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

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Luminosity

- Luminosity measurement is crucial for determining production cross sections
- Strategy: determine the visible cross-section (σ_{vis}) for each detector
  - Uncertainties from the absolute calibration
  - Monitor linearity and stability

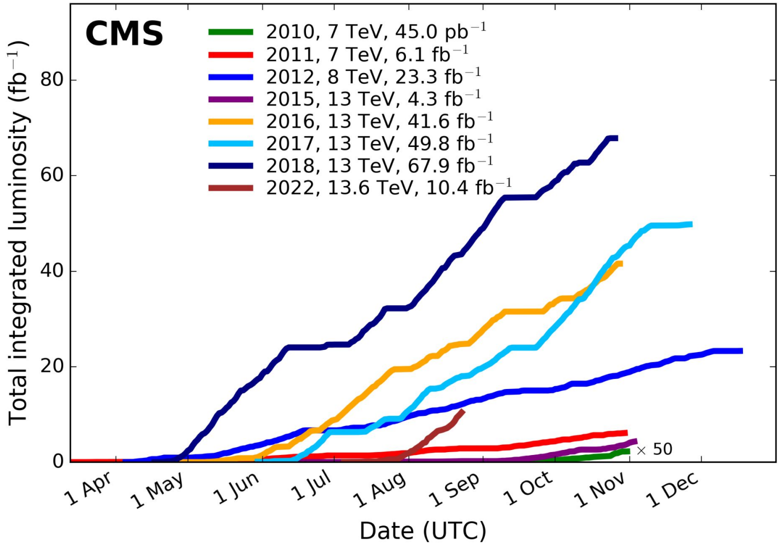
$$dN/dt = L_{inst}\,\sigma_{vis}$$

Detector and method specific calibration constant (obtained in VdM scans)

Specific event rate measured by the actual detector

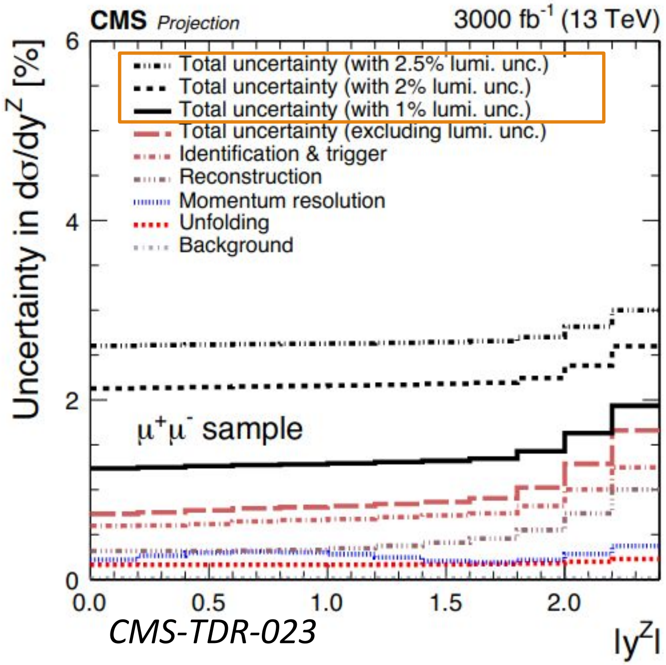
$$L = \int L_{inst}\,dt$$

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



Luminosity measurements

- Luminosity uncertainty: huge fraction of the overall experimental uncertainties
- Running with different conditions
  - Expected peak luminosity in HL-LHC: 7.5×10^{34} $cm^{-2}s^{-1}$, pileup of ~200
  - Run-2 peak: 2×10^{34} $cm^{-2}s^{-1}$ pileup ~50
- 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)



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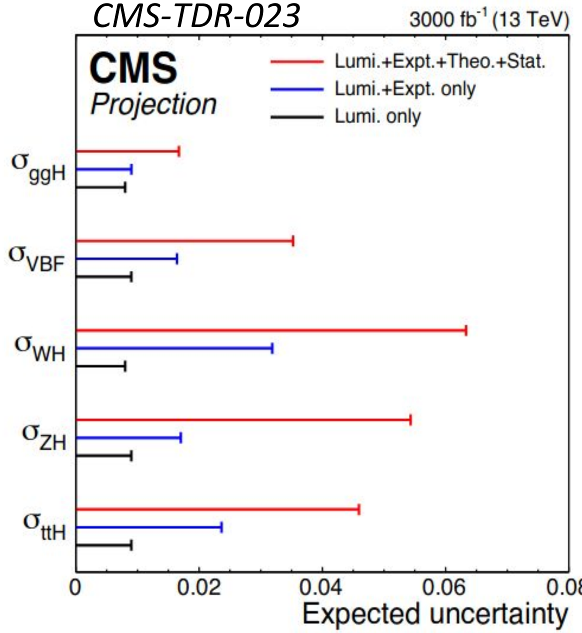


~1% systematic error on luminosity, becomes comparable to other experimental uncertainties

