Precision Luminosity Measurements in CMS with Run 2 and Run 3 Data

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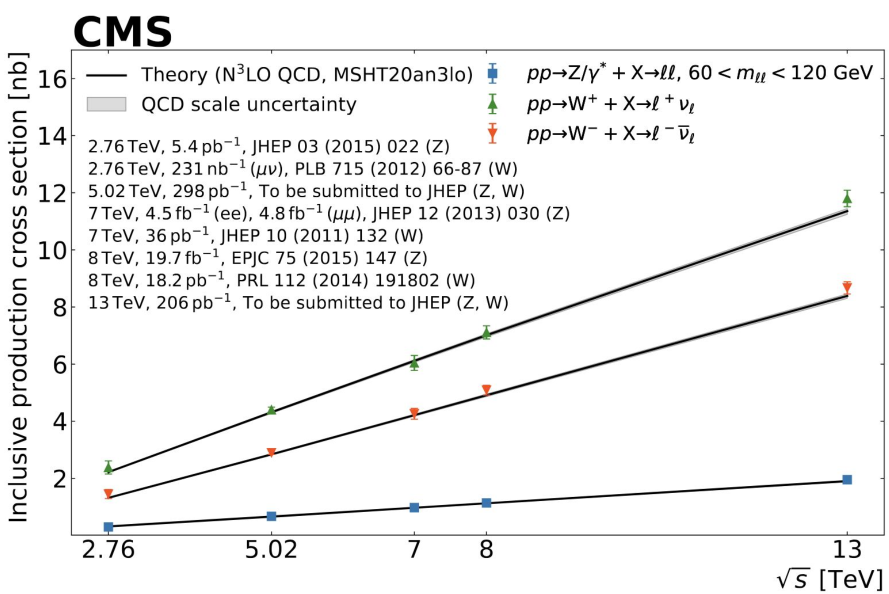
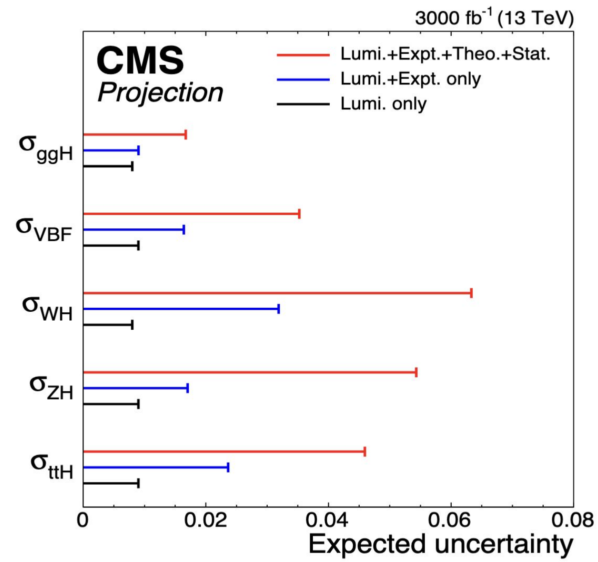
What is luminosity, why do we care?

Luminosity

- Is a measure of the accumulated data
- Connects theory and experiment: $\sigma_{process} L_{int} = \langle N_{total} \rangle$ → **used in all xsec measurements**
- Is amongst the leading sources of experimental uncertainties in SM precision measurements

In lepton colliders it is measured using benchmark physics processes like Bhabha-scattering ($\sigma_{process}$ very well known), but hadron colliders pose many challenges on account of the protons being composite particles (non-trivial PDFs) → large production cross section uncertainties





Outline

Detectors
- Redundancy
- Diverse technologies
- Multiple ranges in occupancy

Calibration
- **The van der Meer method**
- Non-collision background
- Bunch intensity
- Beam-beam interactions
- **Beam positions**
- Lengthscale calibration
- **Non-factorisation**
- Emittance scan evolution
- Unknown biases

Integration
- Out-of-time corrections
- Emittance scans
  - **Efficiency tracking**
  - **Non-linearity**
- Residual effects
  - Consistency
  - Linearity
- **Average luminosity**

Standard candle proxies
- **Z boson rate counting**
- Muon pair production in ultraperipherial collisions

More general overview available in ICHEP24 presentation.

Today: concentrate on some of the recent novel aspects highlighted above

What hardware is used?

Multiple **independent systems** (*luminometers*) using a **diverse set of technologies** are utilized for redundancy and best accuracy

Calibration constant

$$R(t) = \sigma_{\text{vis}} L_{\text{inst}}(t)$$

Deposited energy / Hit rate

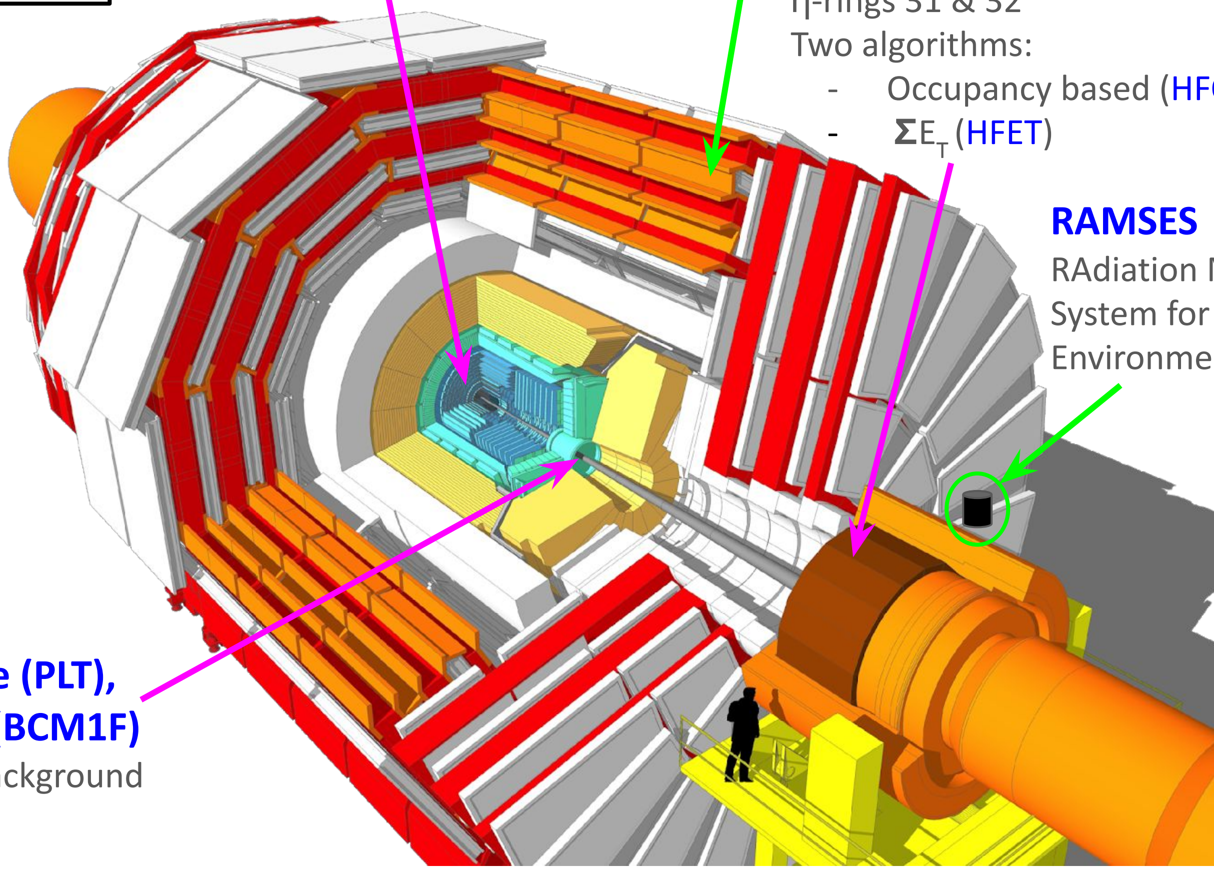
- direct counting
- zero counting

Pixel Cluster Counting (PCC)
On all except the first barrel layer + veto list of modules

Drift Tubes (DT)
L1 muon trigger primitives/objects

Hadron Forward Calorimeter (HF)
η-rings 31 & 32
Two algorithms:
- Occupancy based (HFOC)
- ΣE_T (HFET)

RAMSES
RAdiation Monitoring System for the Environment Safety



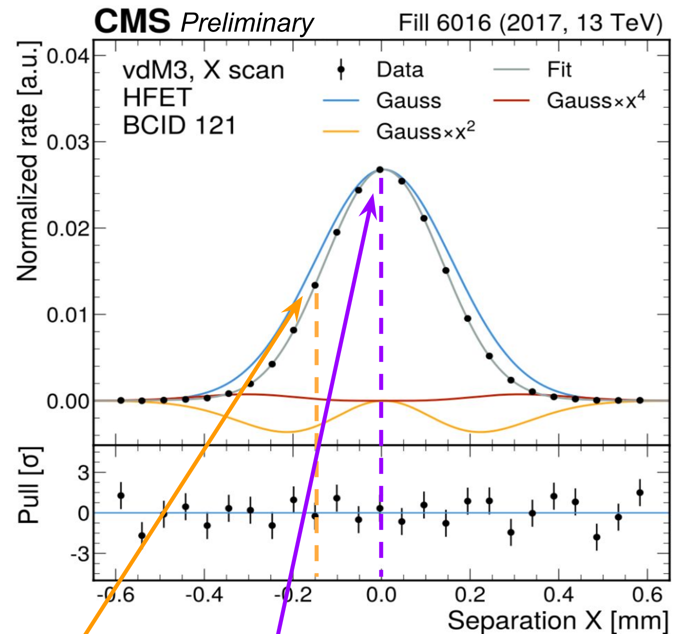
Pixel Luminosity Telescope (PLT), Beam Condition Monitor (BCM1F)
Luminosity + beam induced background
BCM1F has multiple backends

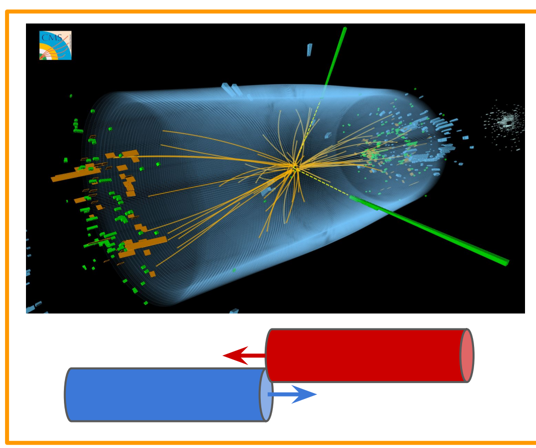
Calibration:

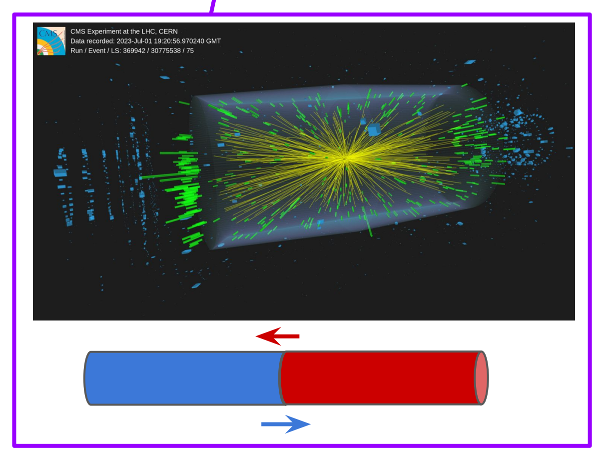
Establishing absolute luminosity in well controlled conditions

The van der Meer method

- ❖ Highly controlled special conditions:
  - ➢ Once a year
  - ➢ Wide beams - finer relative control
  - ➢ Low PU - reduced *linearity effects*
  - ➢ Isolated bunches - reduced *out-of-time*
  - ➢ Tailored bunch tails in injector chain - bunch distributions are approximately *factorisable*
- ❖ Perform an X and a Y beam separation scan

