Precision luminosity measurement at the CMS experiment in Run 2 and prospects for HL-LHC

Attila Rádl

Luminosity

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

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

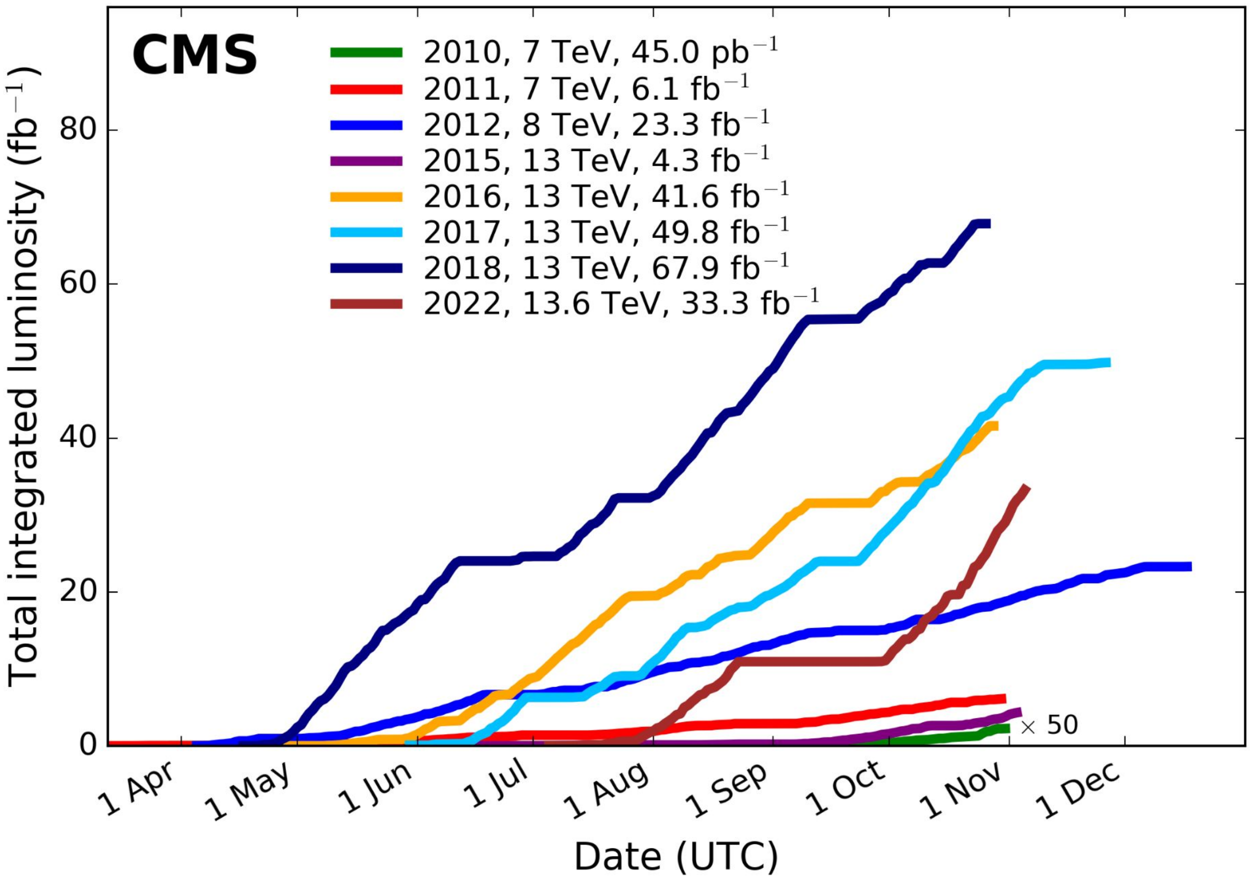
- Time integrated: represents the amount of data recorded

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

- Number of interesting events in a sample

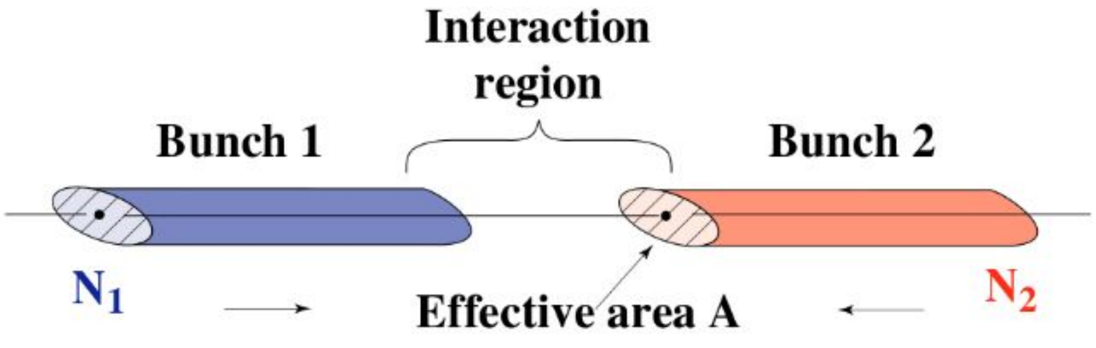
$$N = L\ \sigma_p$$

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
  - Measured properties: proton density function, number of protons in the bunches
  - Effective area: beam overlap integral



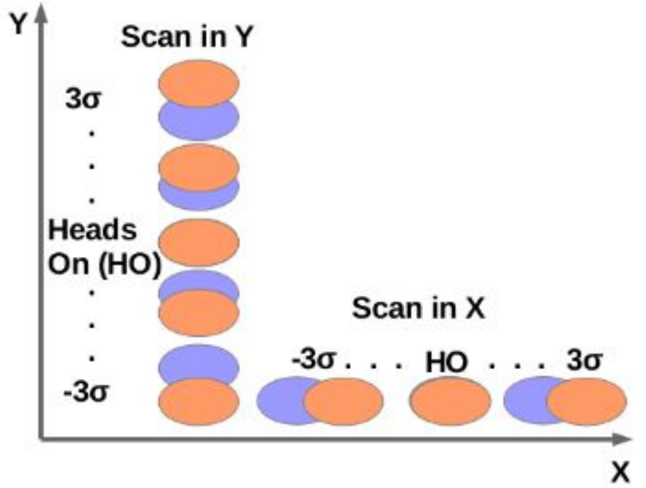
$$\mathcal{L}^i_{\mathrm{inst}} = N^i_1 N^i_2 f \int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y = N^i_1 N^i_2 f \int \rho_{x1}(x)\rho_{x2}(x)\mathrm{d}x \int \rho_{y1}(y)\rho_{y2}(y)\mathrm{d}y$$

Assumption: x-y direction factorization

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

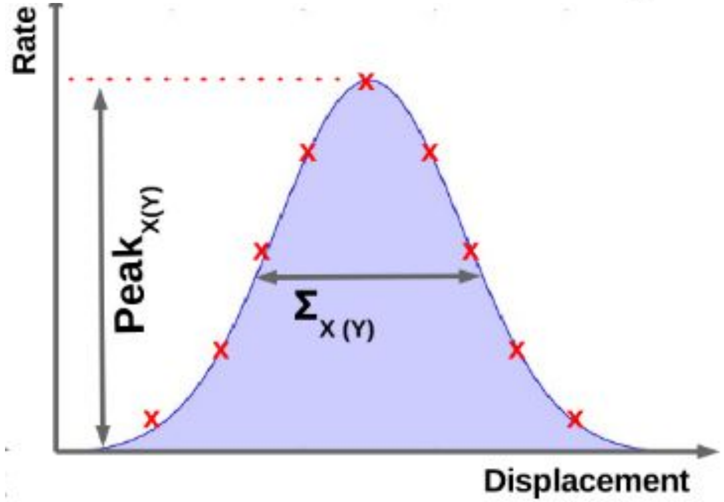
Van der Meer methodology

- Separate the two beams and measure the rate continuously



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

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



$$\mathcal{L}^i_{\mathrm{inst}} = \frac{N_1^i N_2^i f}{2\pi\Sigma_x\Sigma_y}$$

Van der Meer methodology

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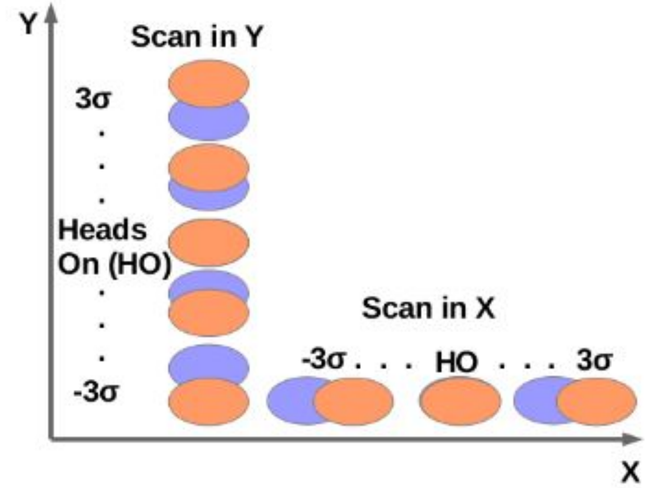

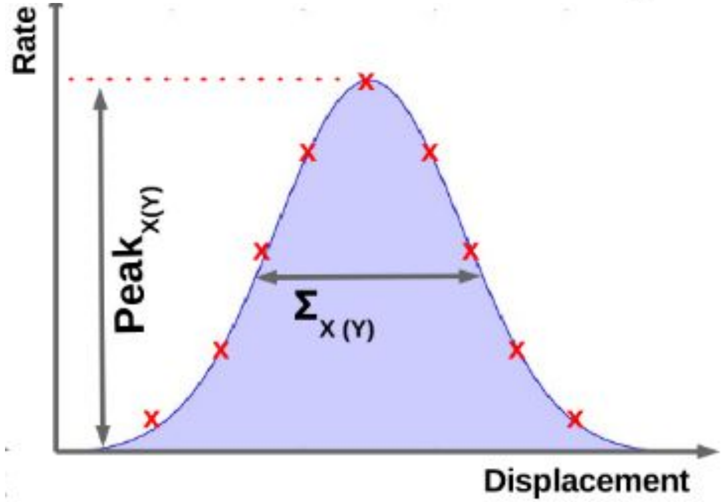

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- Event rate from luminometers
- Beam orbit monitoring with Beam Position Monitors (BPM)