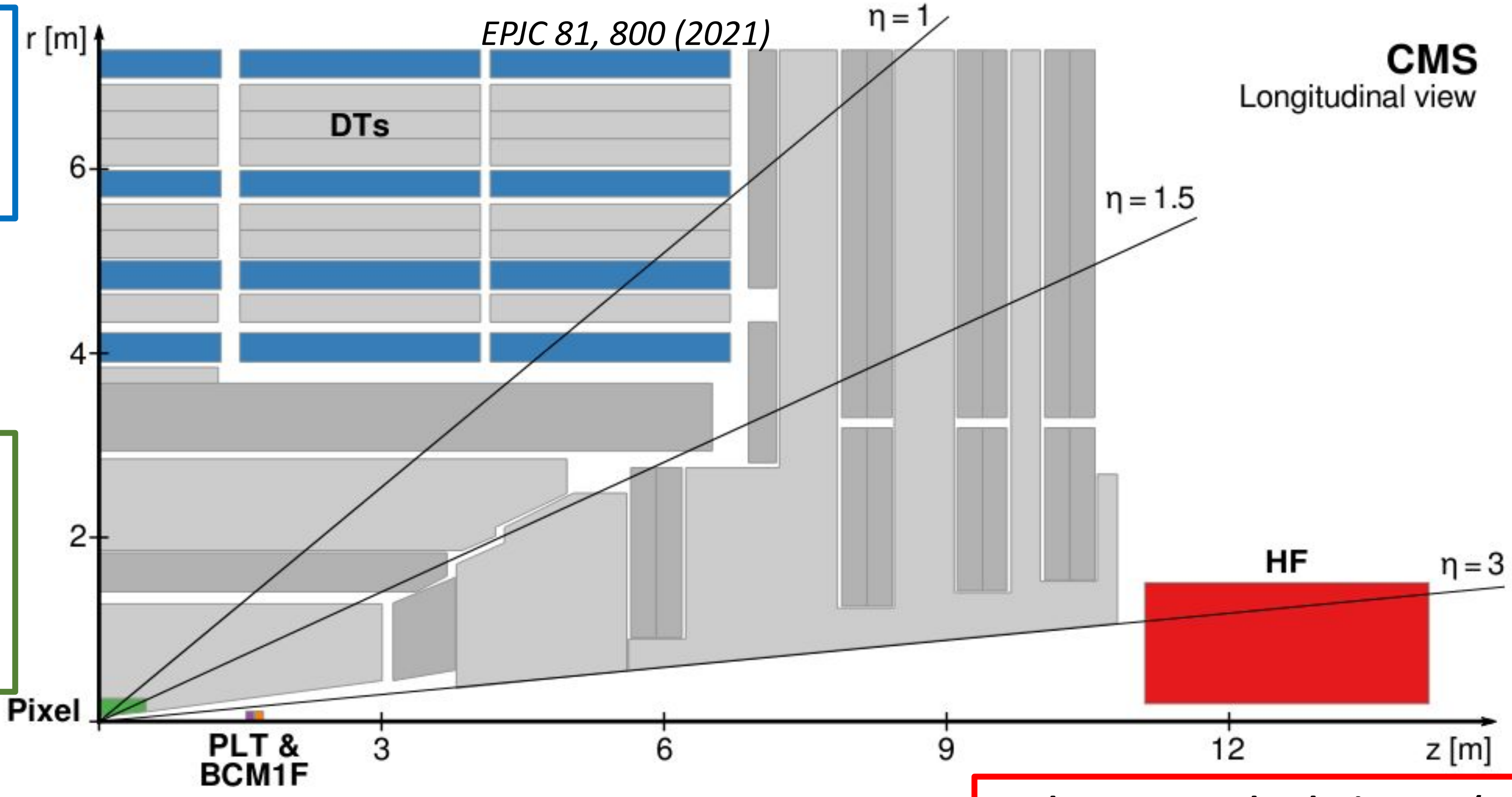
Luminometers at the CMS

RAMSES in the cavern:
- Radiation monitoring system
- Also used for lumi estimation

Muon barrel drift tubes:
- Counting muon track stubs

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

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 (bunch-by-bunch)
- Two algorithms
  - ΣE_t (HFET)
  - Tower occupancy (HFOC)

Other detectors are also used for the calibration

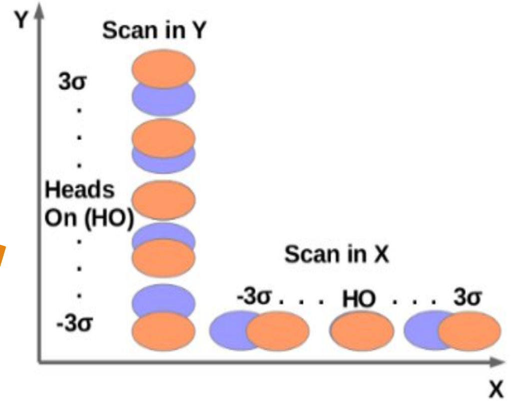
Beam position monitors (BPM) to measure the orbit of the circulating beams
- Diode ORbit and OScillation (DOROS) detectors
- Arc BPM detectors