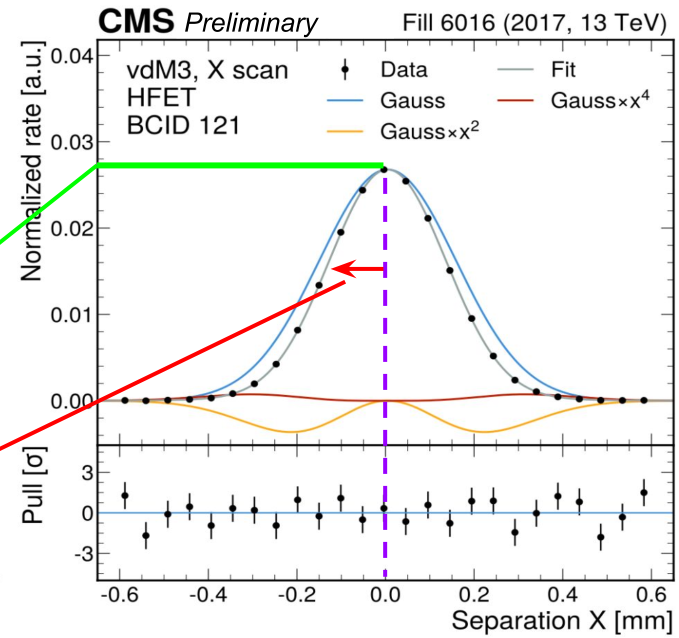




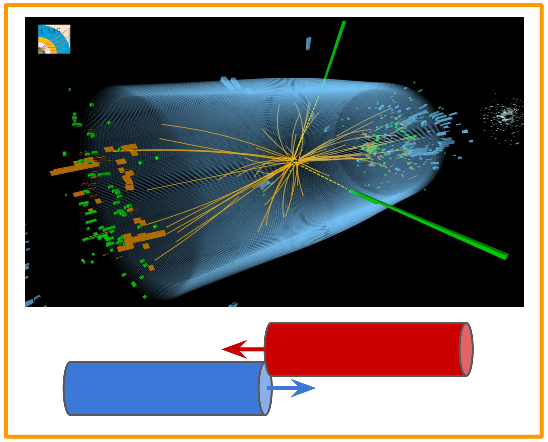


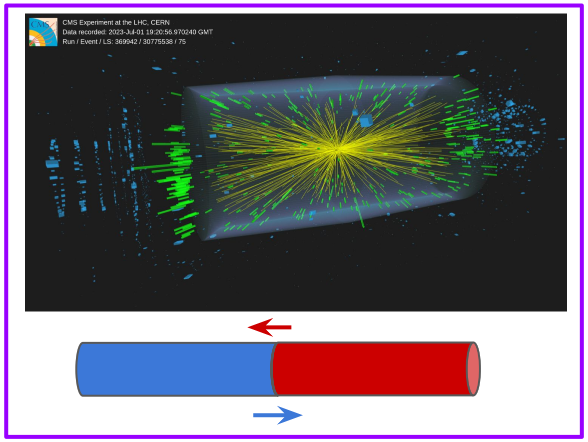
The van der Meer method

- Normalize the rates with the beam currents ($N_1 N_2$) provided by LHC beam instrumentation
- Fit a Gaussian-like function on the scan profile and extract the peak (R_0/N_1N_2) and the profile width (Σ)



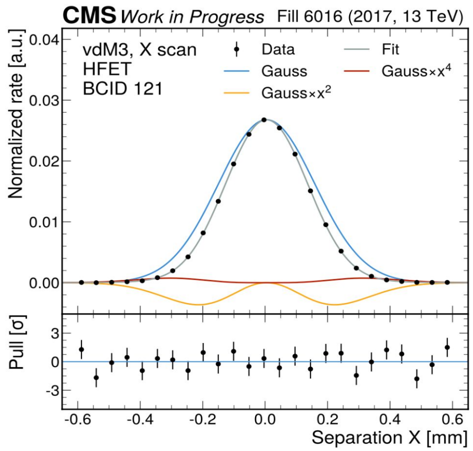
$$\sigma_{\mathrm{vis}} = \frac{R_0}{L_0} = \frac{R_0}{N_1 N_2} \frac{2\pi \Sigma_X \Sigma_Y}{f_{\mathrm{LHC}}}$$





Corrections in the vdM procedure

$$\sigma_{\text{vis}} = F \frac{R_0}{N_1 N_2} \frac{2\pi \Sigma_X \Sigma_Y}{f_{\text{LHC}}}$$



rates (R_0*)

- Background rate of luminometers
- **Orbit drift** in non-scanning direction
- Beam-beam optical effect

- **Emittance** (→ $\Sigma_{x/y}$, R_0) **evolution**

separations (Σ_X, Σ_Y*)

- **Orbit drift** in scanning direction
- Beam-beam deflection
- Transverse length-scale

N_1, N_2

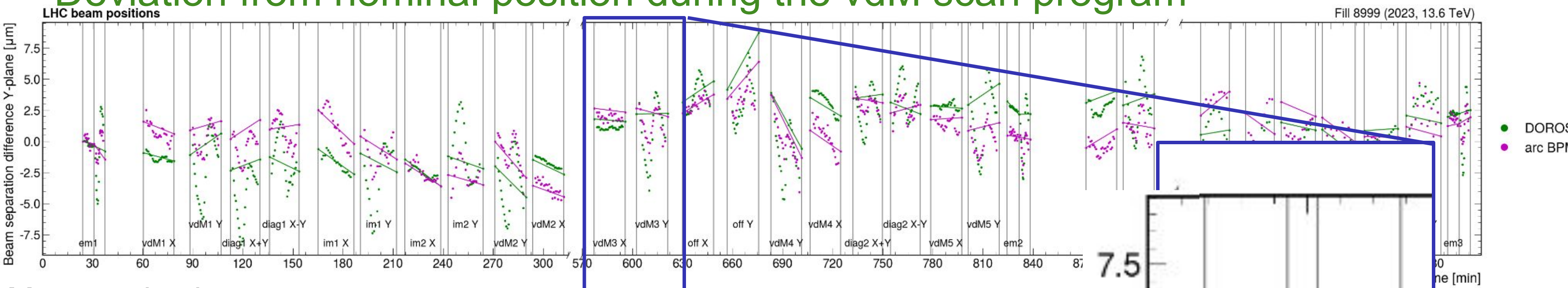
- Bunch current normalization
- Ghost and satellite contributions

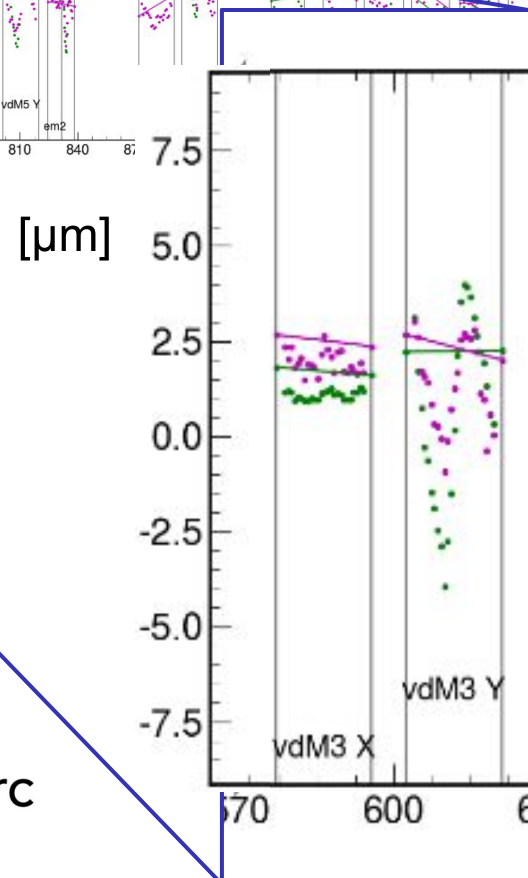
- **Transverse factorizability** (correction factor to σ_{vis} formula: F)

* some of these impact both R and Σ to due to the fit correlating the effects impacting the separations and rates

Orbit drift systematics

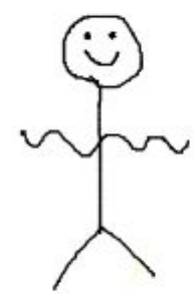
Deviation from nominal position during the vdM scan program



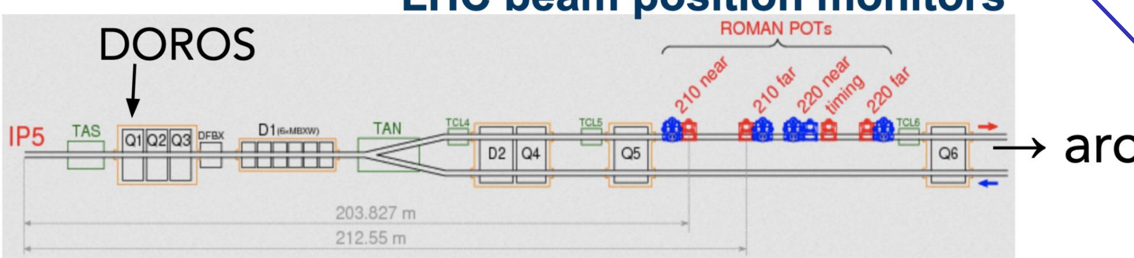


Measured using

- ❖ Arc beam position monitor (BPM)
- ❖ DOROS BPM



LHC beam position monitors



Orbit drift systematics

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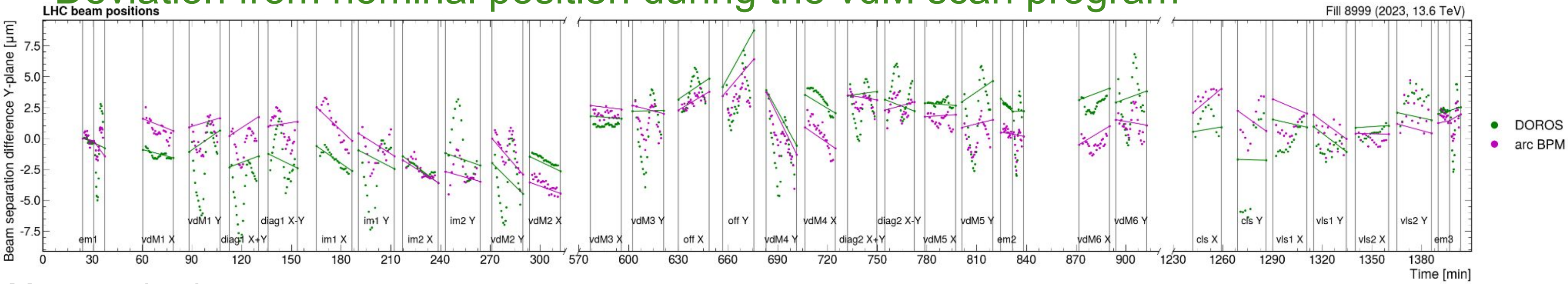


Measured using

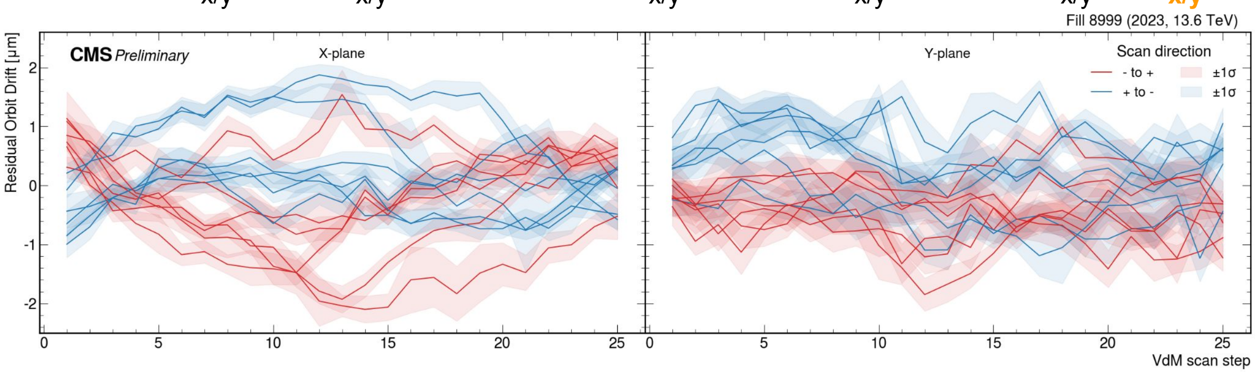
- Arc beam position monitor (BPM)
- DOROS BPM

Contributes:

- Slow, **linear orbit drift** (estimated from before- and after-scan head-on readings)
- **Beam-beam deflection** (BB) (Bassetti-Erskine formula)
- **Residual OD** extracted as the residuals of the fit (only scanning plane fit shown):

$$BPM_{x/y} - linOD_{x/y} = \alpha \times Nominal_{x/y} + \beta \times BB_{x/y}(\Delta Nominal_{x/y}) + c_{x/y}$$