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

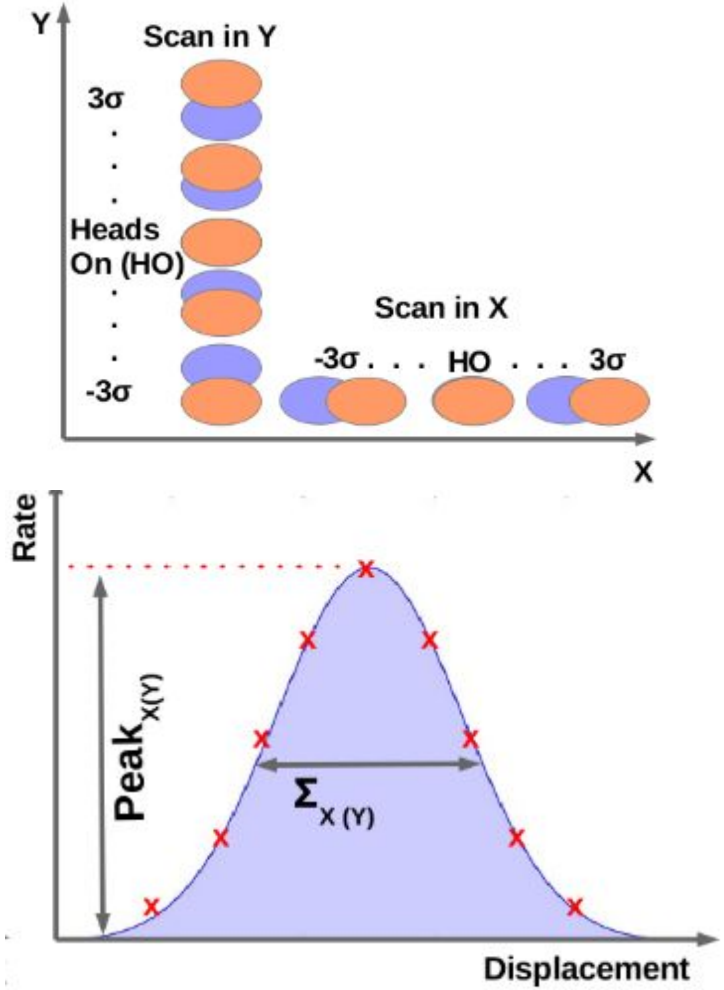
$$\mathcal{L}^i_{\mathrm{inst}} = \frac{\boxed{N^i_1 N^i_2}\,\boxed{f}}{2\pi\boxed{\Sigma_x\Sigma_y}}$$

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



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

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

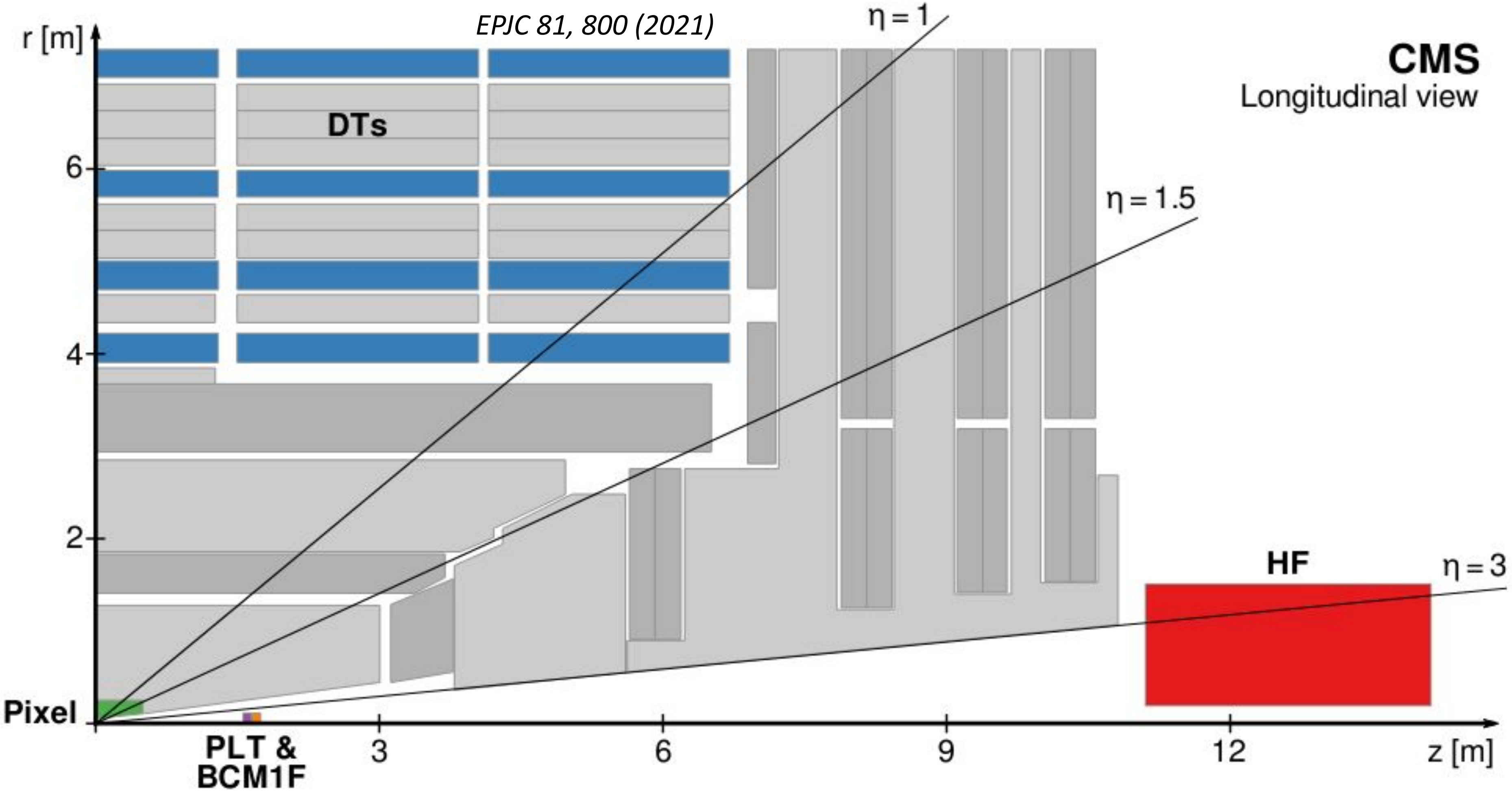
Expectation: same visible cross-section for regular conditions

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

Luminometers at the CMS

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

EPJC 81, 800 (2021)



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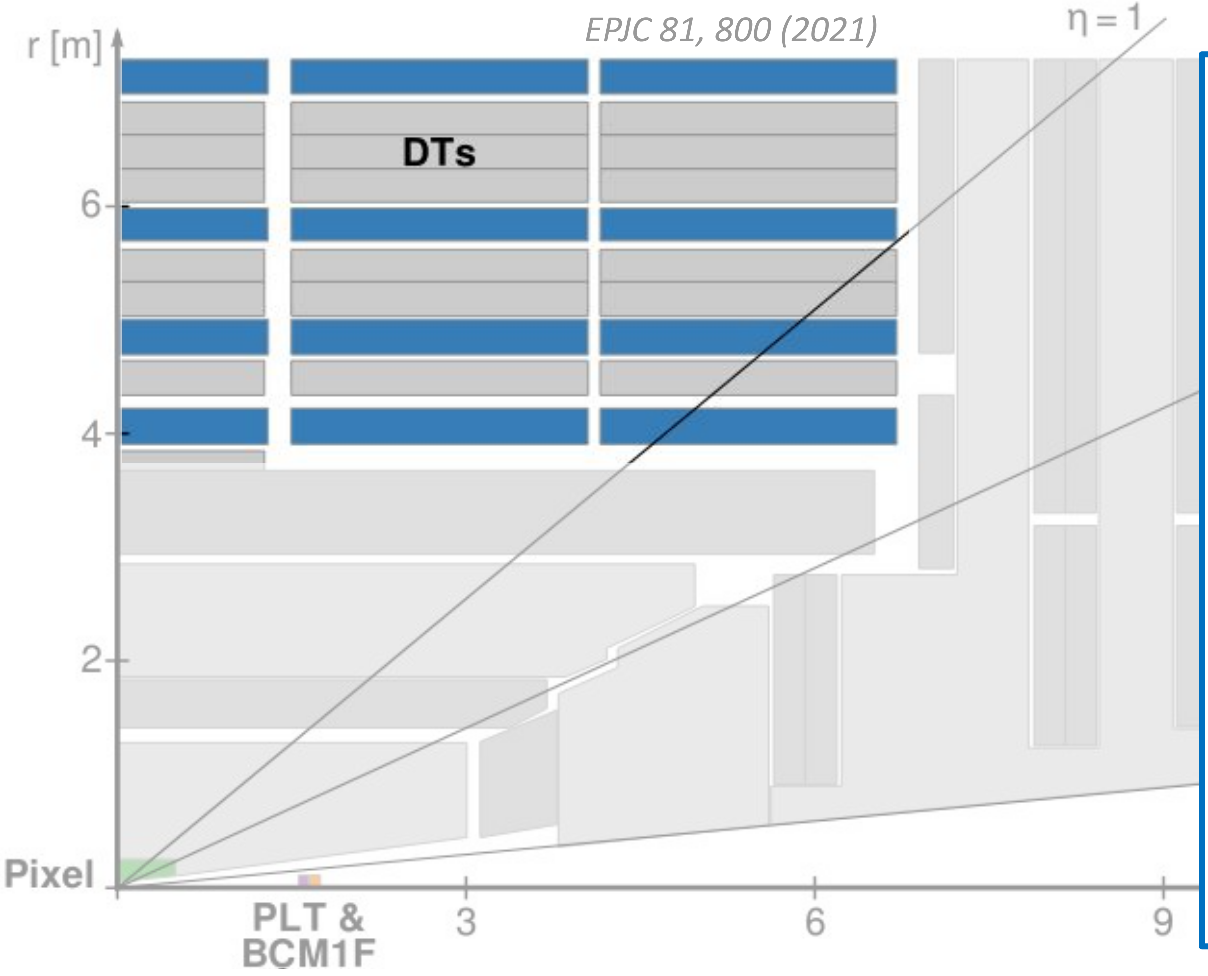