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

Van der Meer methodology

- VdM calibration: precise σ_{vis} estimation under special conditions
  - Bunch-by-bunch interaction rate for several different beam separation values in x and y directions
  - Low pileup ≈ 0.5
  - Smaller number of filled bunches with at least 500 ns separation
  - Relatively large beam size
- Results are extrapolated to physics run conditions
  - Additional uncertainties from linearity and long-term stability studies



Beam overlap widths ($\Sigma_{x,y}$) and rate (R_0) during head-on collisions
- Rate measurement during two separation scans in x and y directions (affected by background)
- Beam orbit monitoring with BPMs (corrections due to length-scale, orbit movements, beam-beam interactions)

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

Assumptions: x-y direction factorization

LHC orbit revolution frequency: f = 11245.5 Hz

Bunch intensity from beam current measurements, corrected for ghost and satellite charges: $N_1, N_2 \approx 8\times10^{10}$

VdM calibration

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

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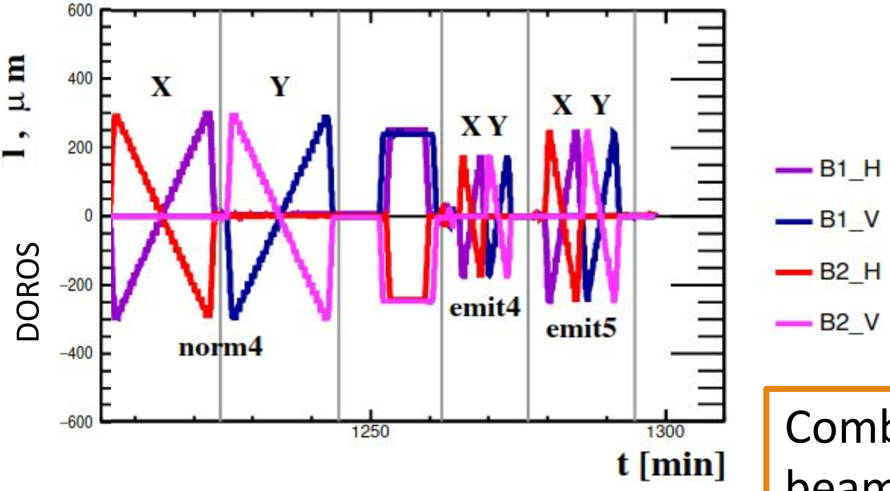