Fitted parameters:
Lengthscale (BPM)
BB dilution
Constant



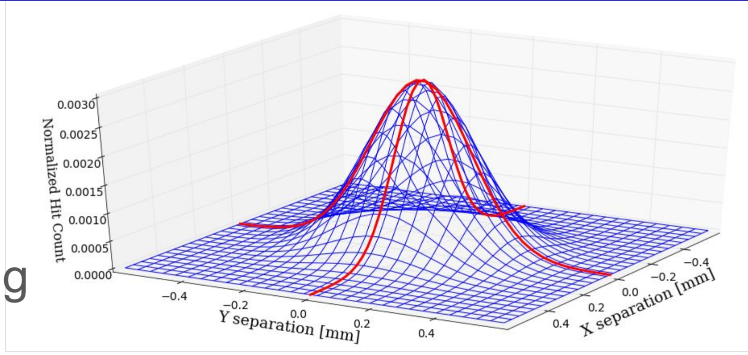
Typical OD uncertainty in 2022-2023: ~0.2%
Large improvement since 2015-16 paper (0.5-0.8%)

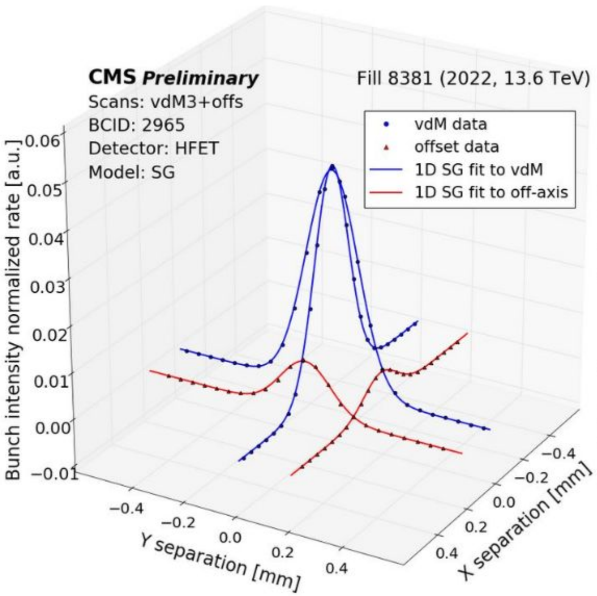
Non-factorisation

VdM method assumes R(x,y) = f(x)g(y)

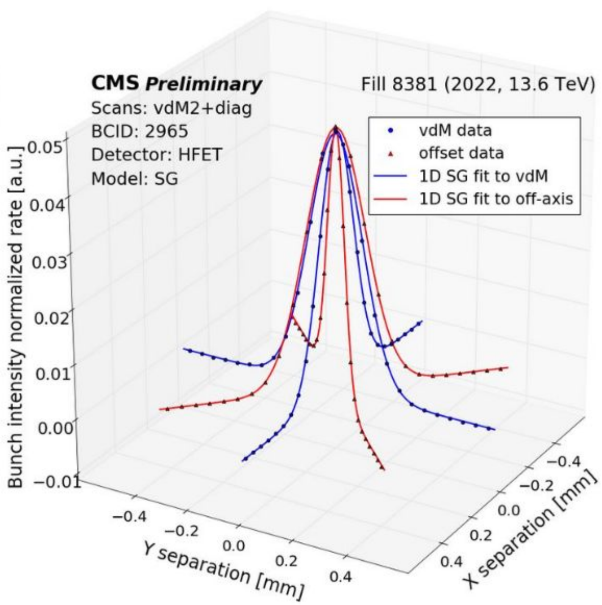
→ two scans are enough to get the integral of R(x,y)

- **2D scans**
  - Fits the bunch overlap shape directly
  - Using complementary scans for off-axis sampling
  - All BCIDs are used
  - Modelling uncertainty dominates
- Luminous region analysis



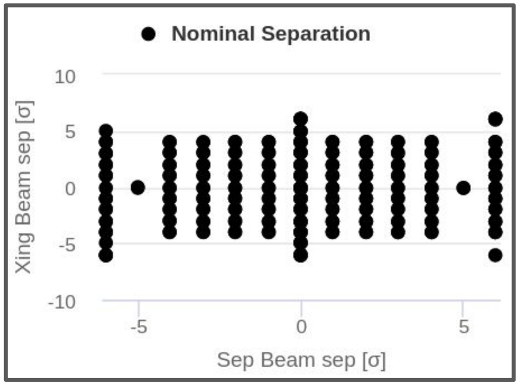


offset scan



diagonal scan

New in 2024 vdM



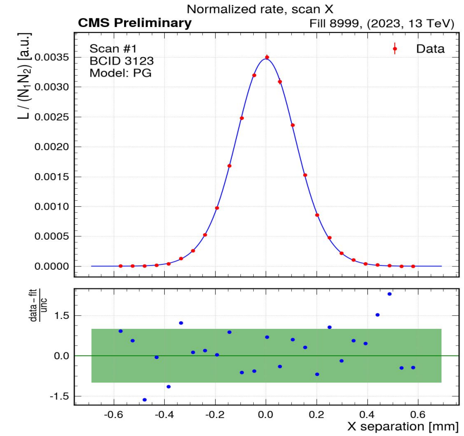
grid scan

Non-factorisation

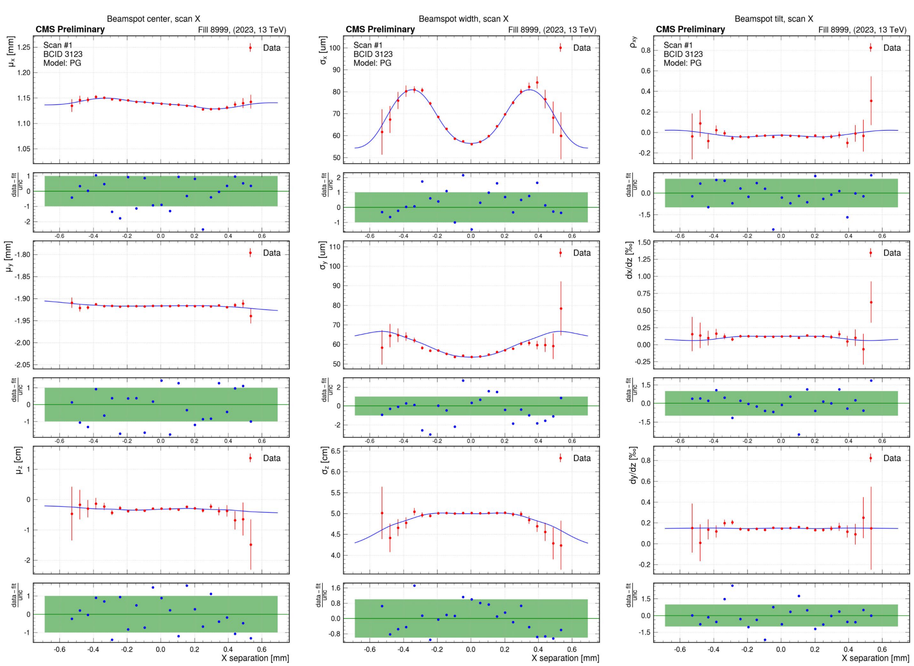
VdM method assumes R(x,y) = f(x)g(y)

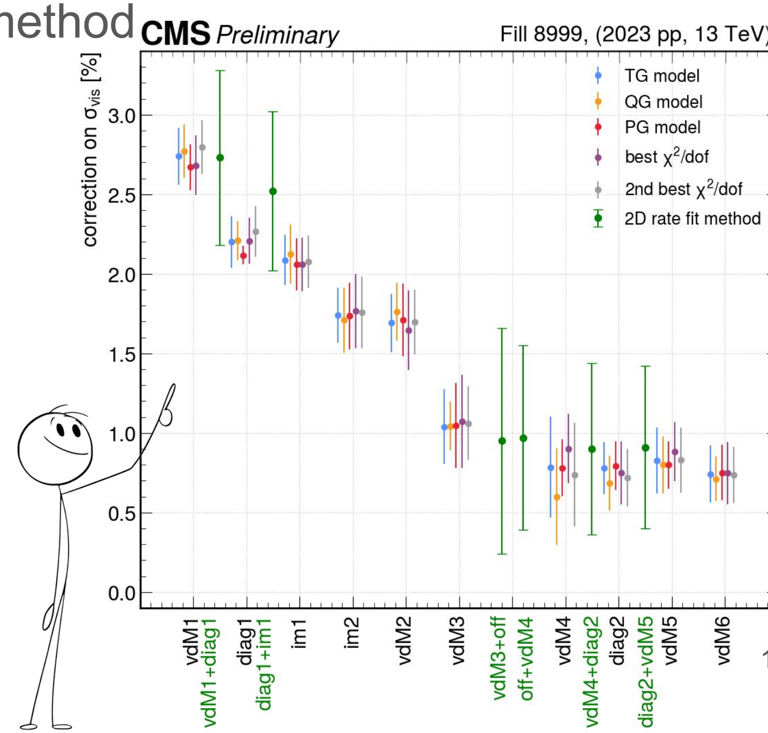
→ two scans are enough to get the integral of R(x,y)

Uncertainty:
2022 (prelim): 0.8%
2023 (prelim): 0.7%



- 2D scans
- **Luminous region analysis**
  - Fits the 3D bunch density function for the two beams
  - Using any scans
  - For few BCIDs with high rate vertex data
  - **Uncertainty dominated by closure** of the method

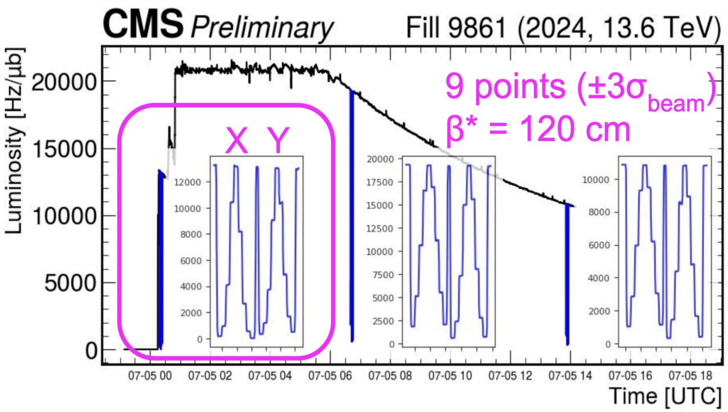




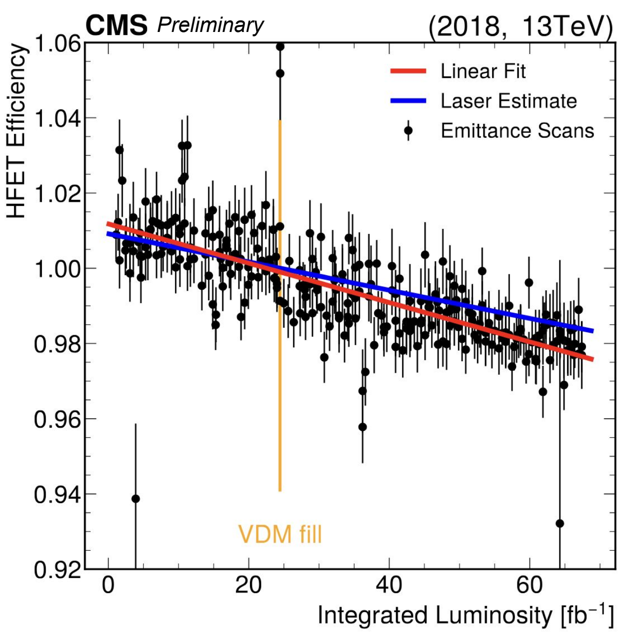
Integration:

