Precision luminosity determination in CMS

Peter Major on behalf of the CMS Collaboration

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Introduction

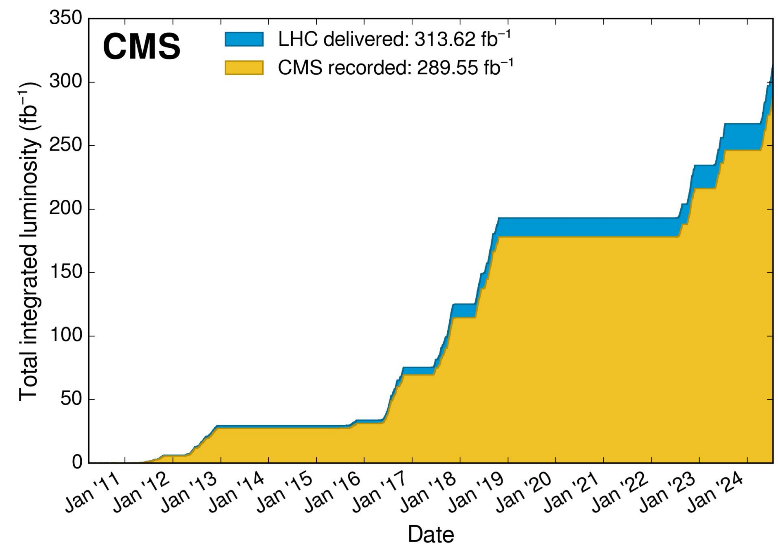
Luminosity

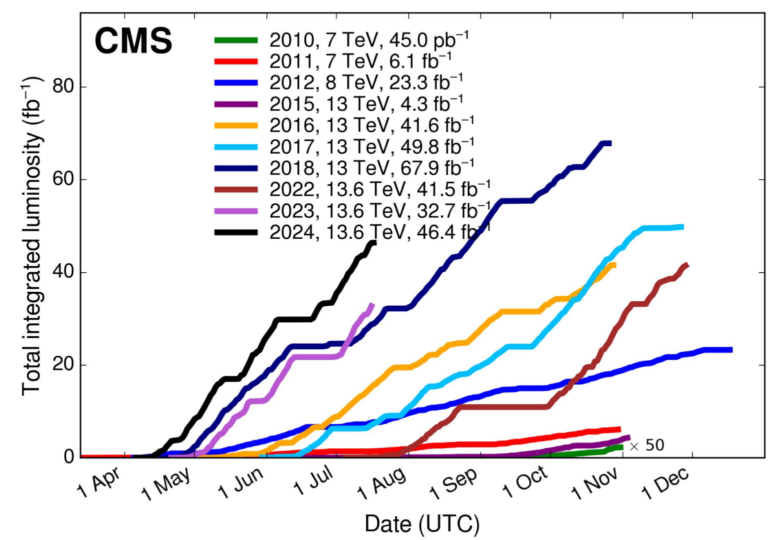
- connects theory and experiment

$$\langle N_{total} \rangle = \sigma_{process} L_{int}$$

- is amongst the leading sources of experimental uncertainties in SM precision measurements

It is measured using benchmark physics processes like Bhabha-scattering in lepton colliders, but hadron colliders pose many challenges due to the non-trivial PDFs