Muon barrel drift tubes

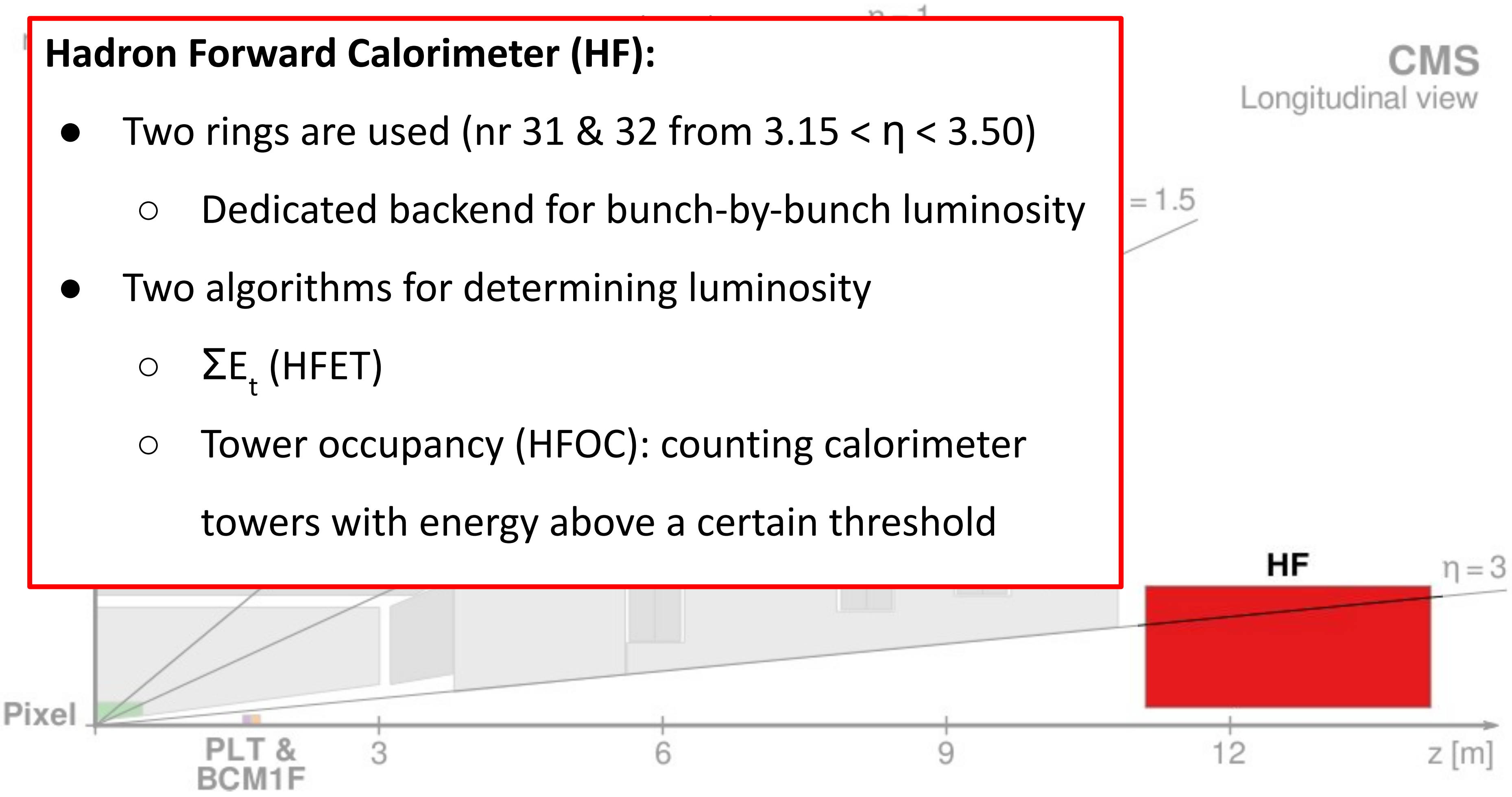
- Counting muon track stubs
- No bunch-by-bunch resolution during Run 2
  - Used for linearity and stability cross-checks
- “40 MHz Scouting” during Run 3
  - Readout level-1 trigger objects with 40 MHz (irrespective of trigger decision)
  - Reduced event size is needed

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 $3.15 < \eta < 3.50$)
  - Dedicated backend for bunch-by-bunch luminosity
- Two algorithms for determining luminosity
  - ΣE_t (HFET)
  - Tower occupancy (HFOC): counting calorimeter towers with energy above a certain threshold



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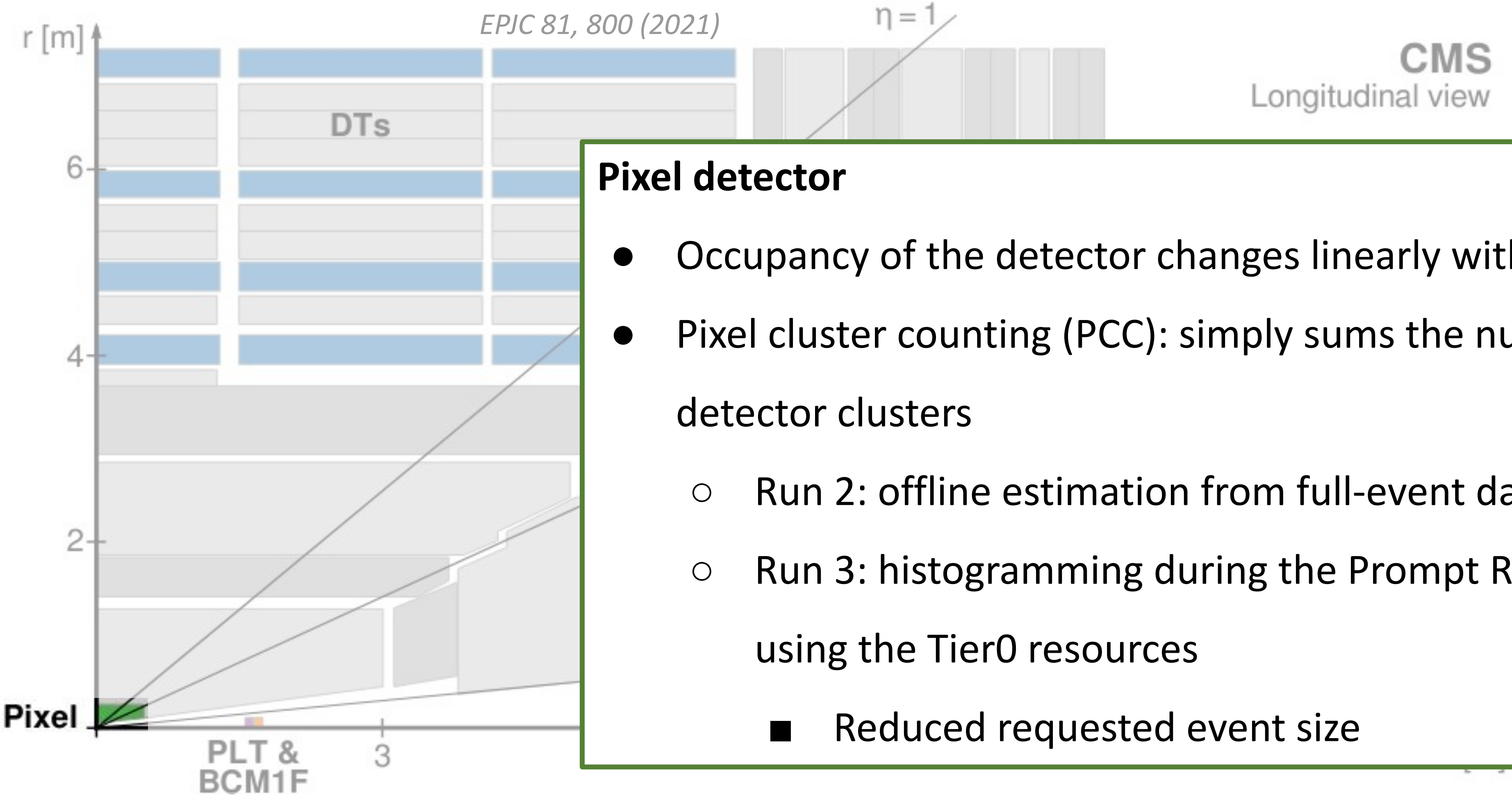
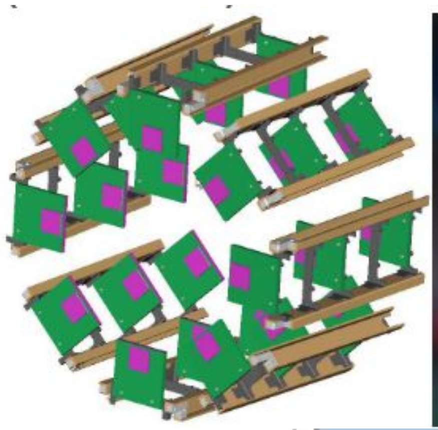


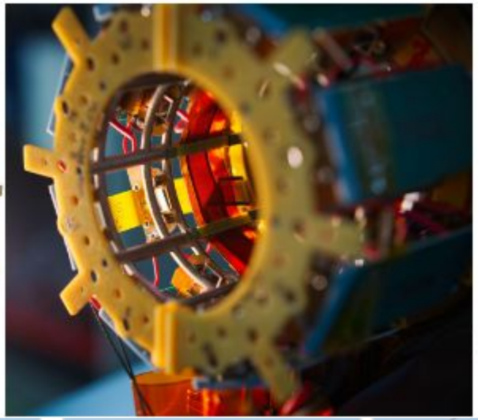
Pixel detector

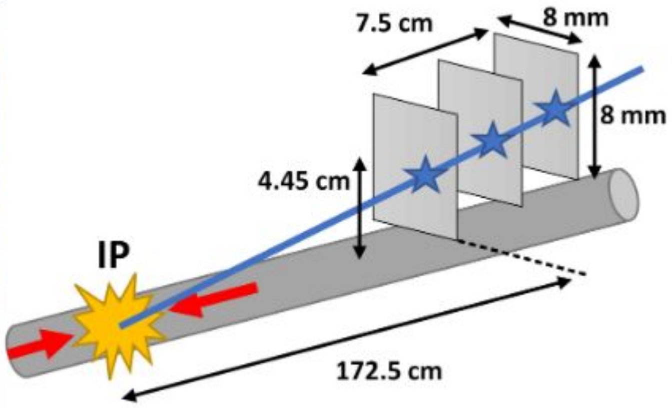
- Occupancy of the detector changes linearly with the luminosity
- Pixel cluster counting (PCC): simply sums the number of hit detector clusters
  - Run 2: offline estimation from full-event data
  - Run 3: histogramming during the Prompt Reconstruction using the Tier0 resources
    - Reduced requested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