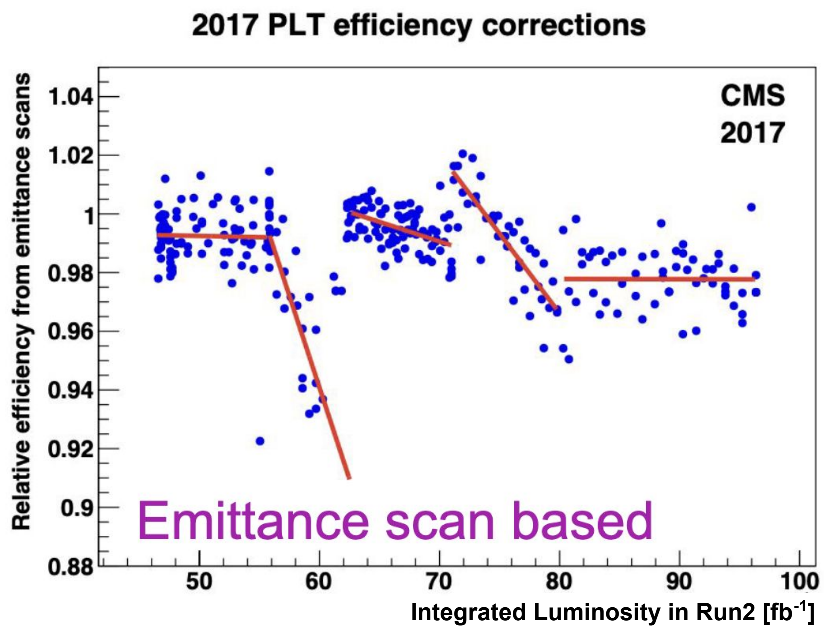
Measurement in high PU conditions

Rate corrections - Efficiency

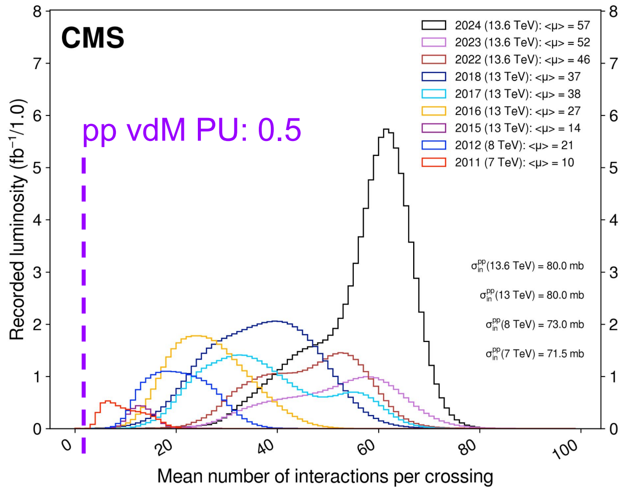


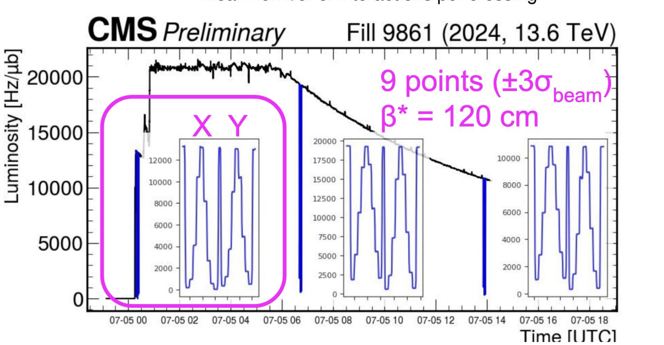
- Aging due to radiation
- Changing conditions (HV, temp, failing modules)
- All detectors potentially affected
- **Intrinsic correction**: Emittance scan-based efficiency tracking (per-module for PLT, BCM1F)
  - Good agreement with alternative methods (Laser-based for HF, tracking-based for PLT)

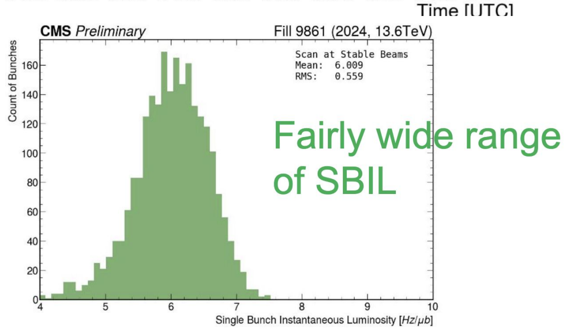




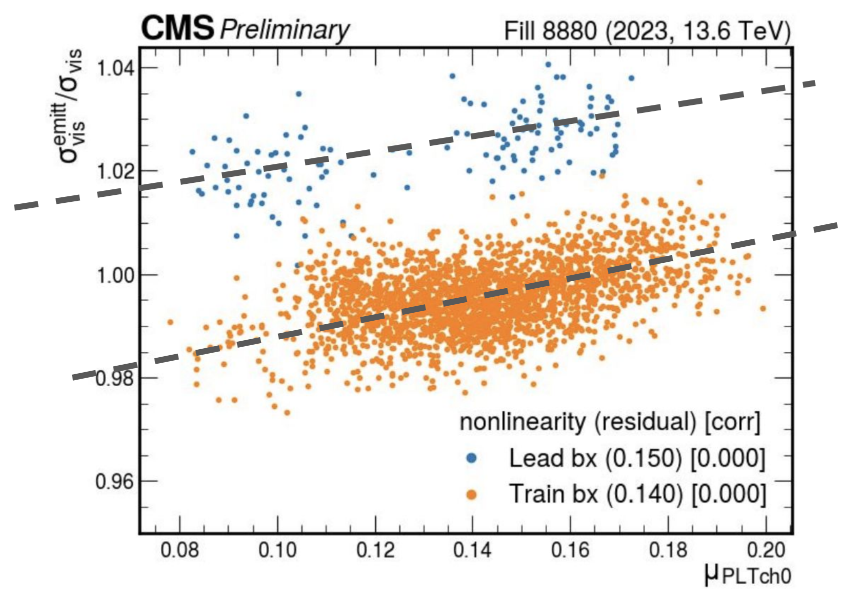
Rate corrections - Nonlinear response





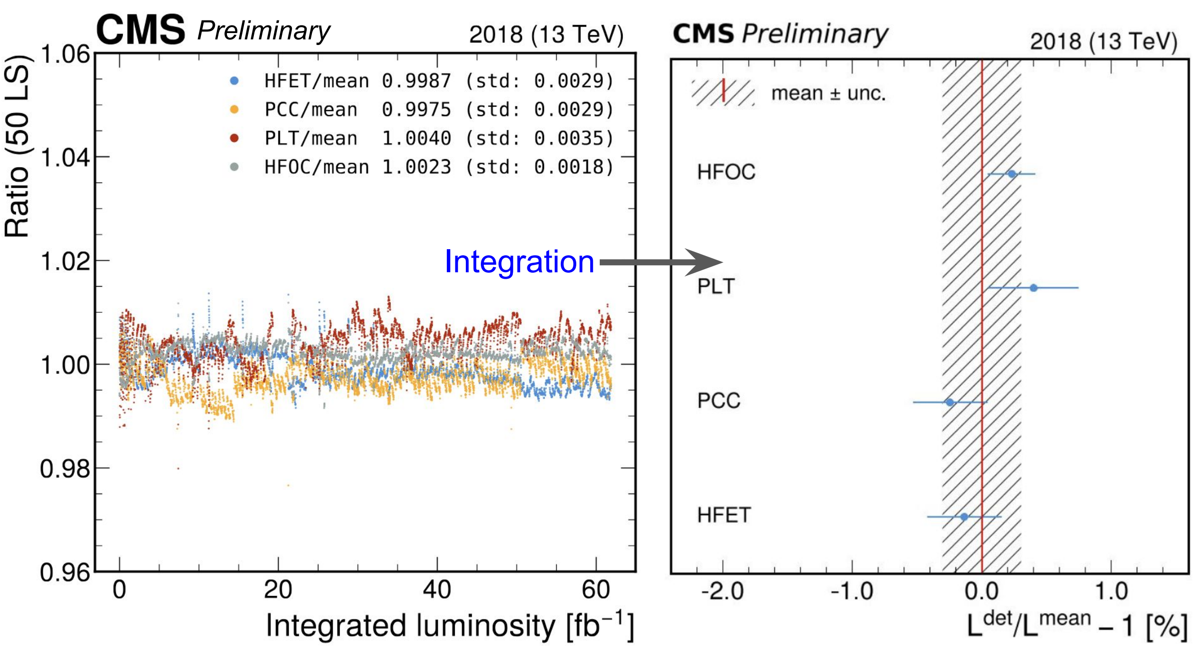


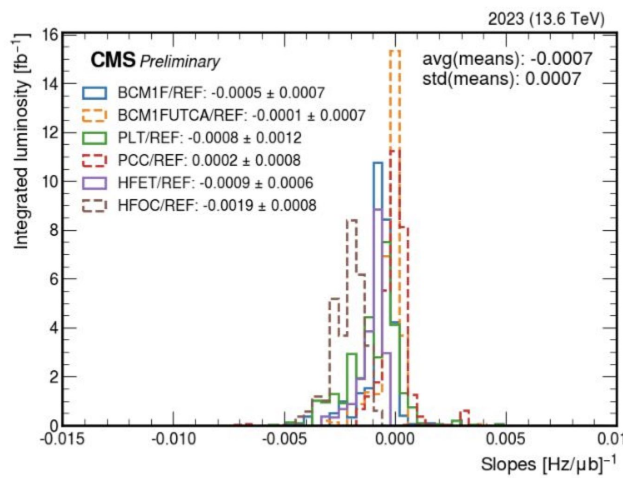
- VdM calibration performed **at 1/100 of the datataking pile-up**
- Model: $\mu_m = \mu_\ell\,(1 + \alpha\,\mu_\ell\,)$
- Mitigation - correction of detectors based on **intrinsic** quantities:
  - Restrictive module selection - based on noise levels and internal consistency (PCC)
  - **Efficiency as a function of peak luminosity** (SBIL) tracked via emittance-scans (per-module for PLT, BCM1F)



Closure: Consistency, non-linearity

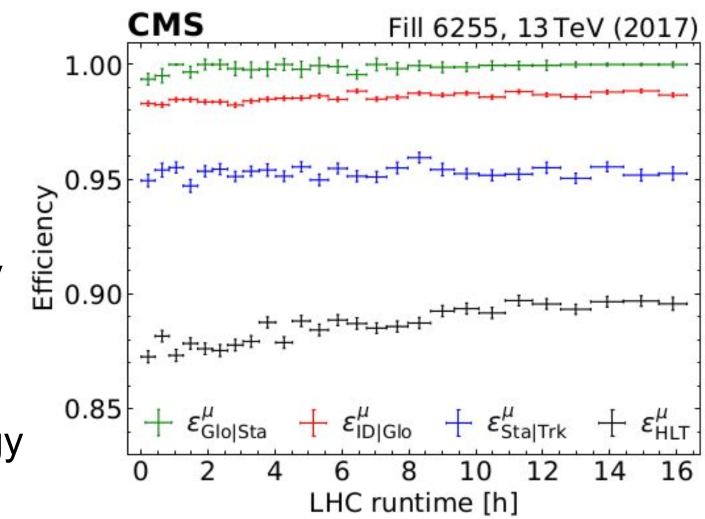
- **Previously:** Detectors ordered according to their dependability:
  The **best available source** provides the luminosity
- **Current non-preliminary approach:** Several detectors calibrated independently to a similar quality → use the **average of the available sources**
- Spread of detectors is tracked throughout the whole year
  - Uncertainty derived from the RMS the mean of all histograms
- Residual nonlinearity of the average lumi is evaluated with respect to DT and RAMSES, the more conservative estimate is used