Detectors

Multiple independent systems (*luminometers*) are utilized for best accuracy

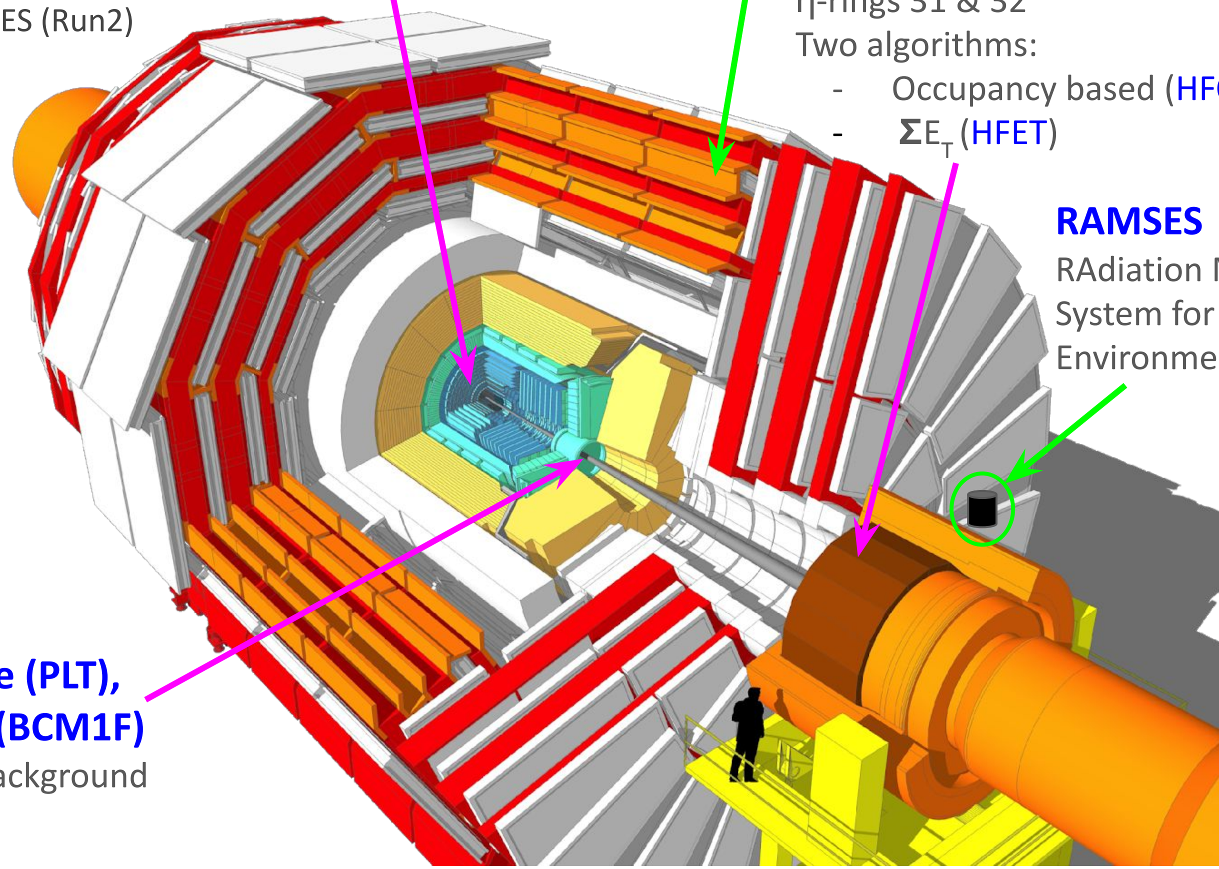
	Independently calibrated	Cross-calibrated
Online	BCM1F*, HF*, PLT	DT, RAMSES (Run3)
Offline	PCC	RAMSES (Run2)

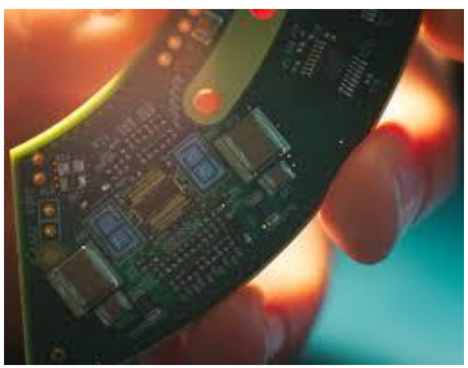
Pixel Cluster Counting (PCC)
On all except the first barrel layer
+ veto list of modules

Drift Tubes (DT)
L1 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

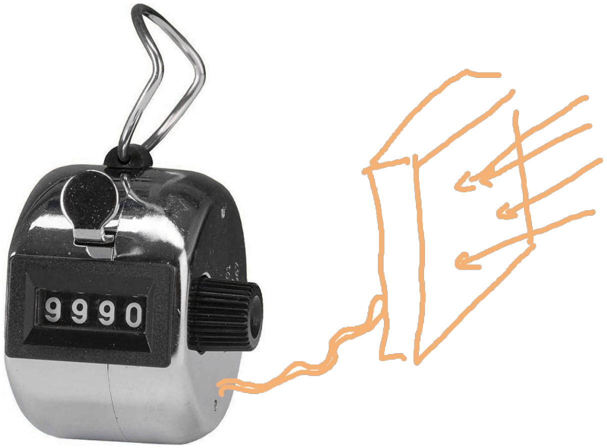
An overview of the lumi measurement

- The hit rate (or deposited energy) is directly proportional to the instantaneous luminosity. The coefficient is the calibration constant of the detector: σ_{vis}