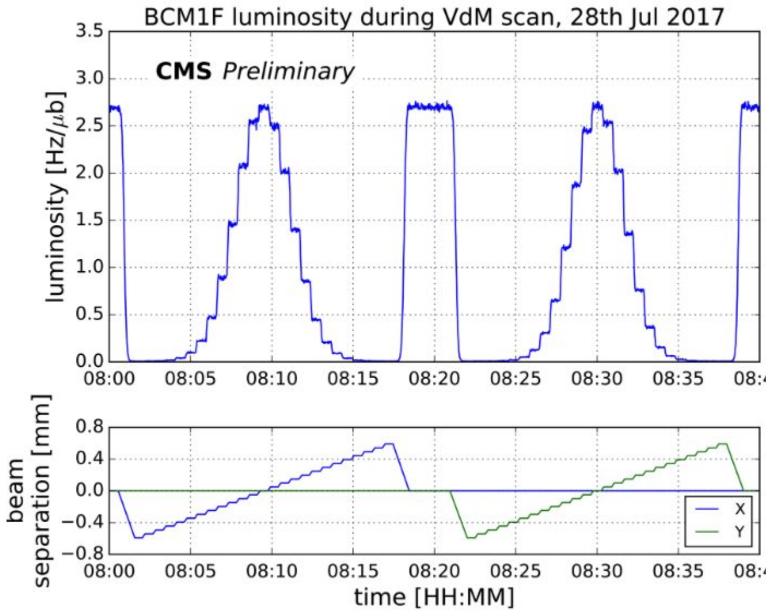

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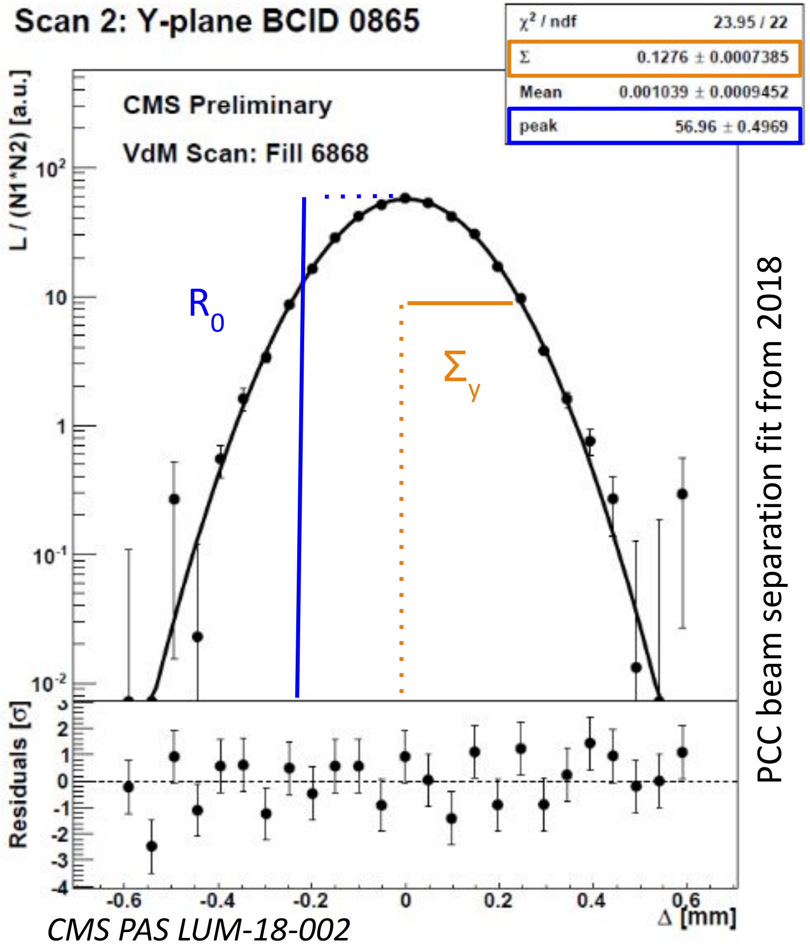


CMS PAS LUM-18-002

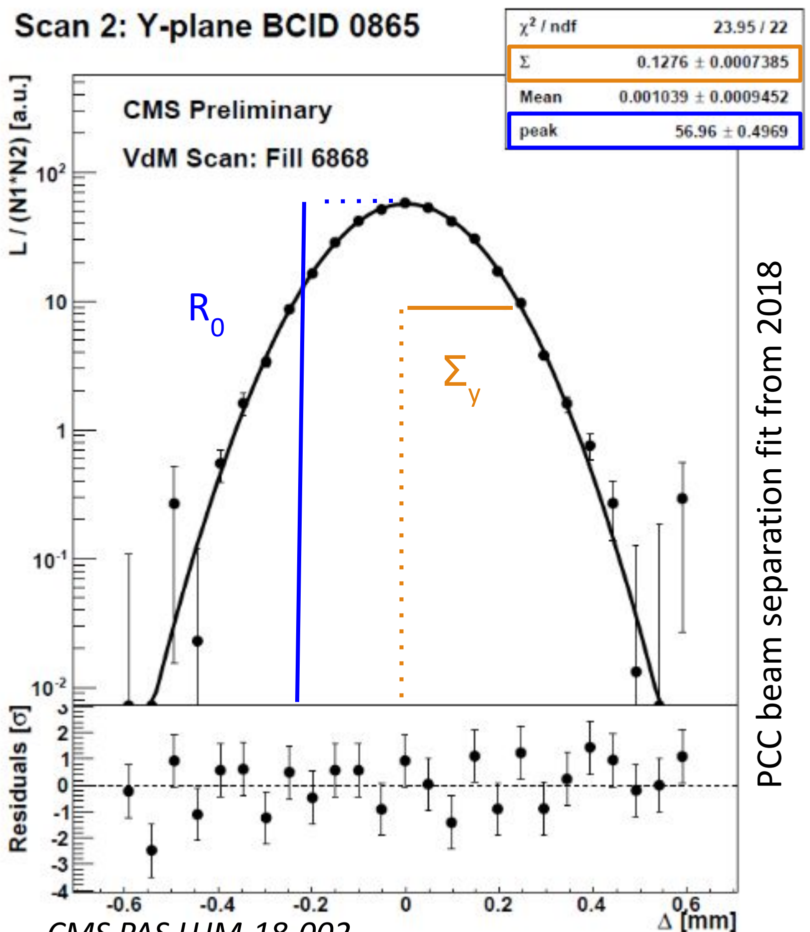
Combination of the two measurements: beam separation fit for $\Sigma_{x,y}$ and R_0

VdM calibration

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

Normalization (VdM) corrections with the largest uncertainties (more corrections in the backup)

- Orbit drift corrections (0.5-0.8%): from the difference between the nominal and the corrected beam positions
- Beam-beam effects (0.5%): electromagnetic interactions between the two beams leads to optical effect (dynamic beta) and a deflection from the nominal position
- X-Y nonfactorisation (0.5-2%): 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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PCC beam separation fit from 2018

Corrections under physics conditions and stability

Relative luminosity corrections from emittance scans recorded during physics runs since 2017