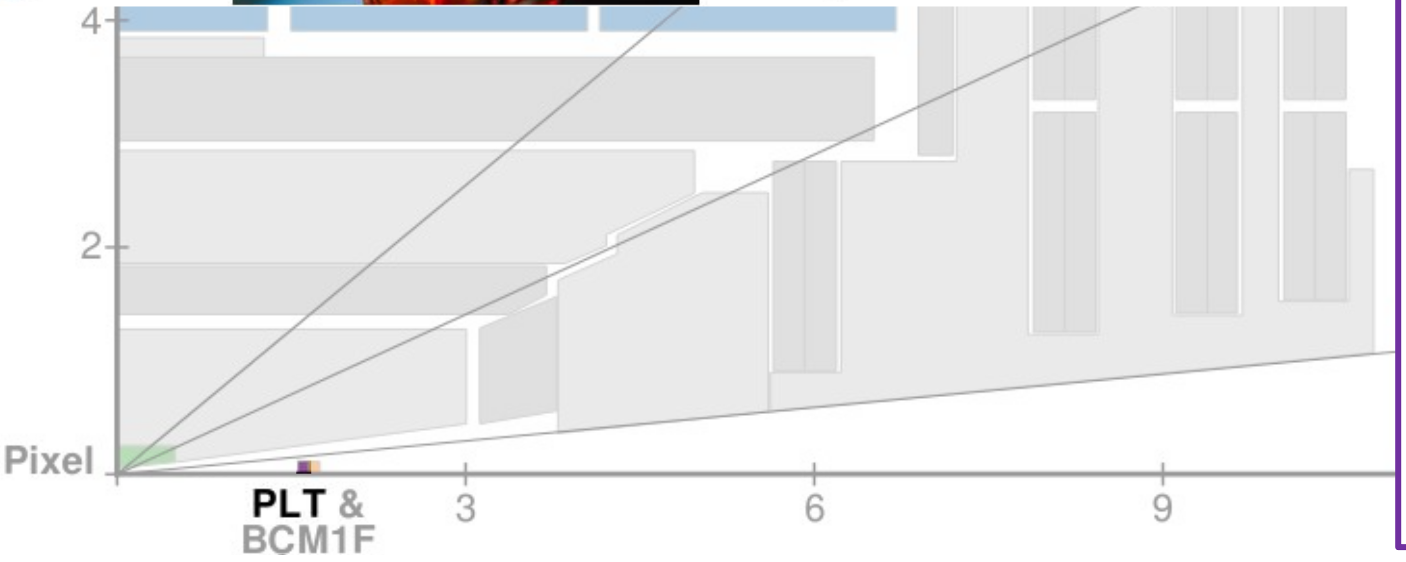
Luminometers at the CMS

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







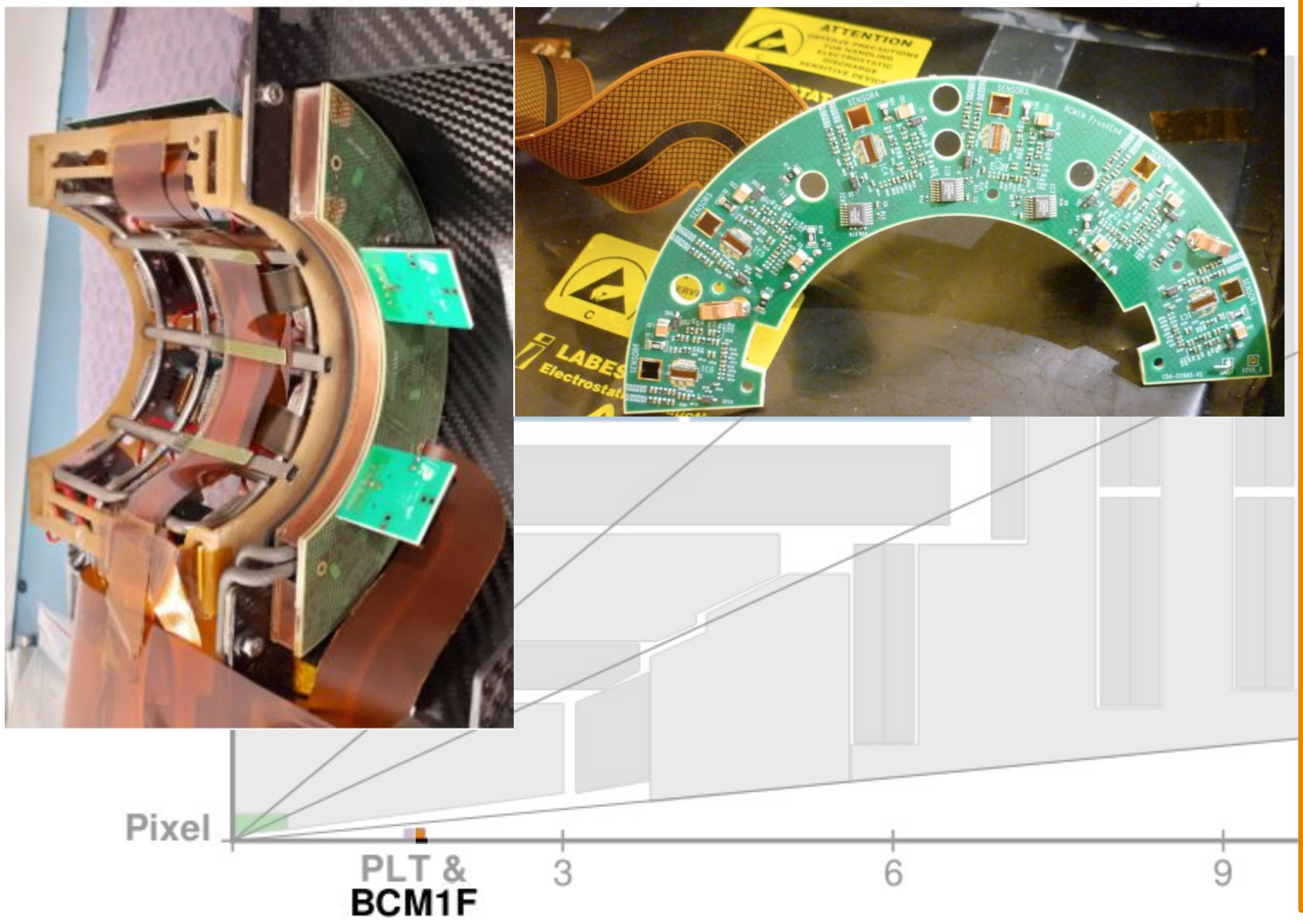


Pixel Luminosity Telescope (PLT)

- 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
- Hit 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

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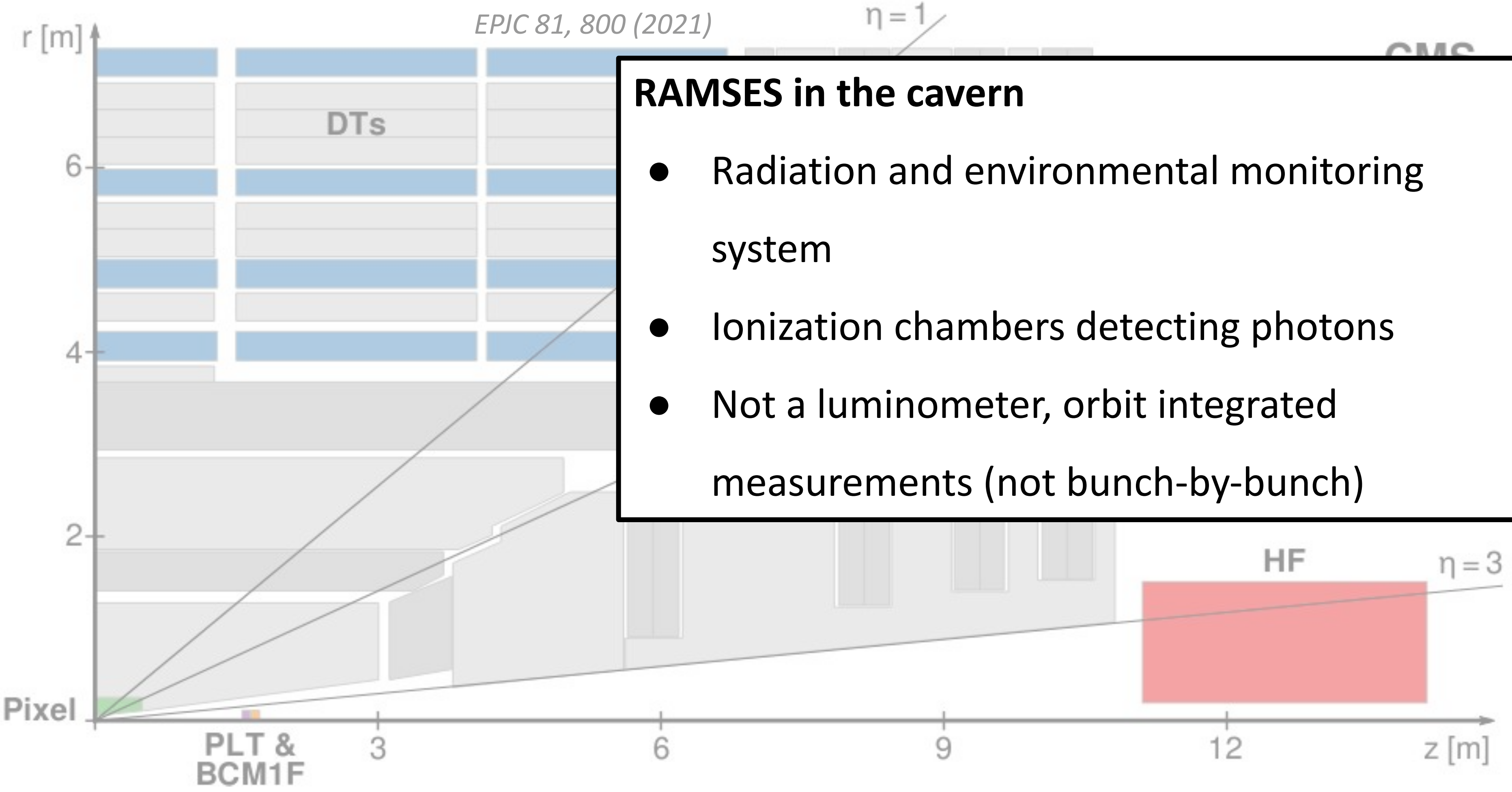
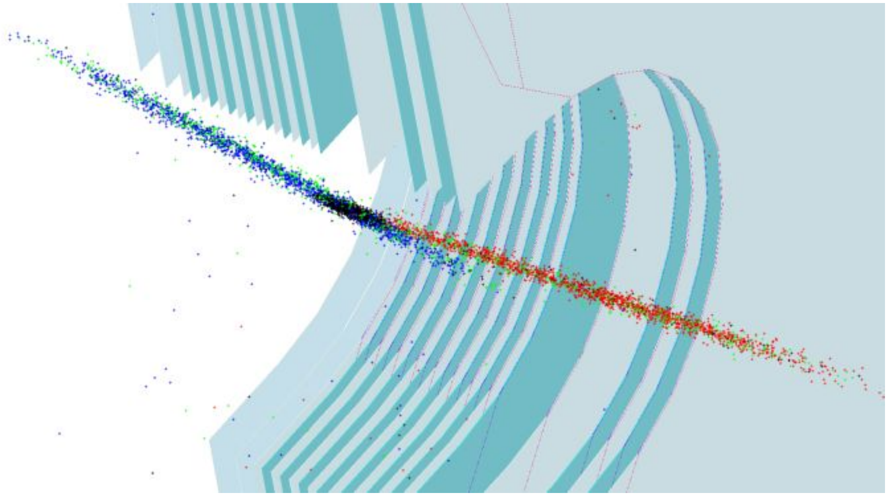