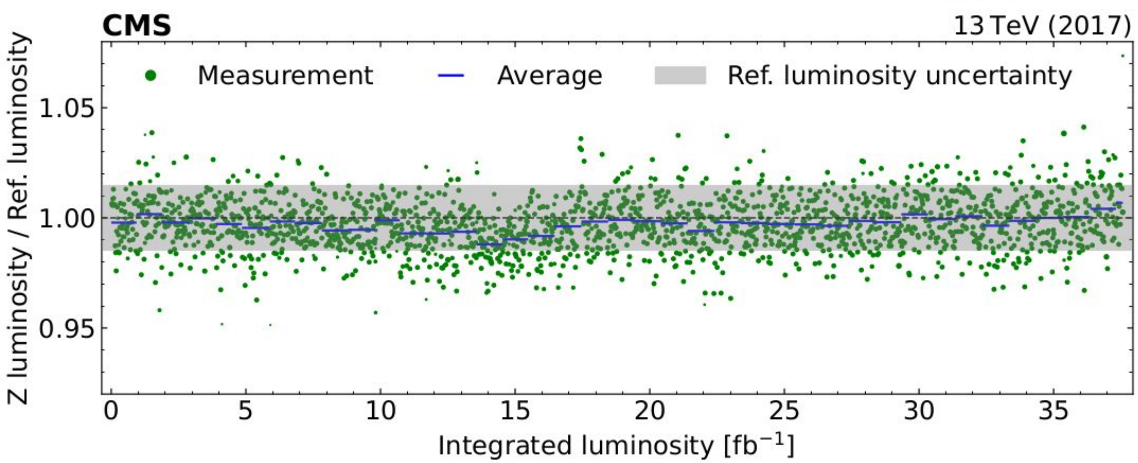


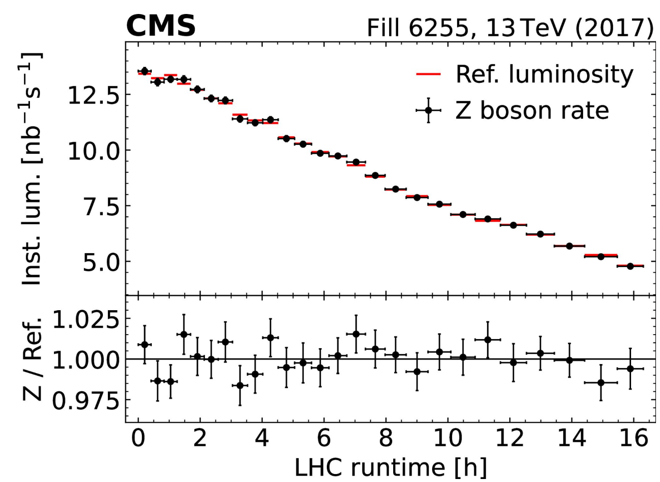


A pp standard candle: Z counting

- Z→μμ has
  - a clean signature
  - relatively large cross section (not enough for vdM)
  - a not-too-well-known fiducial cross section (PDF)
- Trigger and selection efficiencies are measured in situ every 20/pb → **intrinsic linearity and efficiency correction**
- Primary use:
  - common ground for consistency checks at given energy
  - relative luminosity measurement: $\mathcal{L}_{\mathrm{highPU}} = \frac{N^{Z}_{\mathrm{highPU}}}{N^{Z}_{\mathrm{lowPU}}} \mathcal{L}_{\mathrm{lowPU}}.$







See: (Eur. Phys. J. C 84 (2024) 26)

Recent results

- Multiple independent luminometers relying on diverse technologies
- Several corrections applied in calibration and integration - new approaches highlighted in table
  - Dominant sources: Factorisation, Integration, Beam-Beam, Orbit drift,
- Uncertainties treated as 100% or 0% correlated between years in combinations (see colors)
- Recent preliminary results approach 1% uncertainty, foreshadowing the upcoming Run2 precision result

Results since 2020	2015	2016	2022 (prelim)	2023 (prelim)	pp ref 2017 (prelim)	PbPb 2015	PbPb 2018
	EPJ C81 (2021) 800		CMS-PAS-LUM-22-001	CMS-DP-2024-068	CMS-PAS-LUM-19-001	Submitted to EPJC	
Non collision rate	—	—	—	—	—	0.5	0.2
Statistical	—	—	—	—	<0.1	0.1	0.1
Beam current	0.1	0.1	0.2	0.20	0.2	0.2	0.2
Ghost & satellite charges	0.2	0.2	0.2	0.10		0.3	0.5
Beam-beam effects	0.5	0.5	0.4	0.34	0.8	0.2	0.3
Linear (random) orbit drift	0.2	0.1	0.1	0.02	0.3	0.5	0.1
Residual (systematic) orbit drift	0.8	0.5	0.3	0.16	1.0	0.2	0.2
Length scale	0.2	0.3	0.1	0.20	0.8	0.5	0.5
Factorization bias	0.5	0.5	0.8	0.67	0.8	1.1	1.1
Scan-to-scan	0.6	0.3	0.5	0.28	0.4	—	0.5
Bunch-to-bunch			0.1	0.06	0.4	—	—
VdM consistency			0.4	0.16	0.4	2.5	0.4
Calibration	**1.3**	**1.0**	**1.2**	**0.89**	**1.9**	**2.9**	**1.5**
OOT (non coll. rate)	0.3	0.4	0.2	—	<0.1	0.1	0.1
Stability	0.6	0.5	0.5	0.71	0.1	0.7	0.8
Linearity	0.5	0.3	0.5	0.59	<0.1	—	—
Integration	**1.0**	**0.7**	**0.8**	**0.92**	**0.1**	**0.7**	**0.8**
Total	**1.6**	**1.2**	**1.4**	**1.28**	**1.9**	**3.0**	**1.7**

Thank you!

Zero counting

- In certain detectors directly counting individual hits is not feasible either due to resolution or bandwidth / computational limitations, but it is very possible to determine the the lack of a hit (the opposite of any number of hits)
- The hits follow a **Poisson distribution:** $P(n=k) = e^{-\lambda}\lambda^{k}/k!$
- The probability of zero hits is $P(n=0) = e^{-\lambda}$
- Therefore the mean hit count is $\boldsymbol{\lambda = -\ln(P(n=0))}$
- Zeros are counted over several orbits before $-\ln(n_0/n)$ is calculated
- At high pile-up **zero-starvation** can become a problem, as the logarithm explodes near 0, amplifying the **noise** of the detector and introducing a **bias**
- Occupancy measurement via zero counting in PLT, BCM1F*, HFOC

What is σ_{vis}?

$L(\Delta x, \Delta y) = n_1 n_2 f_{LHC} \int_{\mathbb{R}^2} dxdy\, b_1\left(x - \frac{\Delta x}{2}, y - \frac{\Delta y}{2}\right) b_2\left(x + \frac{\Delta x}{2}, y + \frac{\Delta y}{2}\right)$, for b_1,b_2 bunch density functions

$$\int_{\mathbb{R}^2} d\Delta x d\Delta y\, L(\Delta x, \Delta y) = n_1 n_2 f_{LHC},$$

$$R = \sigma_{vis} L$$

$$\int_{\mathbb{R}^2} d\Delta x d\Delta y\, L(\Delta x, \Delta y) = \frac{1}{\sigma_{vis}} \int_{\mathbb{R}^2} d\Delta x d\Delta y R(\Delta x, \Delta y) = n_1 n_2 f_{LHC},$$

$$\sigma_{vis} = \frac{1}{n_1 n_2 f_{LHC}} \int_{\mathbb{R}^2} d\Delta x d\Delta y\, R(\Delta x, \Delta y).$$

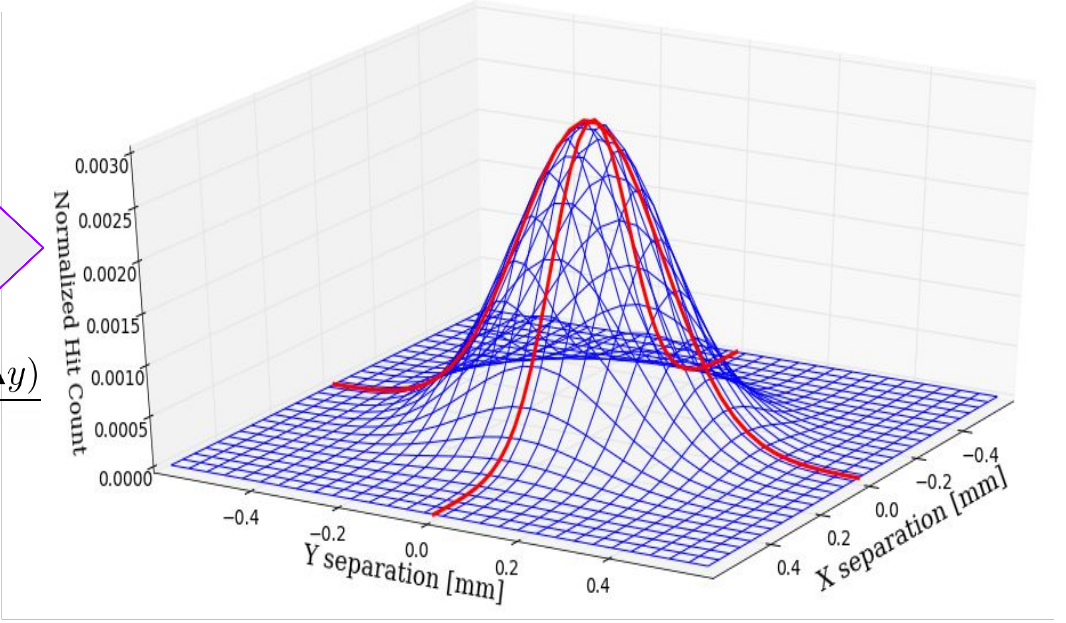
$$\exists f, g : R(\Delta x, 0) = f(\Delta x) g(0)$$

$$R(\Delta x, 0) = f(\Delta x) g(0),\ R(0, \Delta y) = f(0) g(\Delta y)$$

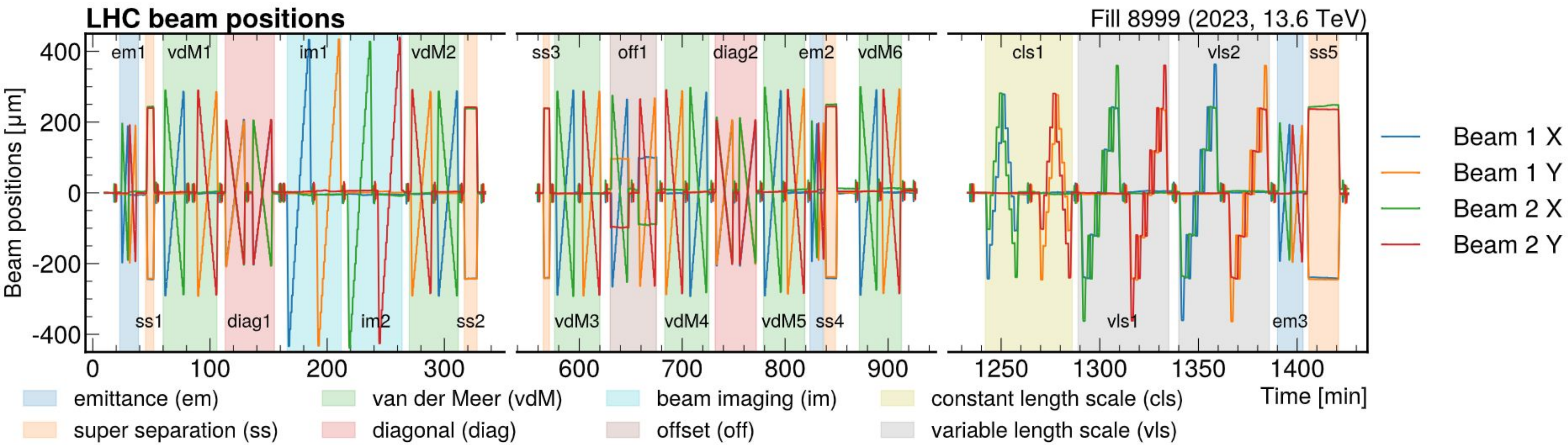
$$R(\Delta x, \Delta y) = \frac{R(\Delta x, 0)}{g(0)} \frac{R(0, \Delta y)}{f(0)} = \frac{R(\Delta x, 0) R(0, \Delta y)}{R(0,0)}$$

$$\int_{\mathbb{R}^2} R(\Delta x, \Delta y) = \frac{1}{R(0,0)} \int_{\mathbb{R}} R(\Delta x, 0) \int_{\mathbb{R}} R(0, \Delta y)$$

$$\int_{\mathbb{R}} R(\Delta x, 0) = \sqrt{2\pi} R(0,0) \Sigma_X$$



The van der Meer method



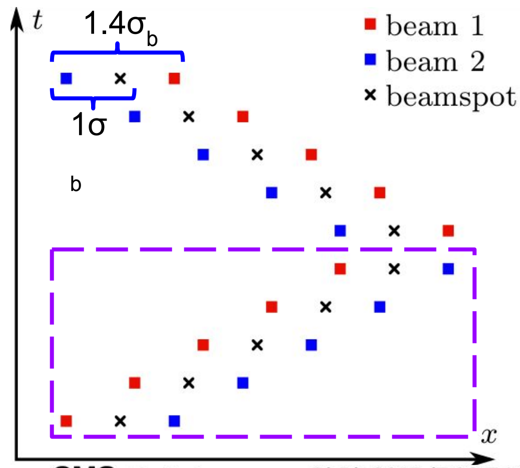
Length scale calibration (LSC)