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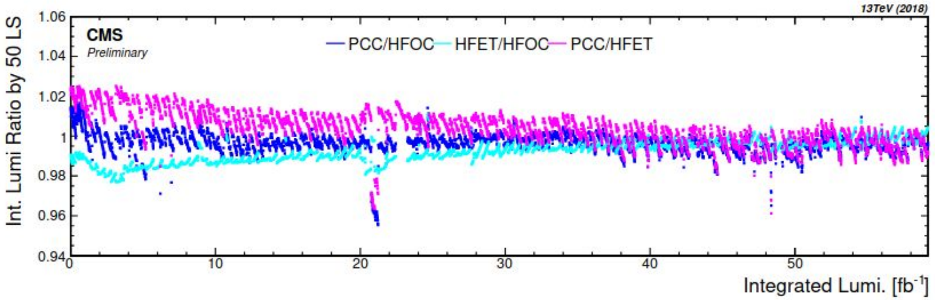

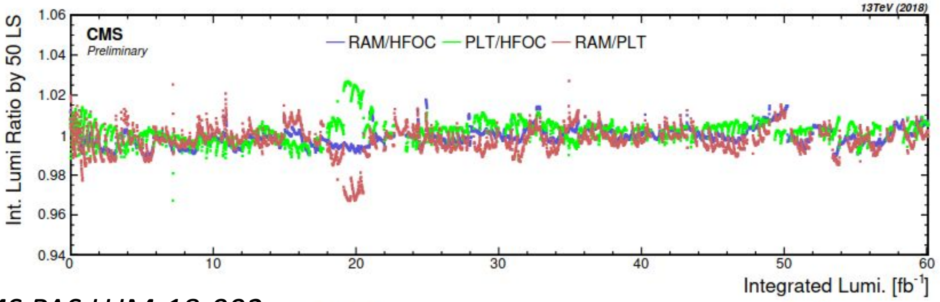

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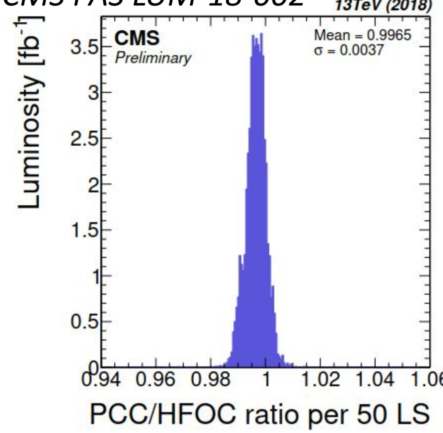
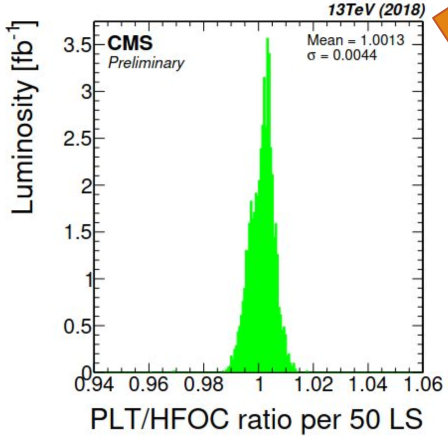
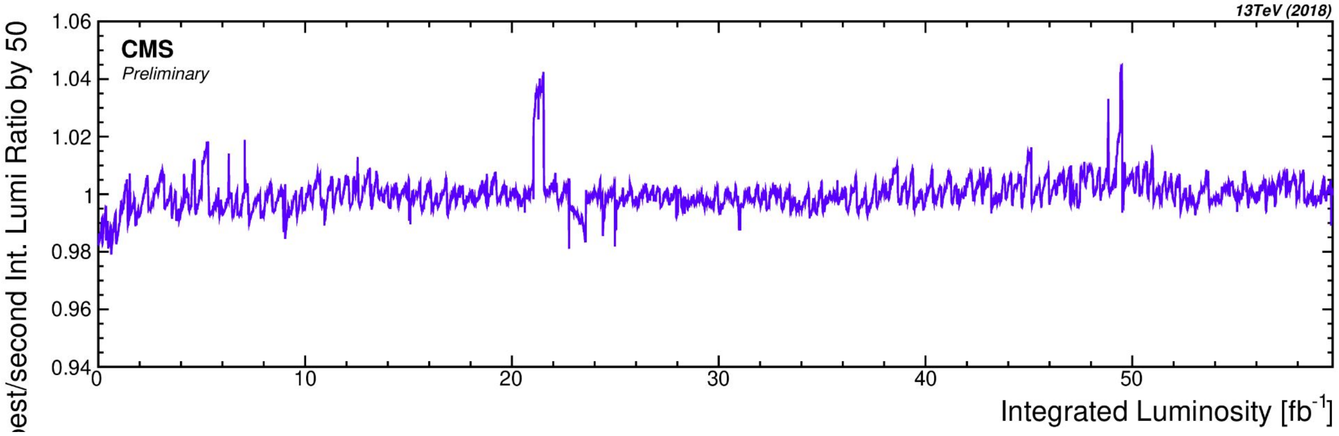




- Final selection of the primary luminometer (PCC in 2018), its data is used for luminosity estimations.
- Uncertainty (more in backup) comes from the comparison of the primary and the secondary luminometer measurements.