RAMSES in the cavern

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

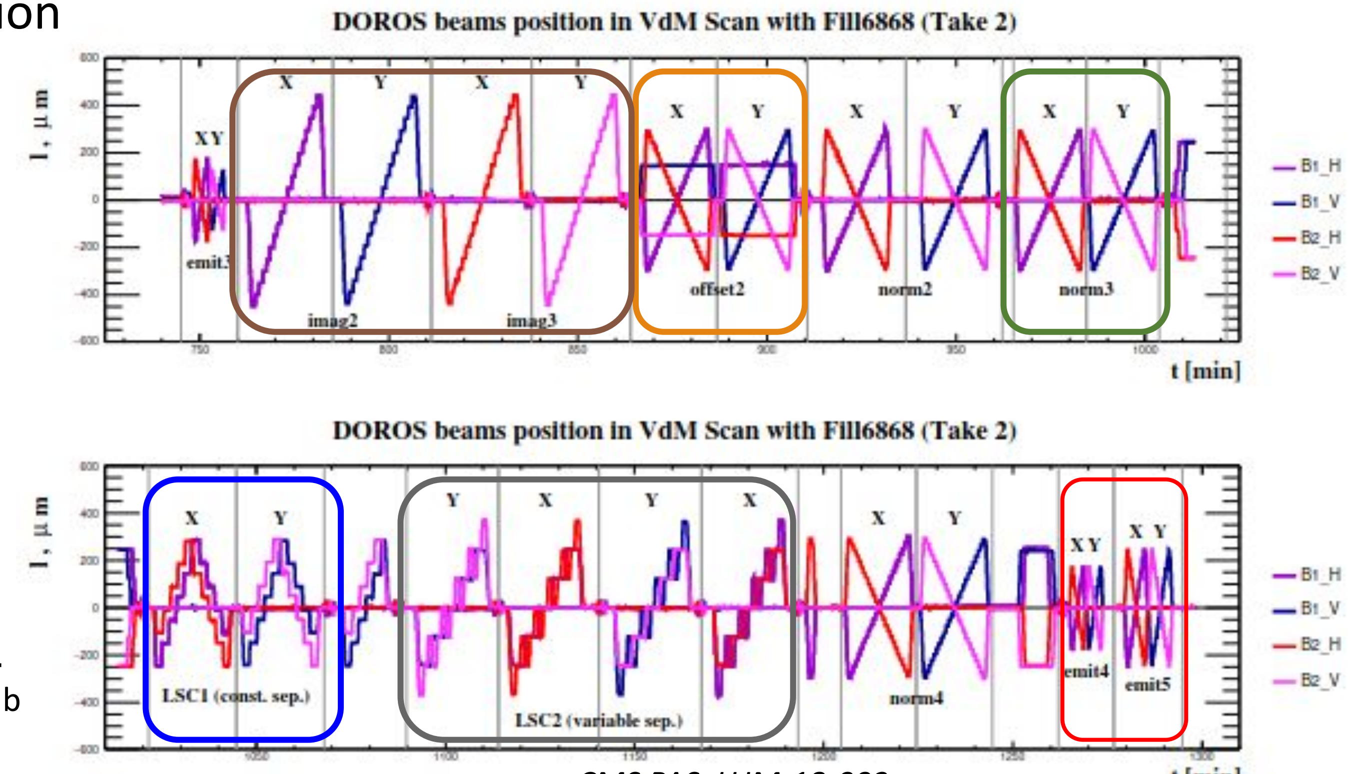
Beam quality and position monitors

- 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



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VdM calibration

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

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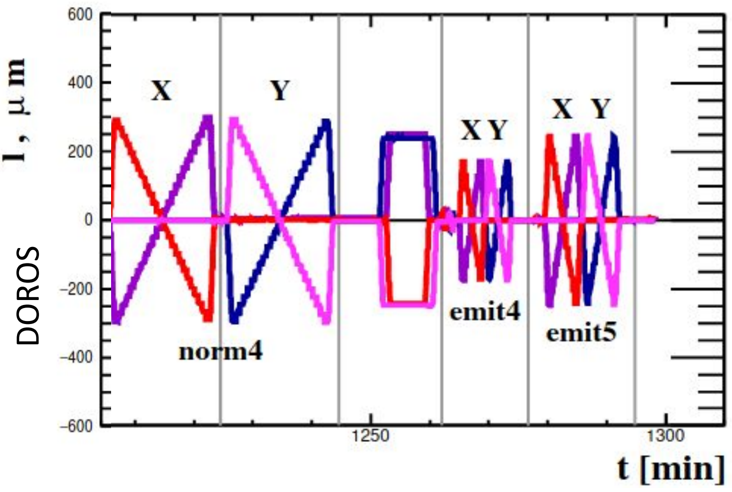
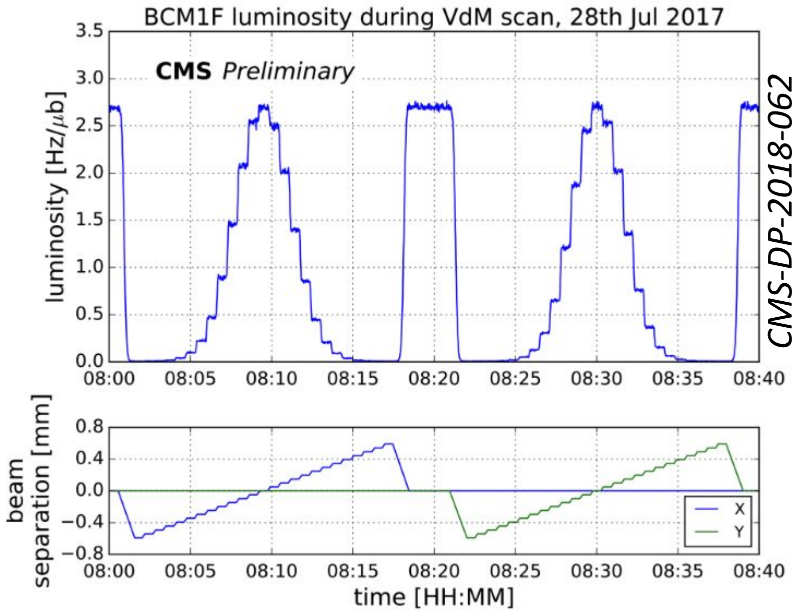
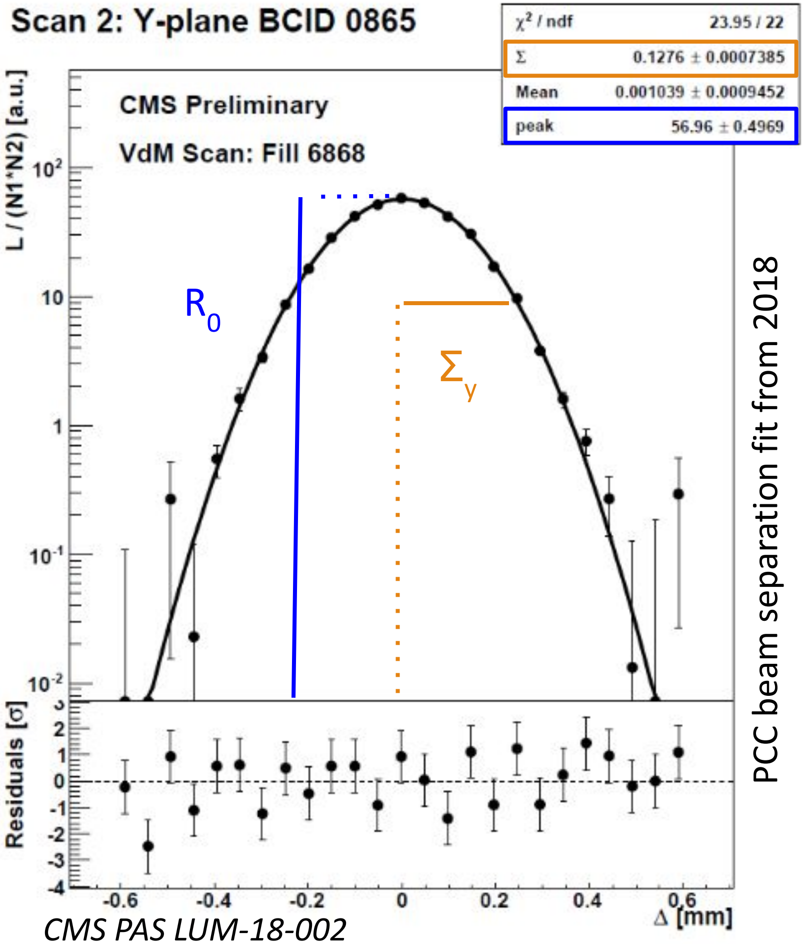