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

- Deposited transverse energy for HFET
- Actual counting for PCC, DT, RAMSES
- Occupancy measurement via zero counting (PLT, BCM1F*, HFOC)

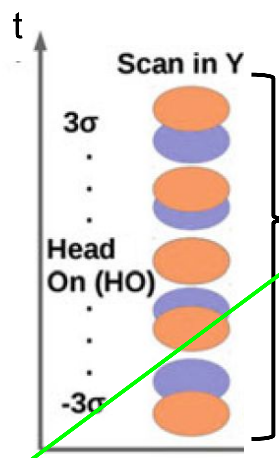
$$\mu = -ln(P_0)$$

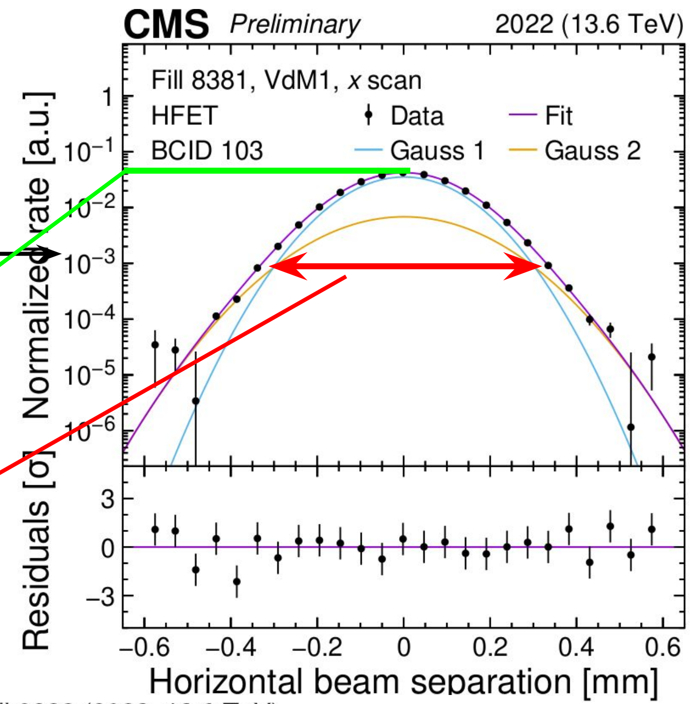


- Potential effects:
  - Spillover of signal (Type I Afterglow)
  - Background due to activation (Type II Afterglow)
  - Stability of the detectors (e.g. radiation damage)
  - Linearity of measurement
  - Zero starvation

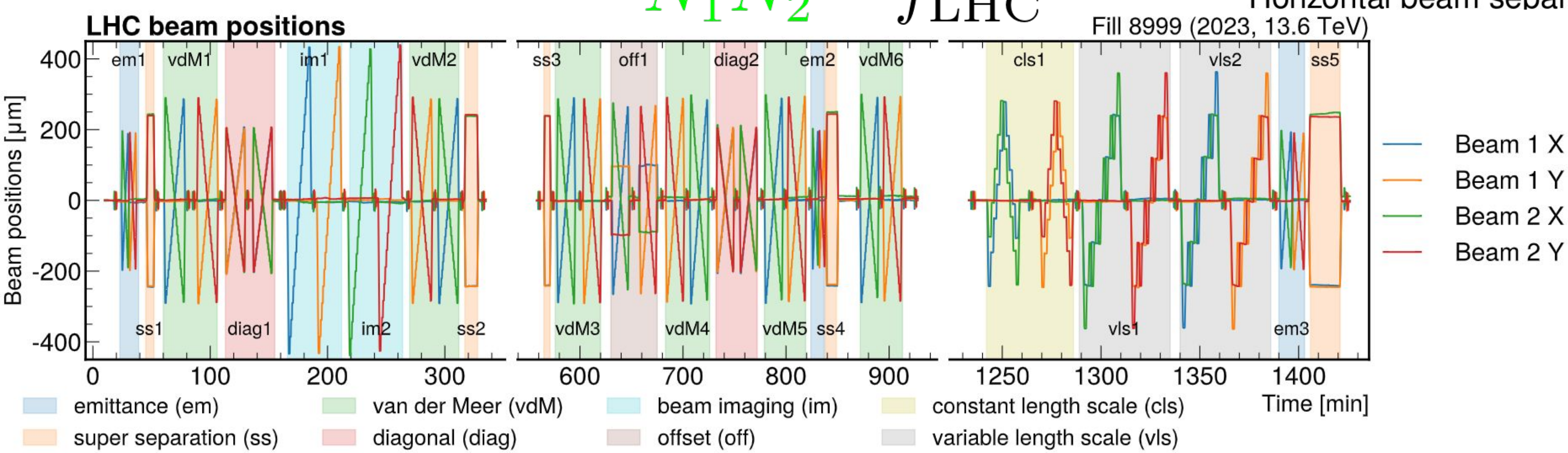
The van der Meer method

- Perform an X and a Y beam separation scan
- 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)