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Ratio plots to check the long-term stability and linearity

Corrections under physics conditions and stability

Relative luminosity corrections from emittance scans recorded during physics runs since 2017

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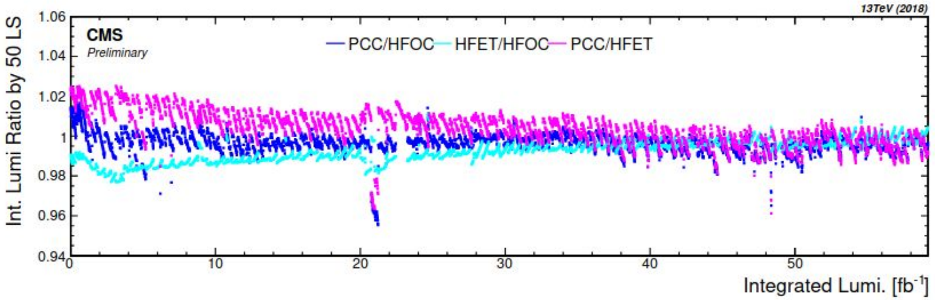
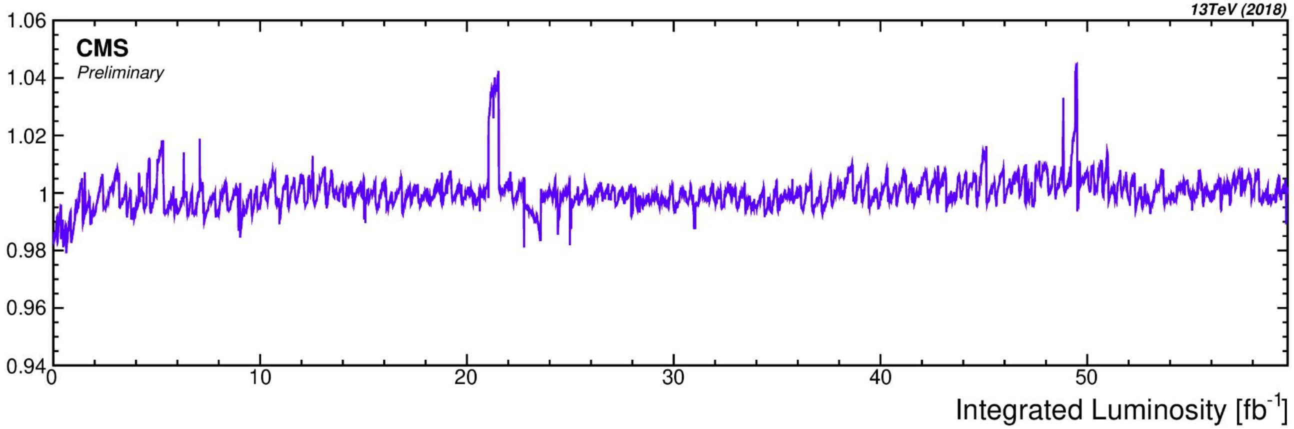


- Final selection of the primary luminometer (PCC in 2018), its data is used for luminosity estimations.
- Uncertainty (more in backup) comes from the comparison of the primary and the secondary luminometer measurements.

Precise luminosity for Run-2

- Altogether 1.2-2.5% total uncertainty on the offline luminosity measurements
  - Most precise final luminosity for 2016 with 1.2% uncertainty



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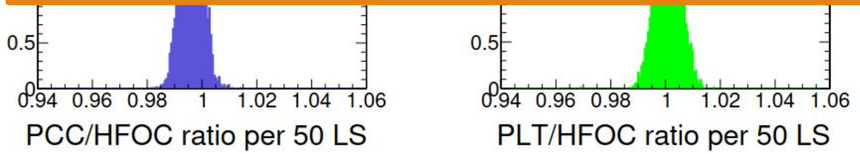

Ratio plots to check the long-term stability and linearity

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
  - Good statistical precision, excellent expected linearity
  - No significant degradation due to irradiation and ageing