Combination of the two measurements: beam separation fit for $\Sigma_{x,y}$ and R_0



CMS PAS LUM-18-002

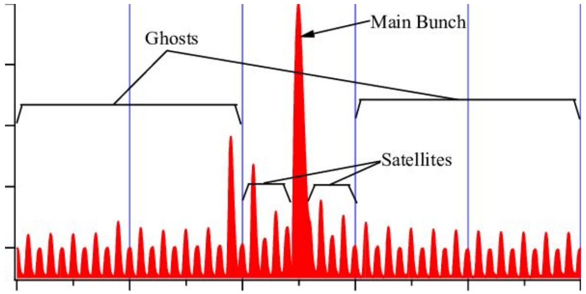
PCC beam separation fit from 2018

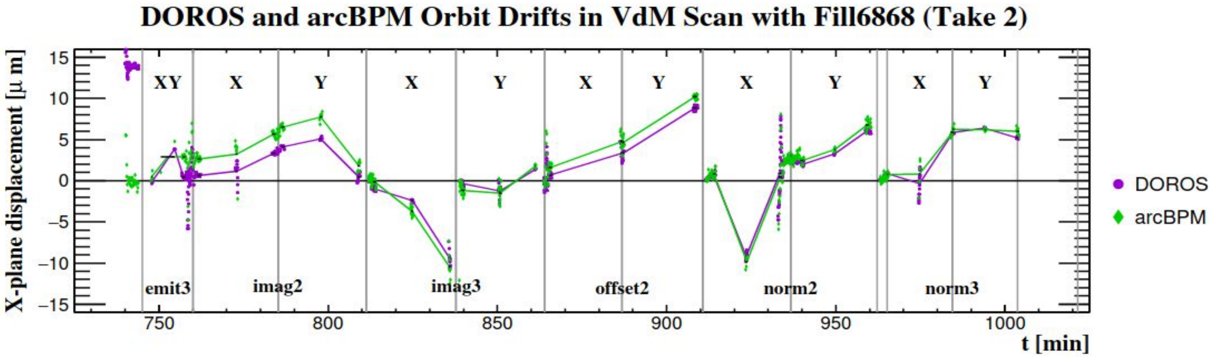
VdM (normalization) corrections I

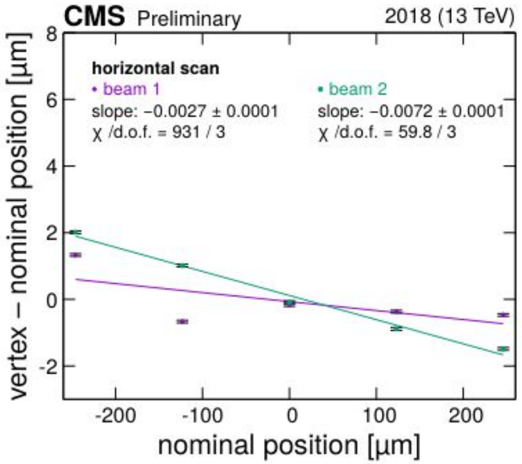
- Charge current per bunch, corrected for ghosts and satellites

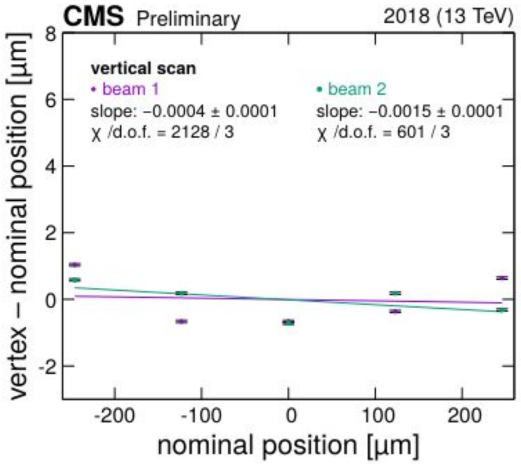
- Linear and residual orbit drift corrections: from interpolation between measured head-on positions and positions per step during scans

- Length scale: correction of the nominal beam positions to use the CMS length scale extracted from vertex positions



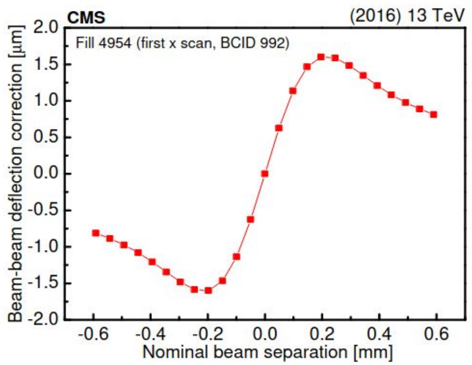


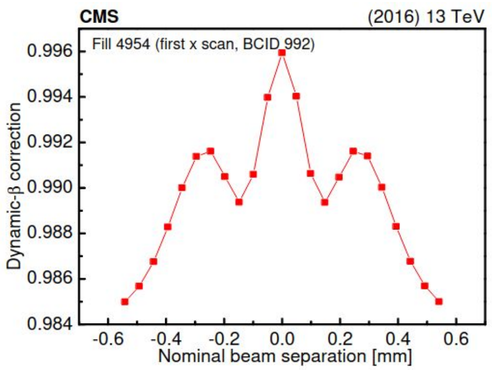




VdM (normalization) corrections II

- Beam-beam effects: electromagnetic interaction between the two beams leads to an optical distortion effect on the bunch shapes (dynamic beta) and a deflection from the nominal position
- Background subtraction (luminometer specific): intrinsic noise measured for empty bunch crossings or using super separation scans (6 σ_b separation in both directions)
- Not completely independent 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





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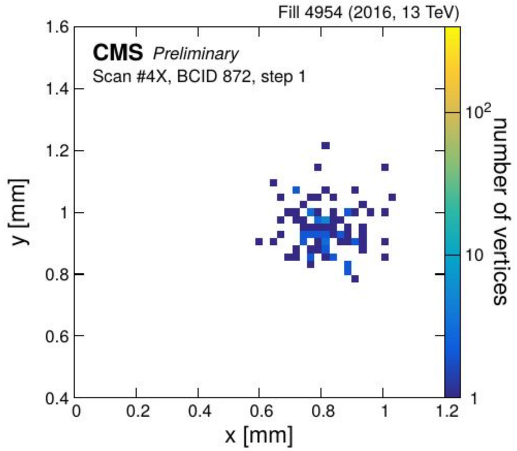

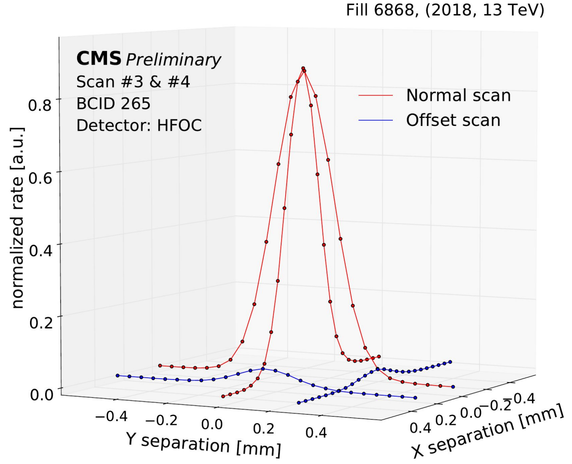

Luminosity under physics conditions

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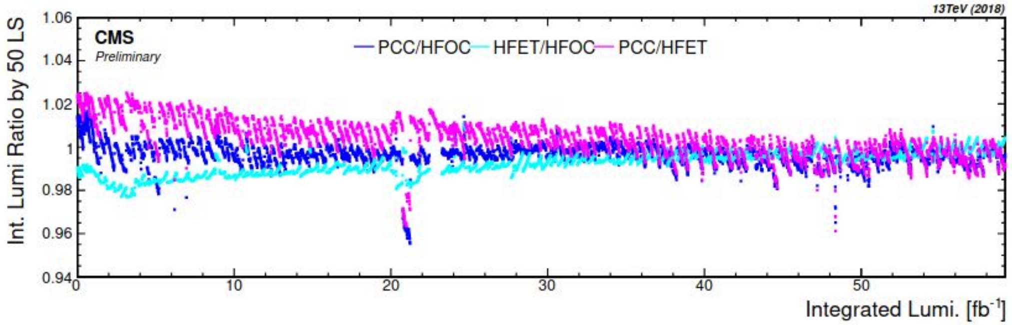