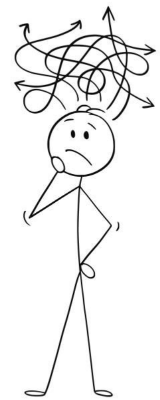


$$\sigma_{\mathrm{vis}} = \frac{R_0}{N_1 N_2} \frac{2\pi \Sigma_X \Sigma_Y}{f_{\mathrm{LHC}}}$$

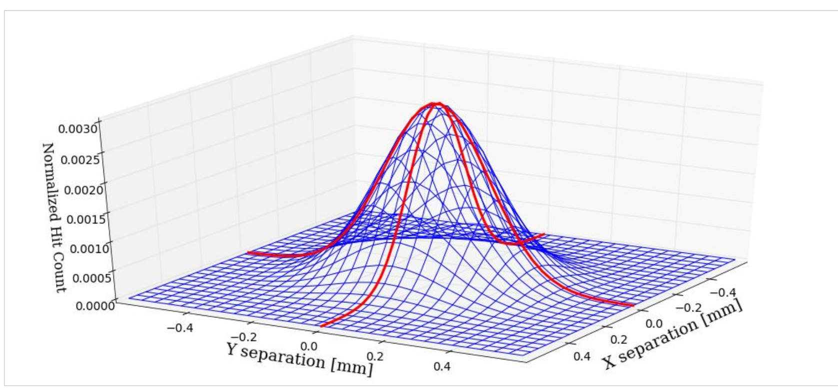


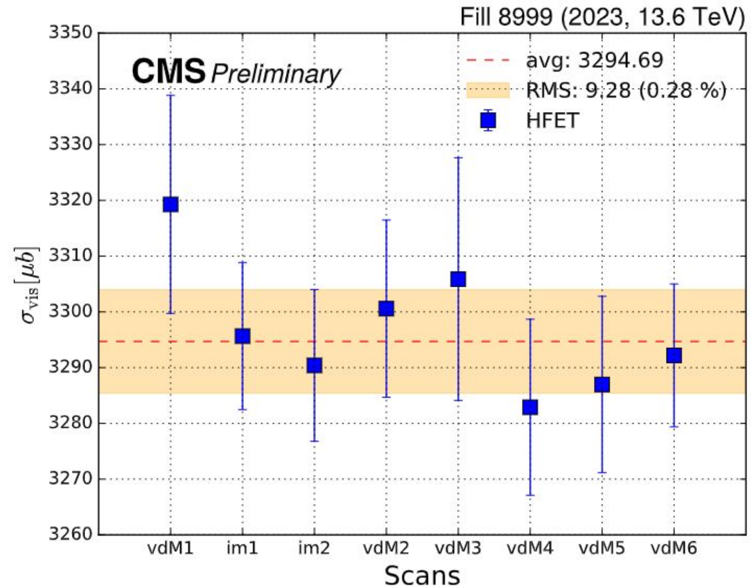
The van der Meer method

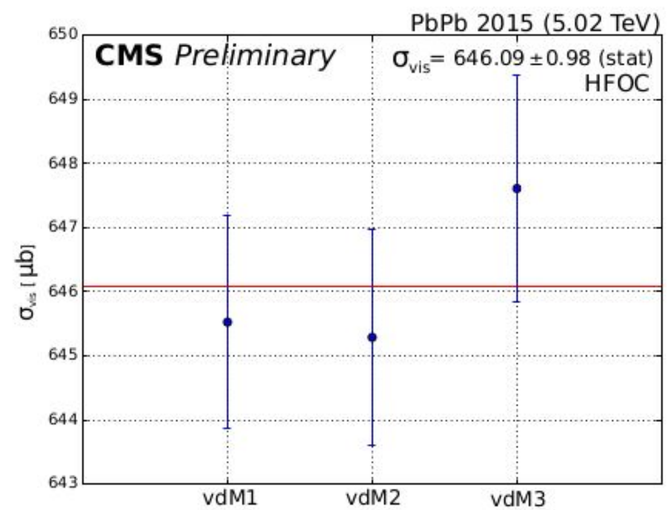
Difficulties:



- ❖ Background of detectors
- ❖ Accuracy of bunch proton count measurement
- ❖ Accuracy of beam position
  - ➢ Orbit drifts
  - ➢ Beam-beam deflection
  - ➢ Length scale
- ❖ Factorizibility of beam overlap shape (a leading source of uncertainty)
- ❖ Bunch shape distortion due to beam-beam EM forces

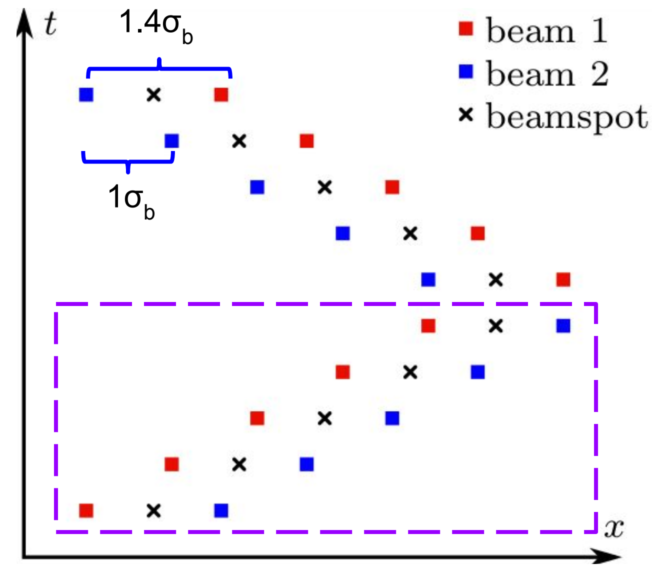


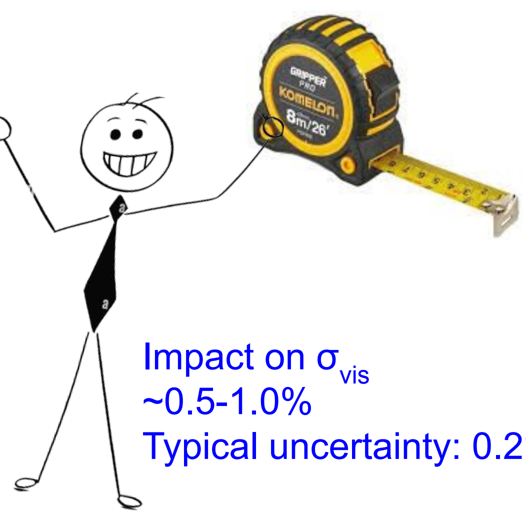




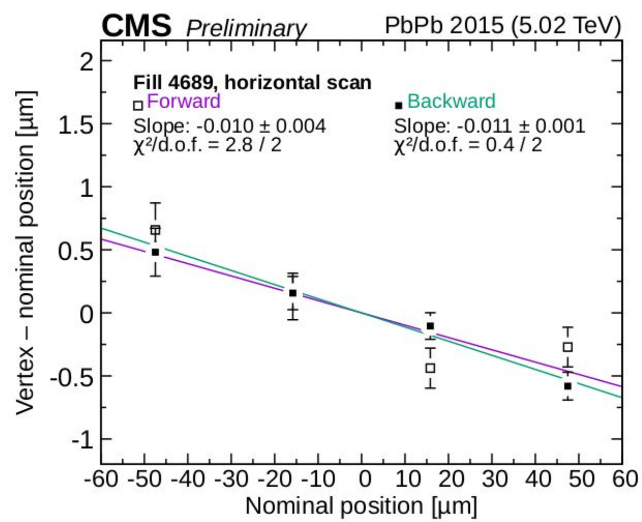
Length scale calibration (LSC)