HL-LHC luminometers

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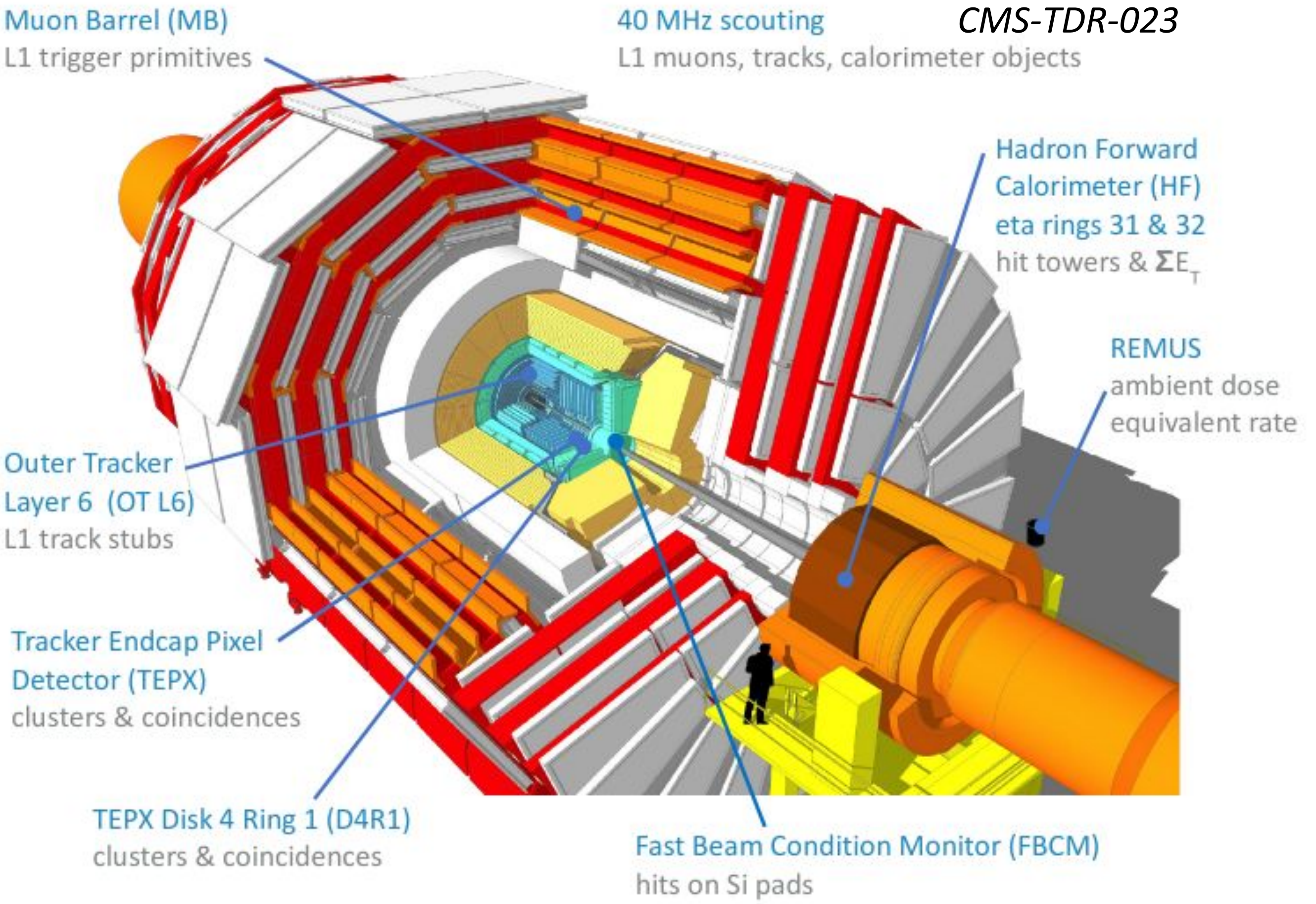


Altogether the needed ~1% uncertainty

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

CMS Collaboration, "The Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity Detectors", *CMS Technical Proposal* CMS-TDR-023
CMS Collaboration, "Precision luminosity measurement in proton-proton collisions at 13 TeV in 2015 and 2016 at CMS", *EPJC 81, 800 (2021)*