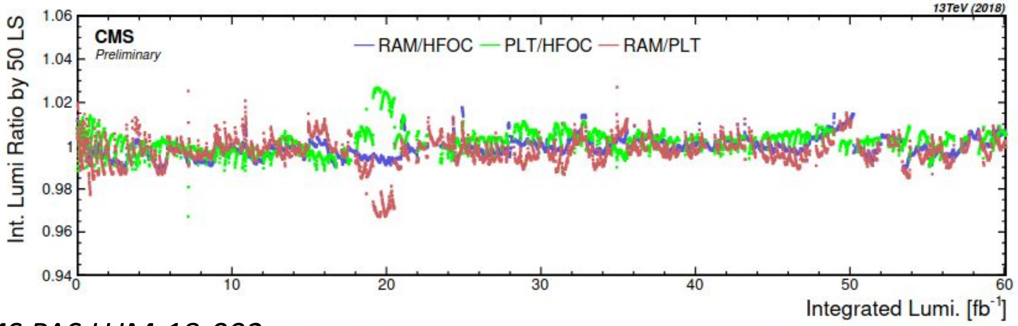

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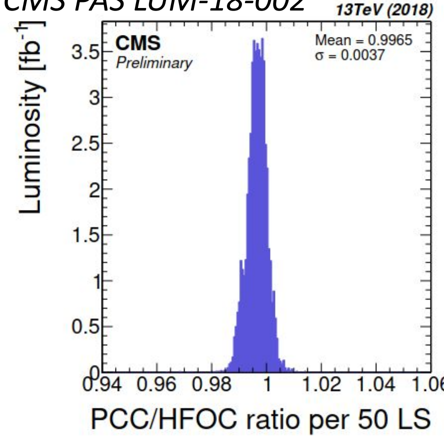
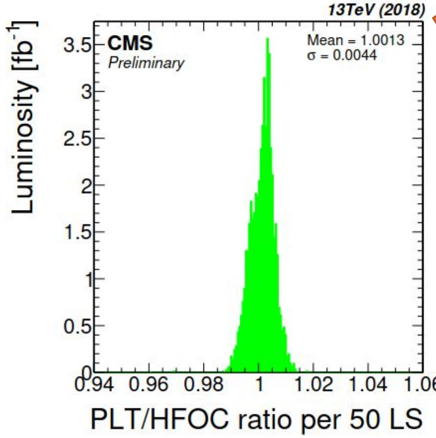
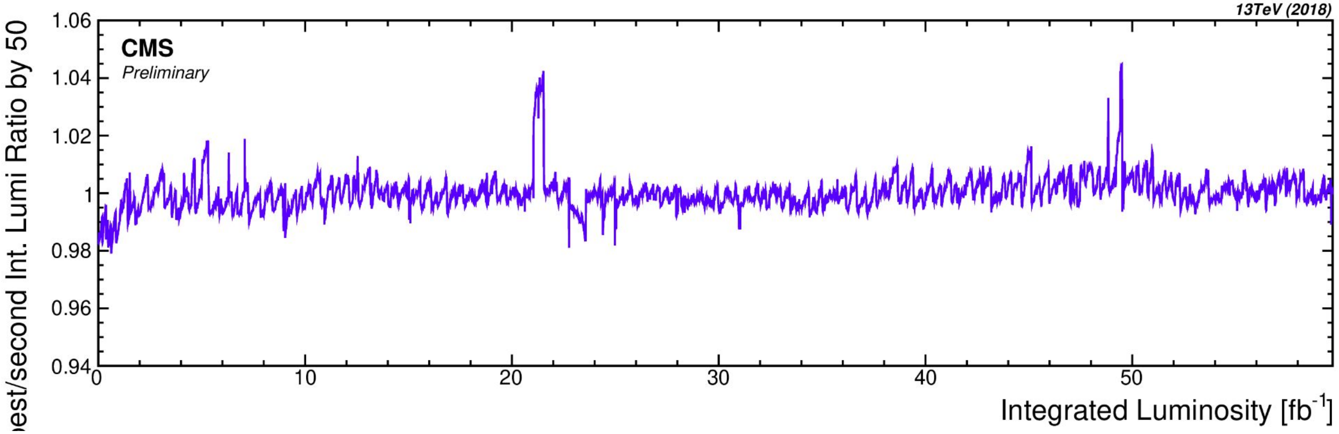




- Final selection of the primary luminometer (HFOC in 2018), its data is used for luminosity estimations.
- Uncertainty comes from the comparison of the primary and the secondary luminometer estimations.



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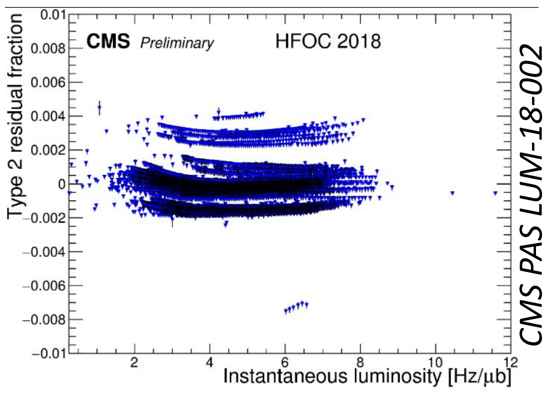
Ratio plots to check the long-term stability and linearity

Corrections for data-taking (integration)

- Out-of-time corrections (more filled bunches arriving in trains during data-taking)
  - type-1: effect on the next bunch crossing
  - type-2: late hits, nuclear excitations, etc
    - exponential time development
- Efficiency, noise and non-linearity corrections: reduced response due to irradiation, ageing or other detector specific effect. Emittance scans recorded during physics runs since 2017
- Cross-detector stability and residual non-linearities: long-term comparison of the measured luminosities



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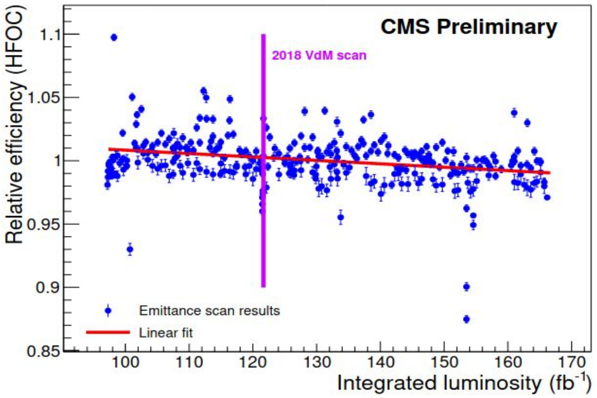
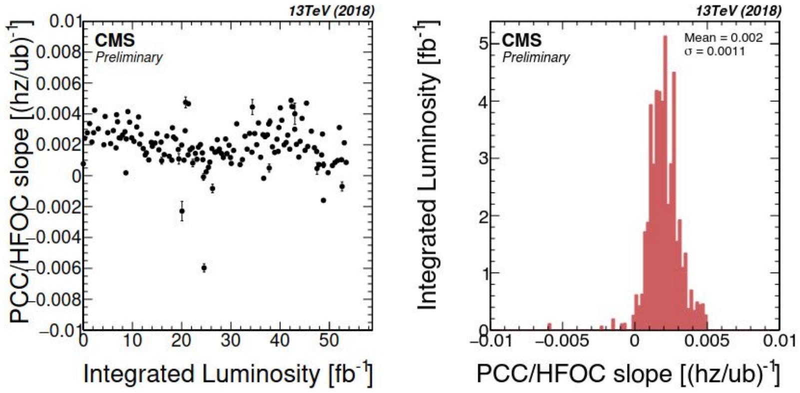




CMS PAS LUM-18-002

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 (data-taking)

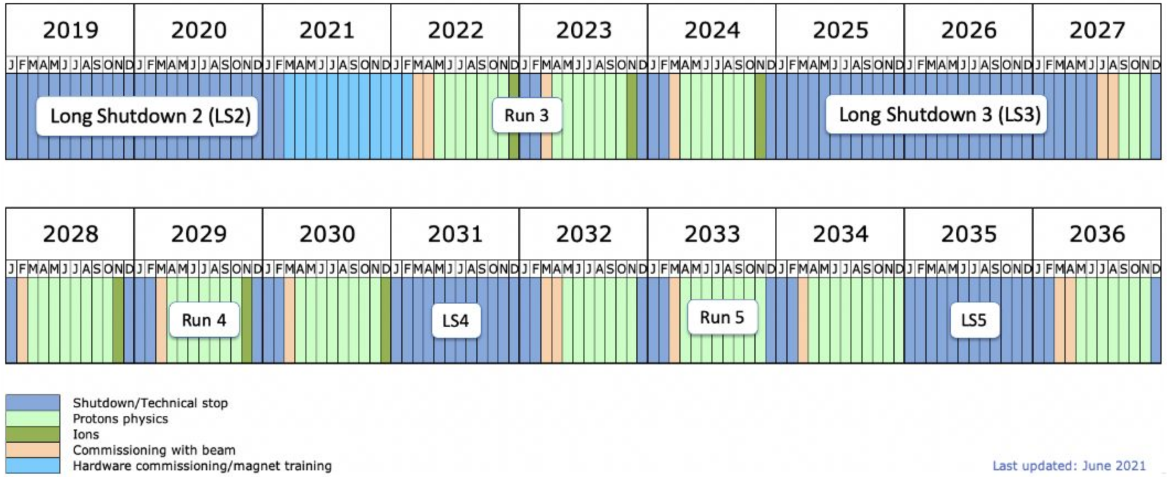
	Systematic	Uncertainty Run 2 (%) preliminary	Uncertainty in 2016 (%)
Normalization	Length scale	0.2–0.3	0.2
	Linear orbit drift	0.1–0.2	0.1
	Residual orbit drift	**0.5–0.8**	**0.5**
	x-y nonfactorization	**0.5–0.8**	**0.5**
	Beam-beam deflection	**0.5**	**0.5**
	Dynamic-β		
	Beam current calibration	0.2	0.2
	Ghosts and satellites	0.1	0.1
	Scan to scan variation	0.3–0.5	0.3
	Bunch to bunch variation	0.1	0.1
	Cross-detector consistency	**0.5–0.6**	**0.5**
	Background (detector specific)	0.1	0.1
Integration	Out-of-time effects (detector specific)	0.3–0.4	0.3
	Cross-detector stability	**0.5–0.6**	**0.5**
	Linearity	0.3–1.5	0.3
	CMS deadtime	< 0.1	< 0.1
	Total	**1.2–2.5**	**1.2**