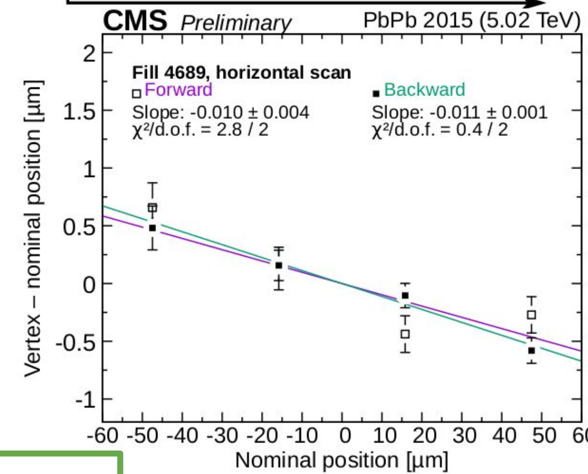
- ❖ Neither the nominal nor the BPM measured beam positions correspond to real values accurately
- ❖ The tracker position is considered as reference
- ❖ The relationship is linear
- ❖ Two special scans used for LSC $x_{true} = \alpha x_{nominal}$
  - ➢ **Constant separation LS scan**
    - ■ Average LS for B1&B2
  - ➢ Variable separation LS scan
    - ■ Separate LS for B1&B2
- ❖ Methods may be highly sensitive to orbit drift under certain OD distribution assumptions
  → **Two-step calibration method**

Tracker/Nominal ≈ Tracker/BPM * BPM/Nominal

Use the fact that this ratio is only marginally sensitive to orbit drift as both instruments see it

Exploit the BPM data available for the entire vdM fill to increase the precision:
- average out random orbit drifts
- allow correction for beam-beam interactions





Impact on σ_{vis} ~0.5-1.0%
Typical uncertainty: 0.2%

Emittance evolution

Issue:

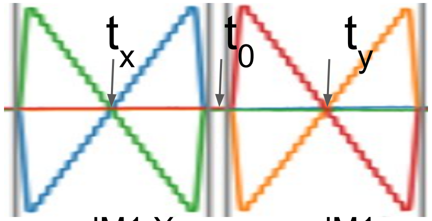
The vdM profile parameters are constantly changing in time

→ the parameters extracted in the X and Y scan are only approximately compatible

$$\sigma_{vis1} = 2\pi \frac{A_x(t_x) + A_y(t_y)}{2} \Sigma_x(t_x)\Sigma_y(t_y)$$

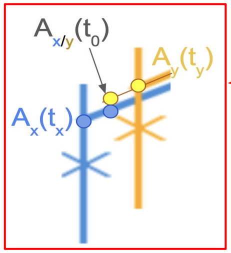
$$\sigma_{vis2} = 2\pi \frac{A_x(t_0) + A_y(t_0)}{2} \Sigma_x(t_0)\Sigma_y(t_0)$$

The impact is $\sigma_{vis2}/\sigma_{vis1}$ where the formulas both use the linear interpolation of the vdM parameters to capture the effect of the trend

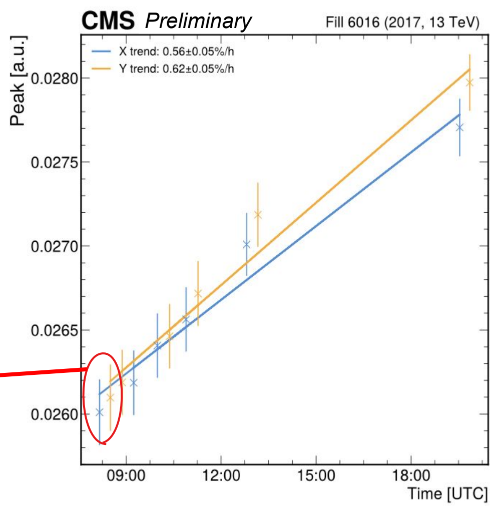


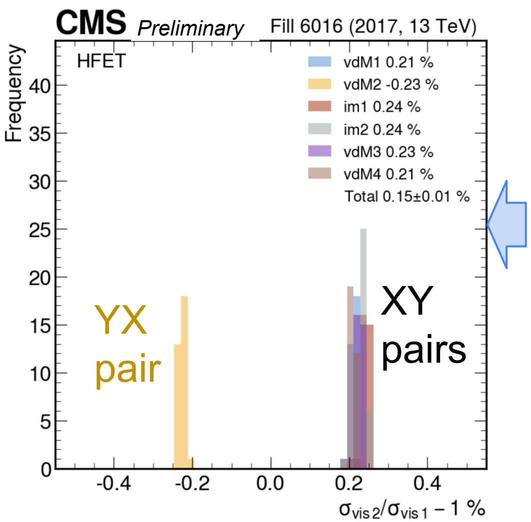
vdM1 X

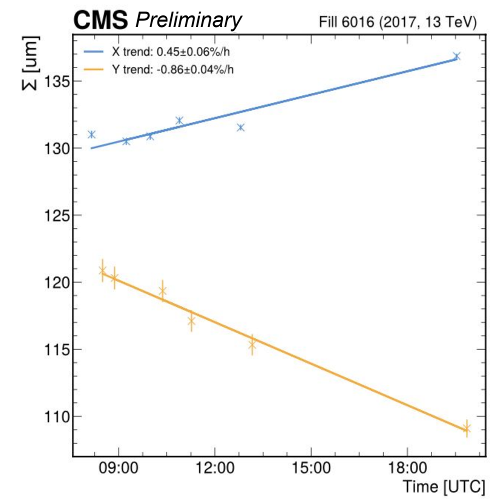
vdM1 Y



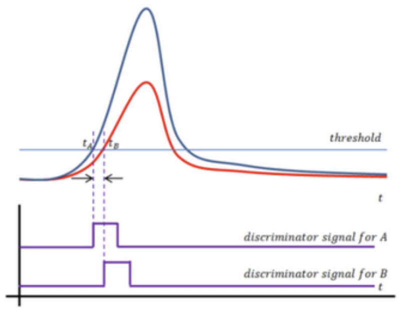
ZOOM



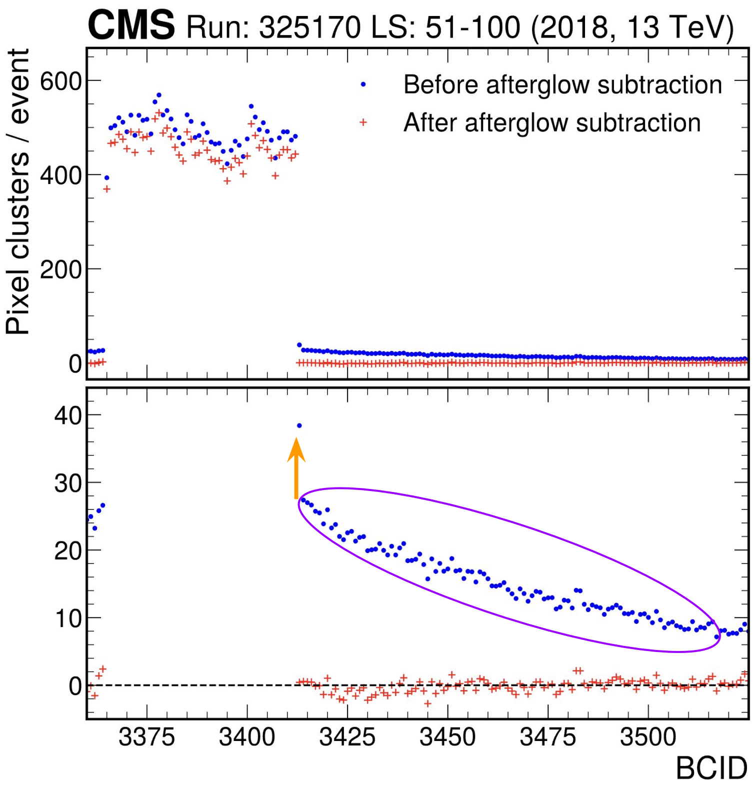




Rate corrections - Out-of-time



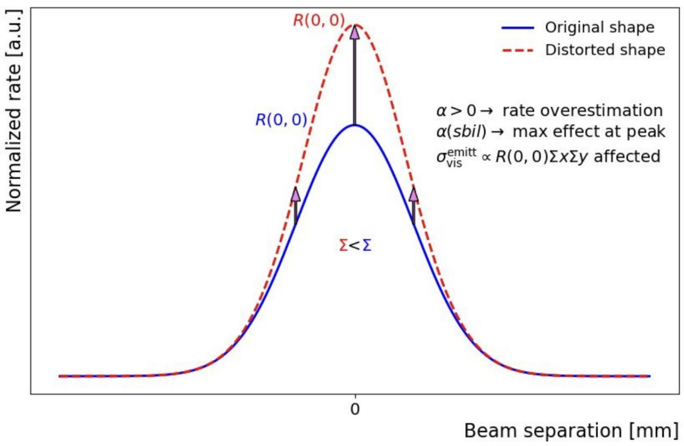
Time walk effect

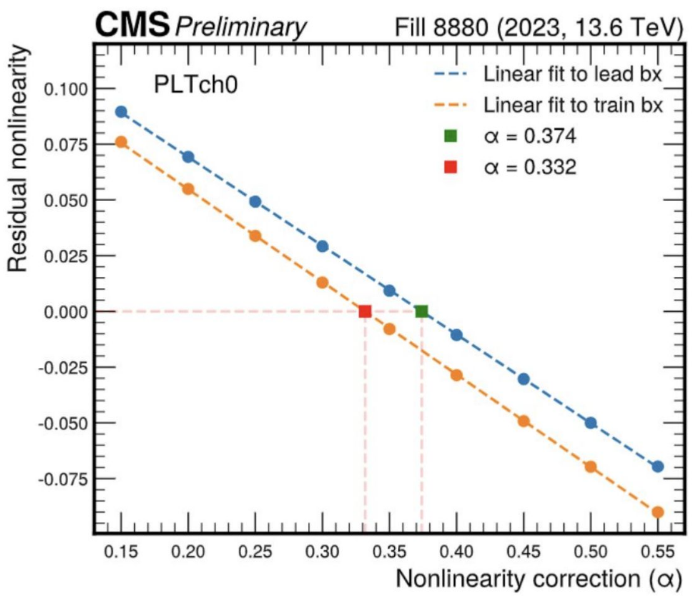


Out-of-time effects:

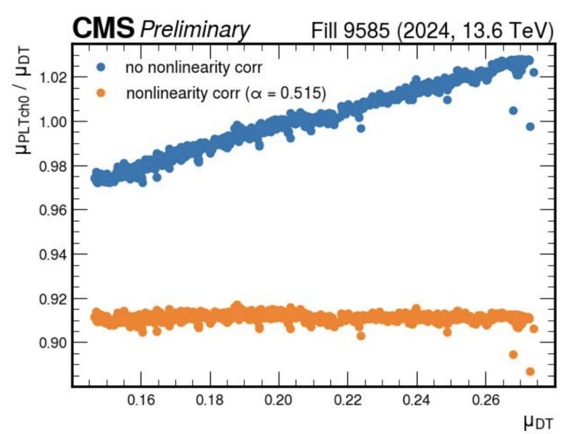
- Components:
  - Type I: Signal spillover, Time walk
  - Type II: Material activation
- Affected: PCC, HFET, HFOC, BCM1F
- Template fit of single-bunch response functions for the two components

Rate corrections - Nonlinear response





- VdM calibration performed **at 1/100 of the datataking pile-up**
- Model: $\mu_m = \mu_\ell (1 + \alpha \mu_\ell)$
- Mitigation - correction of detectors based on **intrinsic** quantities:
  - Restrictive module selection - based on noise levels and internal consistency (PCC)
  - **Efficiency as a function of peak luminosity** (SBIL) tracked via emittance-scans (per-module for PLT, BCM1F)
    - Efficiency can not be used straightforwardly, as the scan curve is not uniformly distorted by the non-linearity
      - Use the Major-factor - mildly profile dependent
      - **Iterative- / interpolation-based procedure**
- Highly linear detectors with a low occupancy are used as reference to evaluate residual effects (DT, RAMSES)
  - For unc. only!