Backup

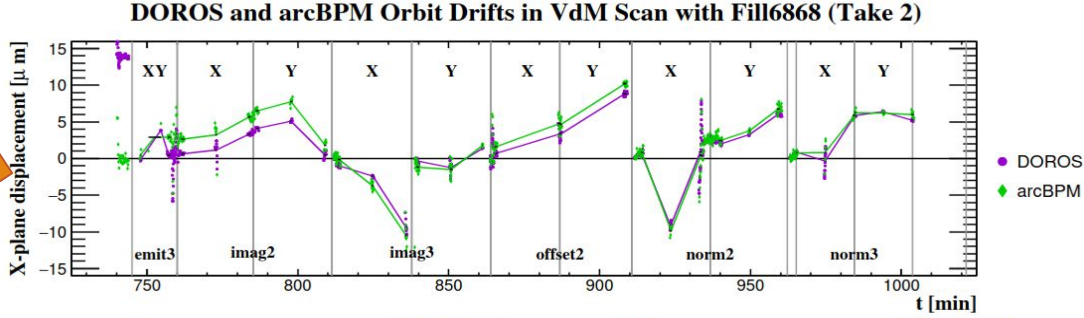
References

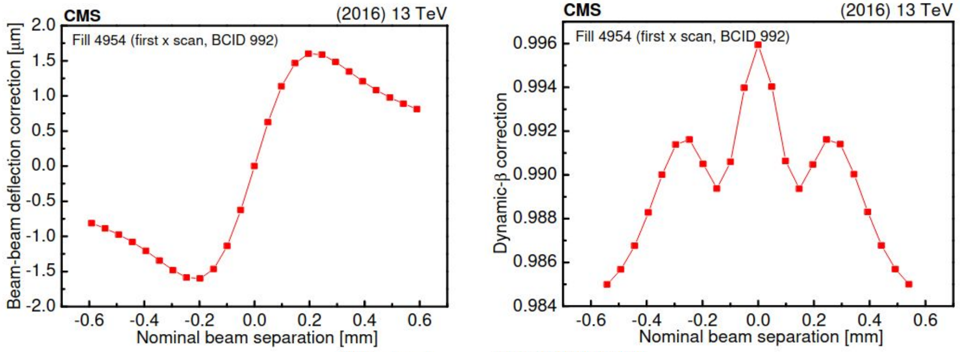
- CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST 3 (2008) S08004*
- CMS Collaboration, “CMS Luminosity Measurement for the 2017 Data-Taking Period at 13 TeV”, *CMS PAS LUM-17-004*
- CMS Collaboration, “CMS Luminosity Measurement for the 2018 Data-Taking Period at 13 TeV”, *CMS PAS LUM-18-002*
- CMS Collaboration, “The Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity Detectors”, *CMS Technical Proposal CMS-TDR-023*
- 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*

VdM (normalization) corrections

- 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
- 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
- X-Y nonfactorisation from specific separation scans or by studying the luminous region parameters in standard VdM scans

CMS PAS LUM-18-002





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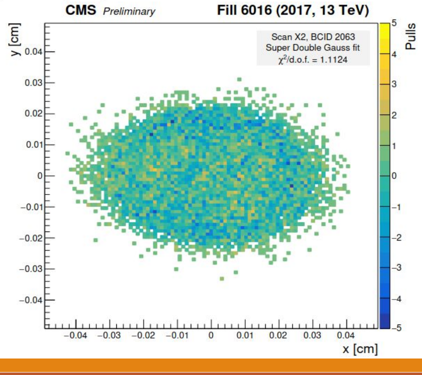
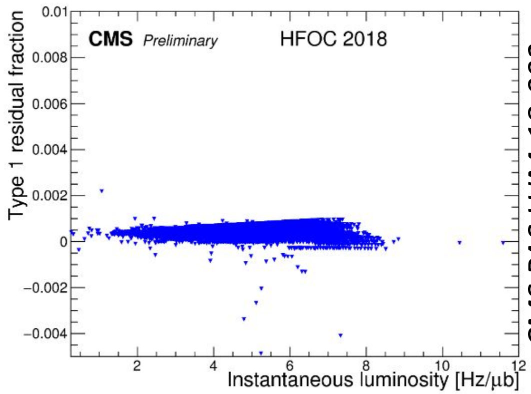


CMS PAS LUM-17-004

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…
    - exponential time development
- Efficiency and noise corrections: reduced response due to irradiation, ageing or other detector specific effect
- Non-linearity corrections
- Cross-detector stability: long-term comparison of the measured luminosities



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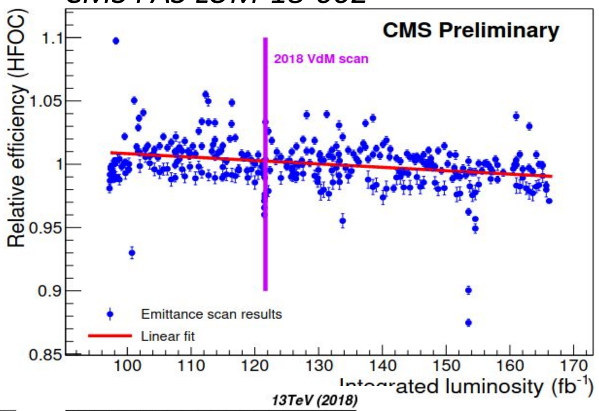

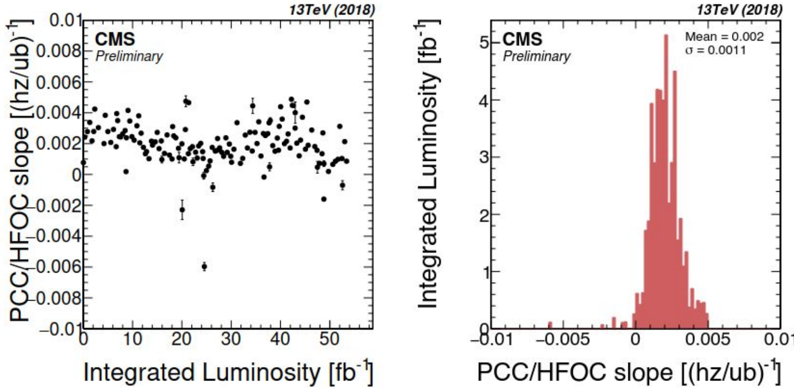

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Uncertainties in Run 2

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**

Phase-2 expectations: ~1% total systematic uncertainty