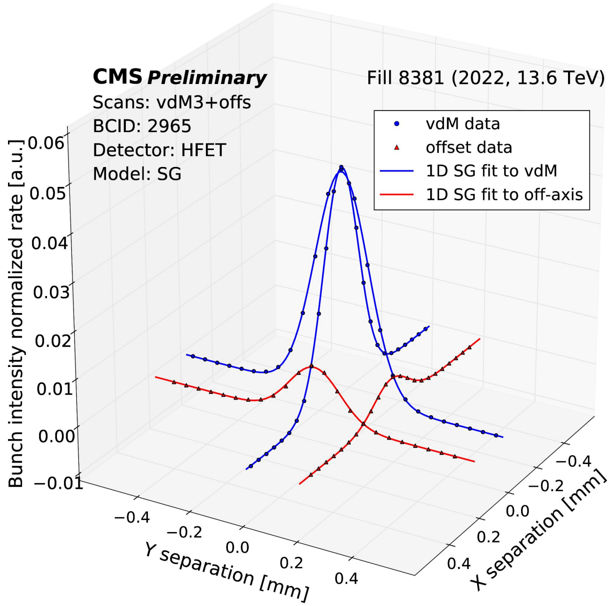
VdM (normalization) corrections II

- 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)



CMS PAS LUM-22-001

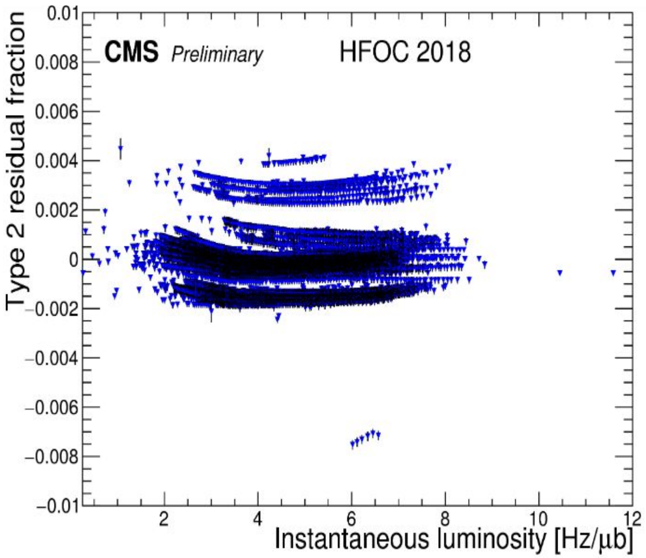
- Non-factorizable x and y bunch proton density function, calculated from specific separation scans (imaging, offset and diagonal) or by studying the luminous region parameters in standard VdM scans



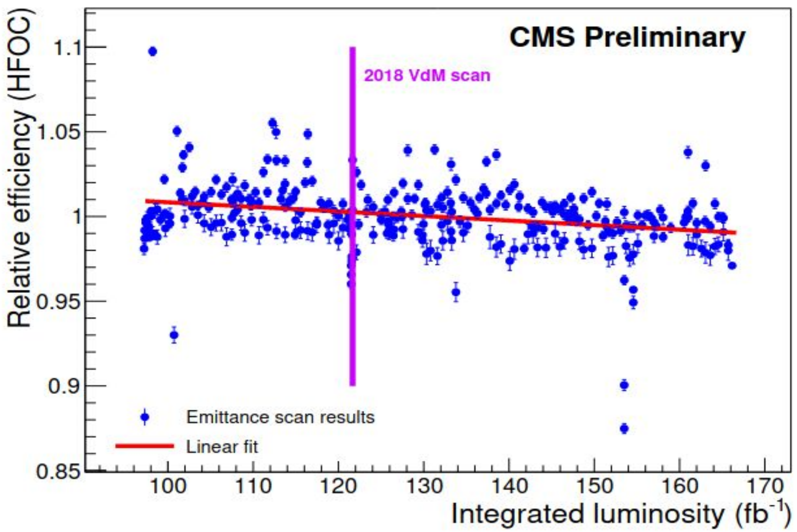
CMS PAS LUM-22-001

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



CMS PAS LUM-18-002



CMS PAS LUM-18-002

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

BUL-NA-2015-257