Standard candles:

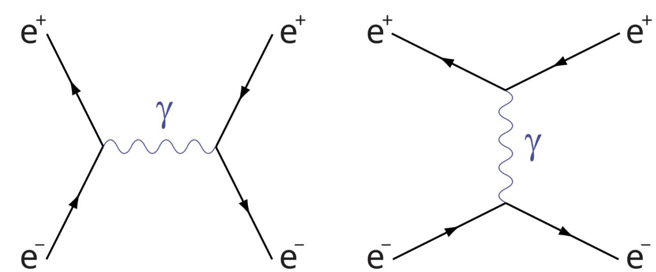
From cross-year consistency checks to the future of precision luminosity

Standard candle concept

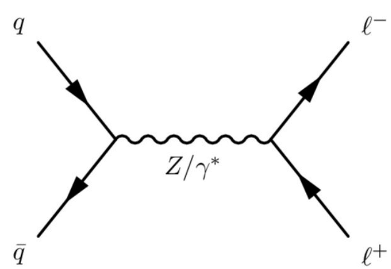
In e^+e^- colliders: forward elastic (Bhabha) scattering

$$\mathcal{L} = \frac{N^{ee}_{\mathrm{reco}}}{\sigma^{ee\to ee}_{\mathrm{fid}}\,\epsilon^{ee}}$$

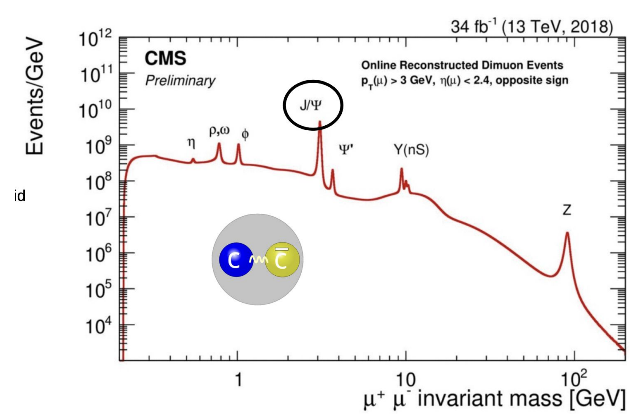
- Well known QED cross section
- Clean signature
- Only detector efficiency needs to be tracked
- LEP: 0.15% uncertainty



In pp collisions:

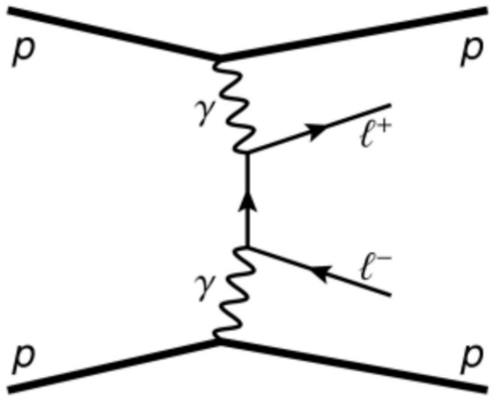


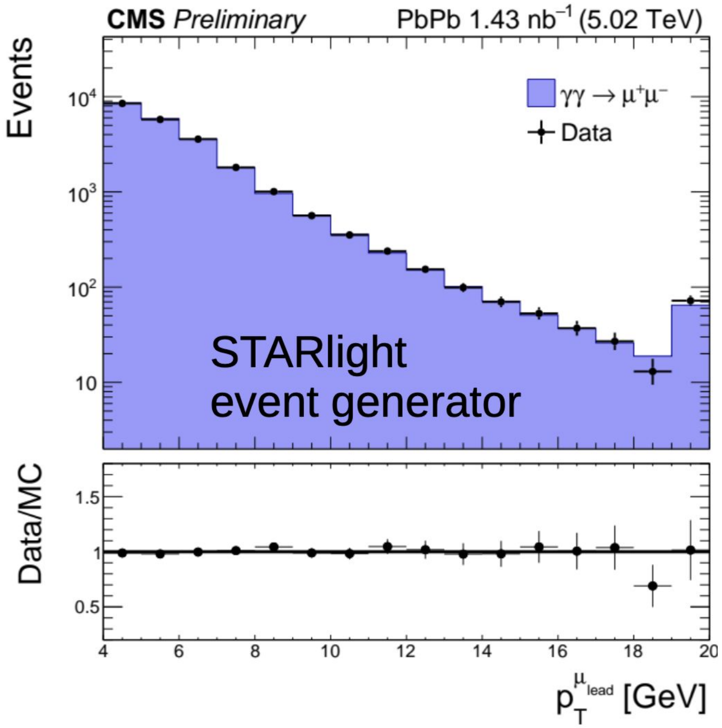
- $Z\to\mu\mu$ has
  - a clean signature
  - relatively large cross section (not enough for vdM)
  - a not-too-well-known fiducial cross section
- $J/\Psi\to\mu\mu$
  - Much higher rate → could be calibrated in vdM
  - Requires prescaled trigger in high PU
  - Low PU muons are difficult to handle
  - Allows for transfering to $Z\to\mu\mu$ as well



PbPb: Exclusive dimuon production

- $\gamma\gamma \rightarrow \mu\mu$ in ultraperipherial collisions has
  - a clean signature
  - well-known QED-based procedure BUT uncertainty from photon flux!
  - normalization to previous calibrations possible
- Publication in approval

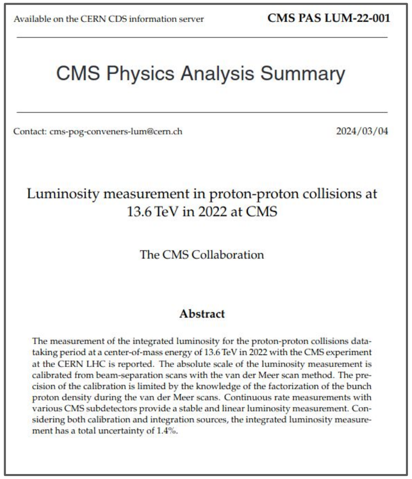




Publications

2015	1.6%	Published paper	
2016	1.2%		
2017	2.3%	prelim	Paper in preparation
2018	2.5%	prelim	
2022	1.4%	prelim	Paper in future
2023	1.28%	prelim	Paper in future

Title	Date of approval	Pub
pp@13 TeV (2015 + 2016)	12 Nov 2020 (public: Apr 2021)	Paper
Z counting (2017)	2 Mar 2023 (public: Sep 2023)	Paper
pp@13 TeV (2017 + 2018) + Run 2 combination	In preparation	Paper
pp@13.6 TeV (2022)	23 Feb 2024 (public: Mar 2024)	PAS
pp@13.6 TeV (2023)	This month	DPS note
Run 2 (2015+2018) PbPb	In preparation	Paper


 CMS PAS LUM-22-001

CMS Physics Analysis Summary

Contact: cms-pog-conveners-lum@cern.ch 2024/03/04

Luminosity measurement in proton-proton collisions at 13.6 TeV in 2022 at CMS

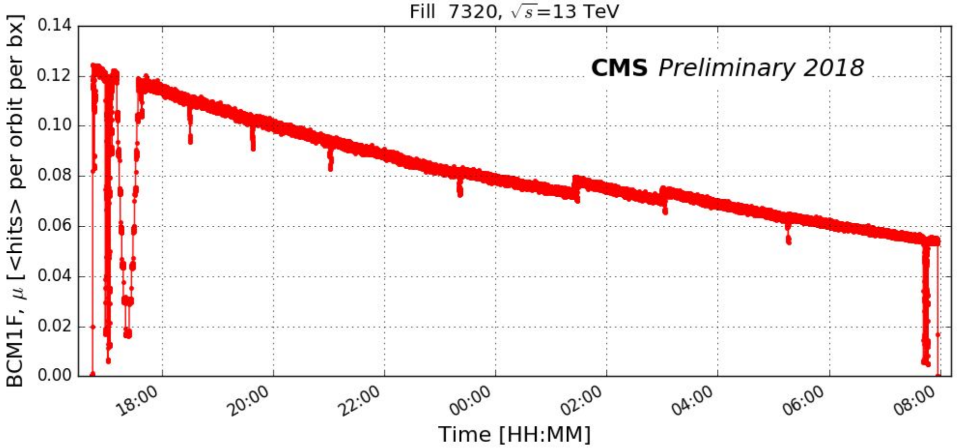
The CMS Collaboration

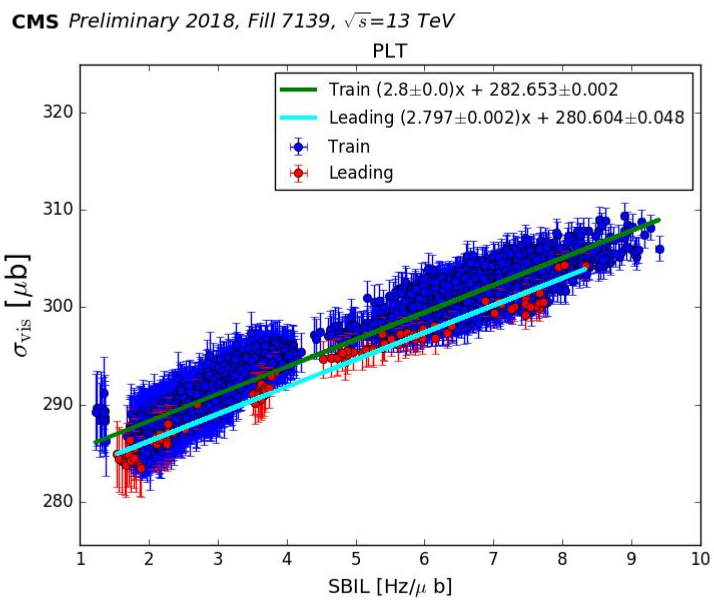
Abstract

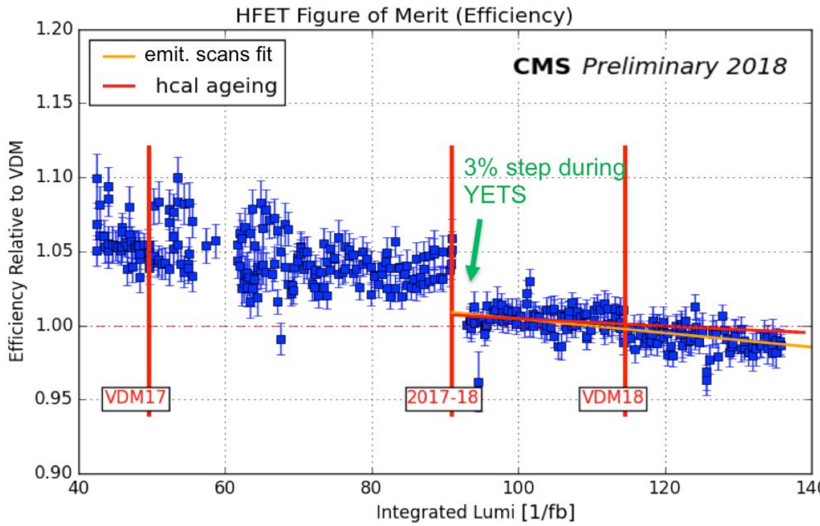
The measurement of the integrated luminosity for the proton-proton collisions data-taking period at a center-of-mass energy of 13.6 TeV in 2022 with the CMS experiment at the CERN LHC is reported. The absolute scale of the luminosity measurement is calibrated from beam-separation scans with the van der Meer scan method. The precision of the calibration is limited by the knowledge of the factorization of the bunch proton density during the van der Meer scans. Continuous rate measurements with various CMS subdetectors provide a stable and linear luminosity measurement. Considering both calibration and integration sources, the integrated luminosity measurement has a total uncertainty of 1.4%.