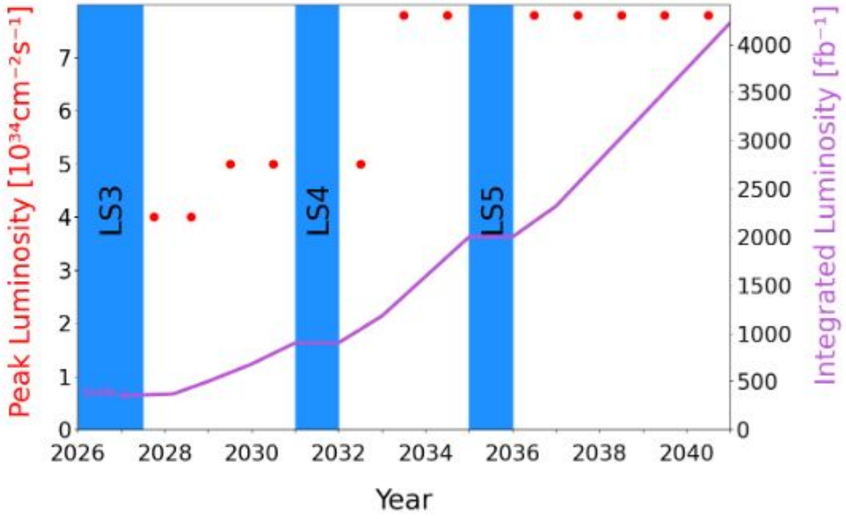
High-Luminosity LHC expectations: ~1% total systematic uncertainty

High-Luminosity LHC

- Future of the LHC and the corresponding experiments
  - Plan for Phase-2: more than 4000 fb^{-1}
  - Collected data so far: ~210 fb^{-1}
- Running with different conditions
  - Run-2 peak: $2x10^{34}$ $cm^{-2}s^{-1}$ pileup ~50
  - Expected peak luminosity in HL-LHC:

    $7.5x10^{34}$ $cm^{-2}s^{-1}$, pileup of ~200
- Upgraded or completely replaced systems

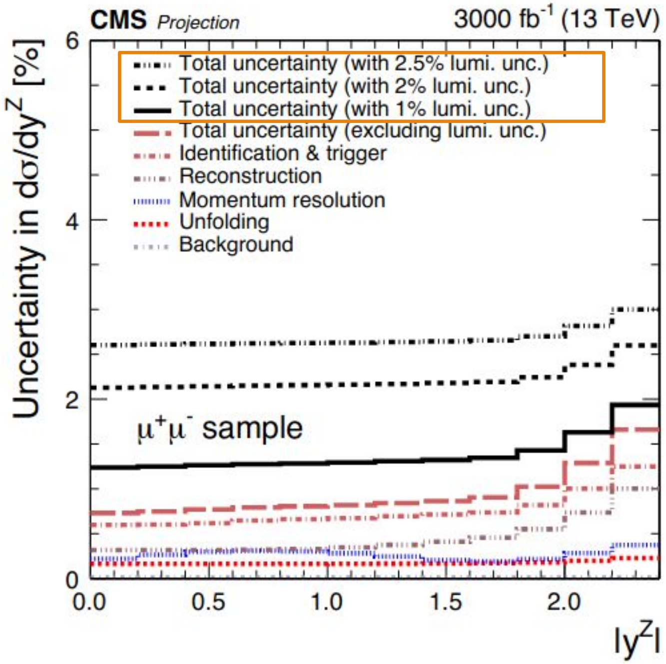


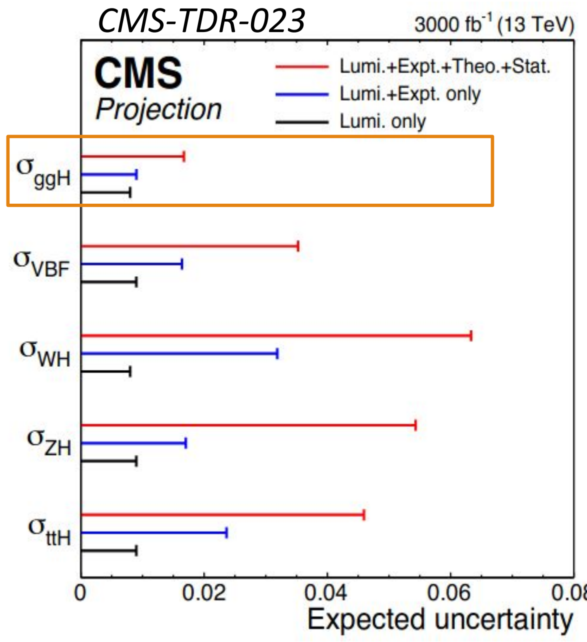


Luminosity precision requirements

- Luminosity uncertainty: huge fraction of the overall experimental uncertainties

- Goals: sufficiently accurate
  - Online measurements: ~5% uncertainty in all conditions (reach ~2% for HL-LHC)
    - monitoring the LHC running conditions
  - Offline integrated luminosity per data-taking period: ~2.5% preliminary, best final in 2016 pp: 1.2% (reach 1% for HL-LHC)





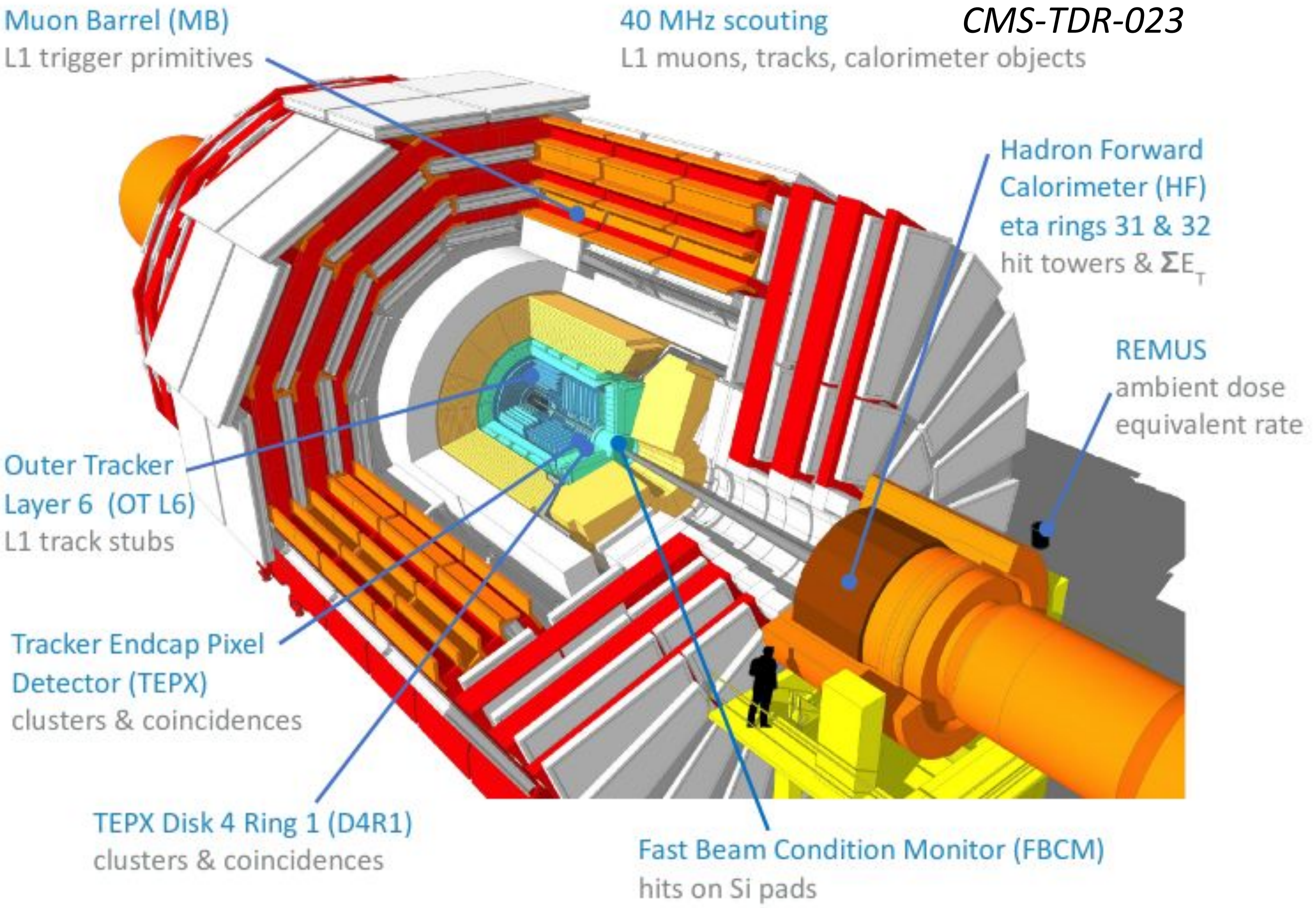
~1% systematic error on luminosity, becomes comparable to other experimental uncertainties

Instruments for Phase-2 luminosity

- Exploitation of the available sub-detector systems
  - Online bunch-by-bunch readout if feasible
- New tracking detector system
  - Inner Tracker Endcap Pixel Detector (TEPX): online pixel cluster counting
  - TEPX Disk 4 Ring1 (D4R1): exclusively for lumi and beam-induced background measurements
  - Outer Tracker Layer 6 (OT L6): counting track stubs (coincidences)
- Extended access to the trigger primitives with 40 MHz frequency (scouting): muons, tracks, calorimeter objects
- Muon barrel: extended bunch-by-bunch resolution
- Fast Beam Condition Monitor: completely new standalone luminometer
  - Asynchronous timing: sub-BX time resolution
  - Measurements during the full LHC filling cycle
  - No significant degradation due to irradiation and ageing

HL-LHC luminometers

CMS-TDR-023



Altogether the needed ~1% uncertainty

Overview

- Precise luminosity measurements during Run-2
  - Reaching 1.2% precision in 2016 pp@13 TeV
- 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 systems: muon barrel stubs and “40 MHz Scouting” (muon candidates, potentially calorimeter observables), semi-online pixel cluster counting
- Ambitious upgrade program for Phase-2 HL-LHC: robust systems with improved linearity and constant monitoring
  - Upgraded or completely replaced instrumentation
- Better understanding of the beam parameters, sources and determination of systematics bias
- Ultimate goal in sight: luminosity measurements with ~1% total uncertainty at pileup 200

References

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- CMS Collaboration, “CMS Luminosity Measurement for the 2017 Data-Taking Period at 13 TeV”, *CMS PAS LUM-17-004*
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- 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*