Emittance scans

- Luminometers are intrinsically corrected for all linearity affecting effects
- Emittance scans are treated like mini vdM calibrations
- Linearity and efficiency corrections

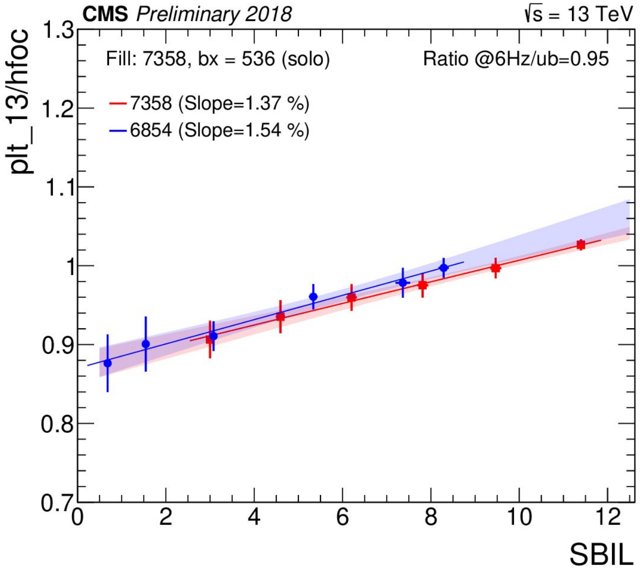


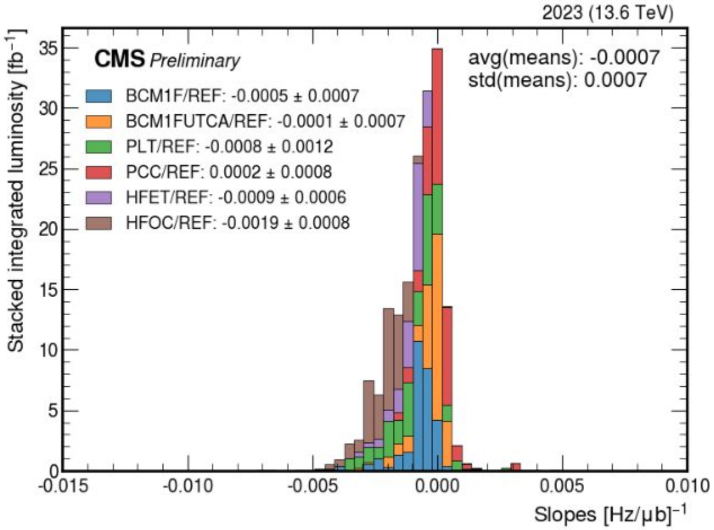


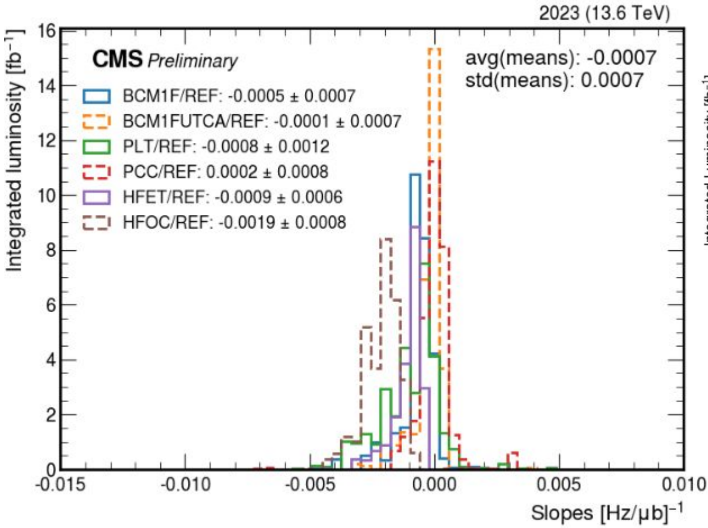


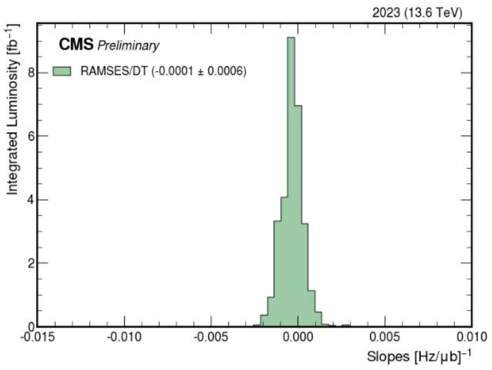
Linearity

- ❖ Luminometers are intrinsically corrected for all linearity affecting effects in situ
  - ➢ Data driven out-of-time corrections
  - ➢ Linearity from emittance scans
- ❖ Residual relative non-linearity is studied with respect to DT and RAMSES
  - ➢ Very low occupancy, highly linear detectors



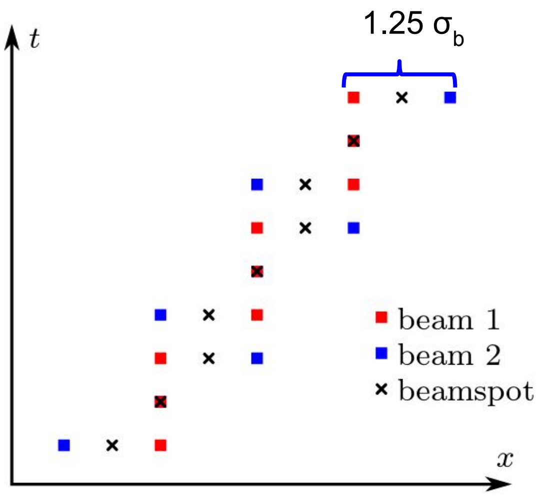


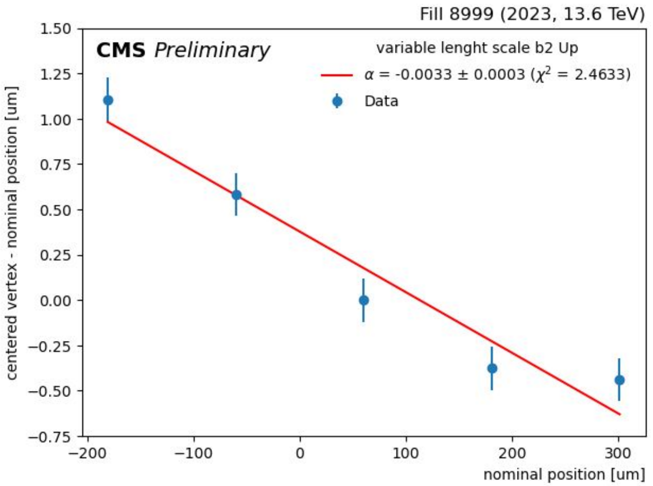




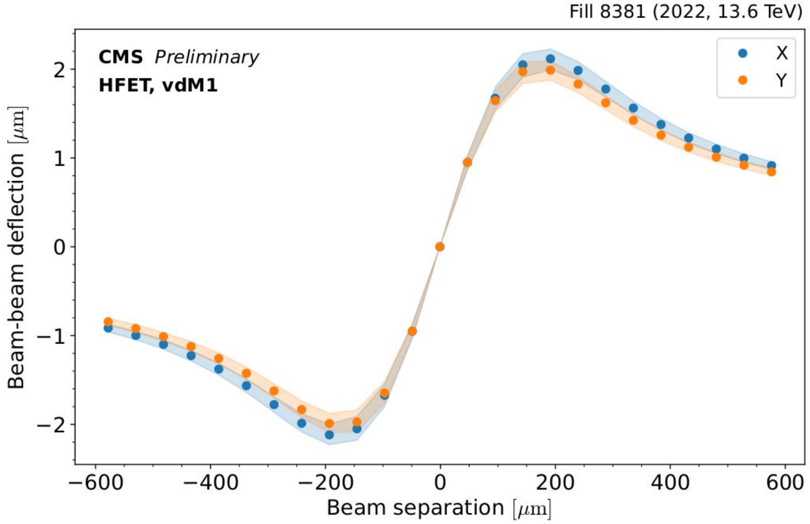
Length scale calibration (LSC)

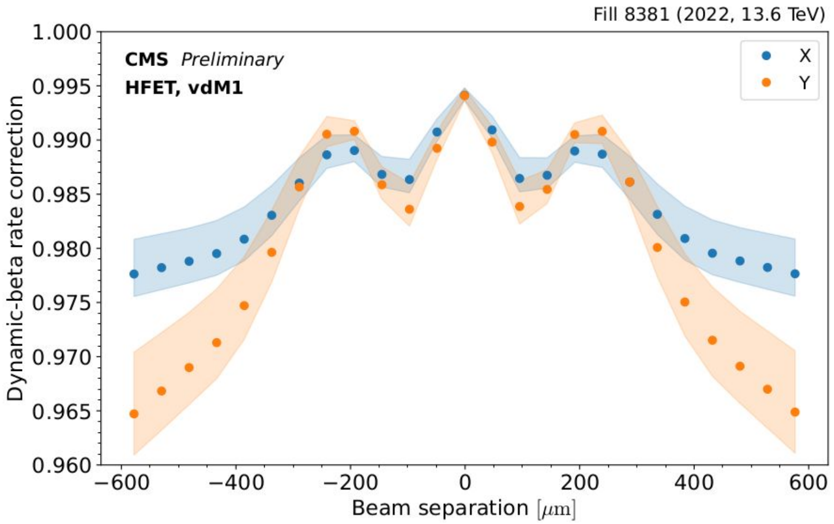
- Neither the nominal nor the BPM measured beam positions correspond to real values accurately.
- The tracker position is considered as reference
- The relationship is linear $x_{true} = \alpha x_{nominal}$
- Two special scans used for LSC
  - Constant separation LS scan
    - Average LS for B1&B2
  - **Variable separation LS scan**
    - Separate LS for B1&B2



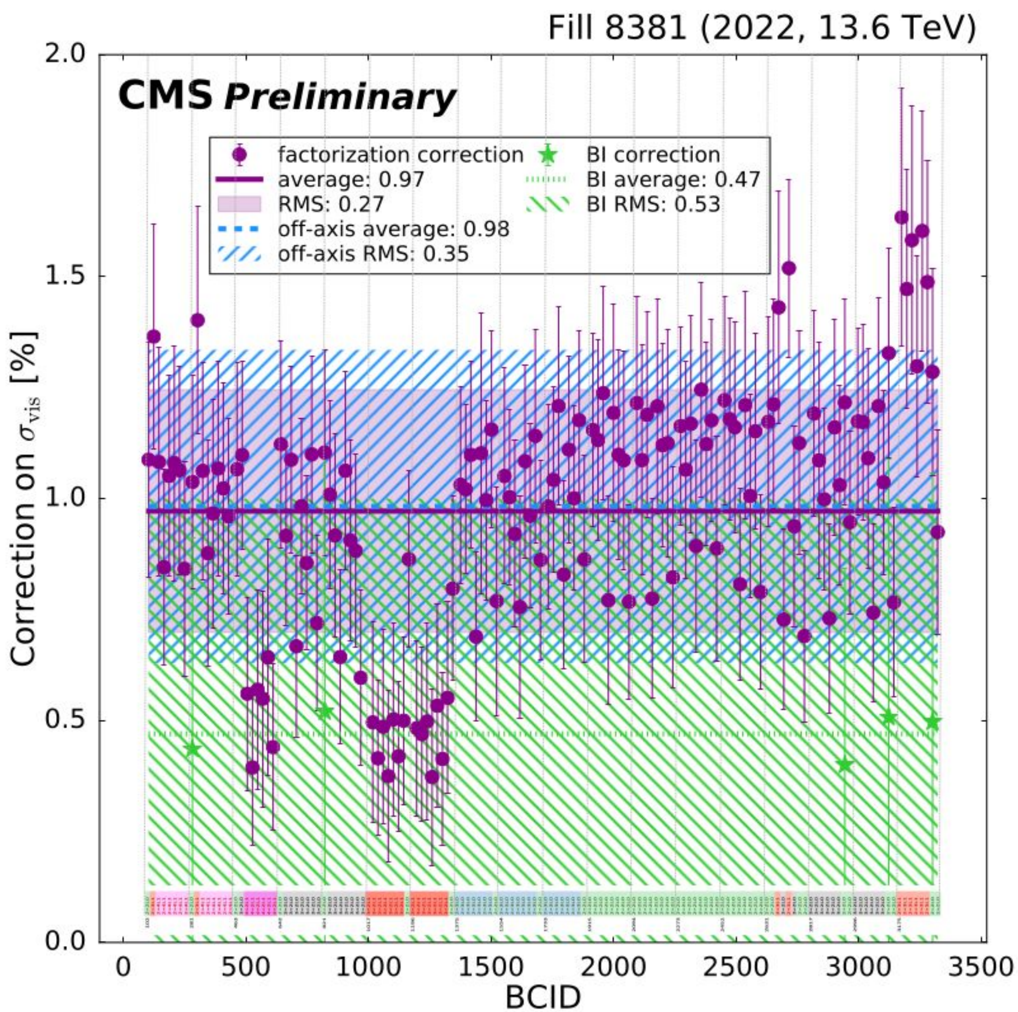


Beam-Beam effects





Non-factorisation BCID structure



Non-factorisation

❖ **Imaging scan analysis**

- Fits the 2D bunch density function
- Using a set of 4 special scans
- For few BICDs with high rate VTX data