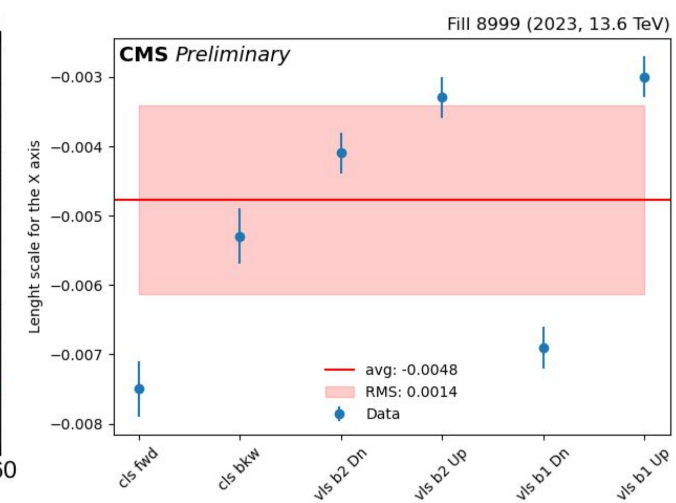
- Neither the nominal nor the BPM measured beam positions correspond to real values accurately
- The tracker position is considered as reference
- The relationship is linear $x_{true} = \alpha x_{nominal}$
- Two special scans used for LSC
  - **Constant separation LS scan**
    - Average LS for B1&B2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





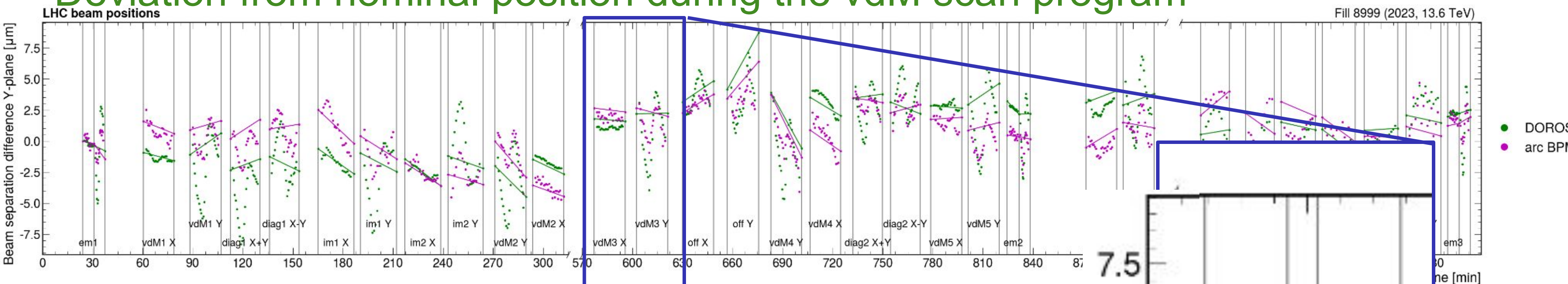
Impact on σ_{vis} ~0.5-1.0%
Typical uncertainty: 0.2%

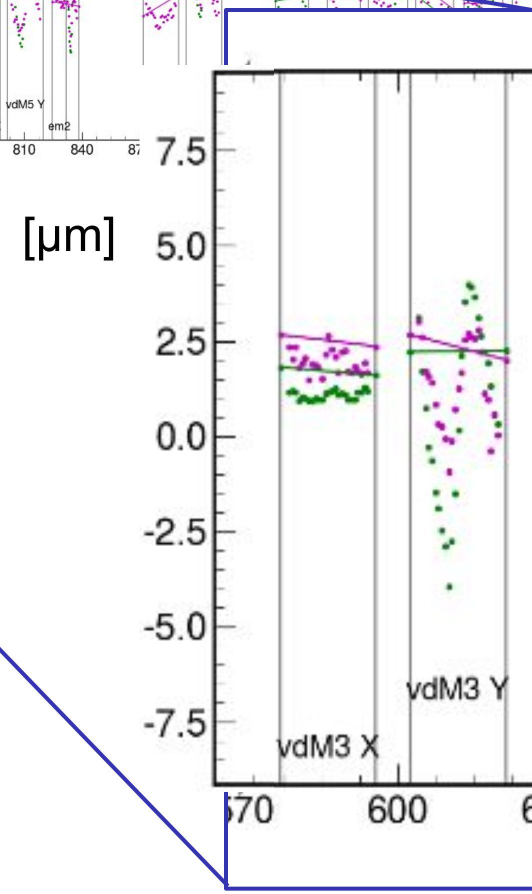




Beam position systematics

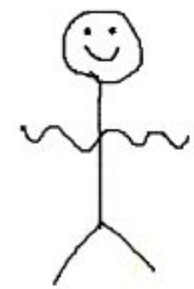
Deviation from nominal position during the vdM scan program





Measured using

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



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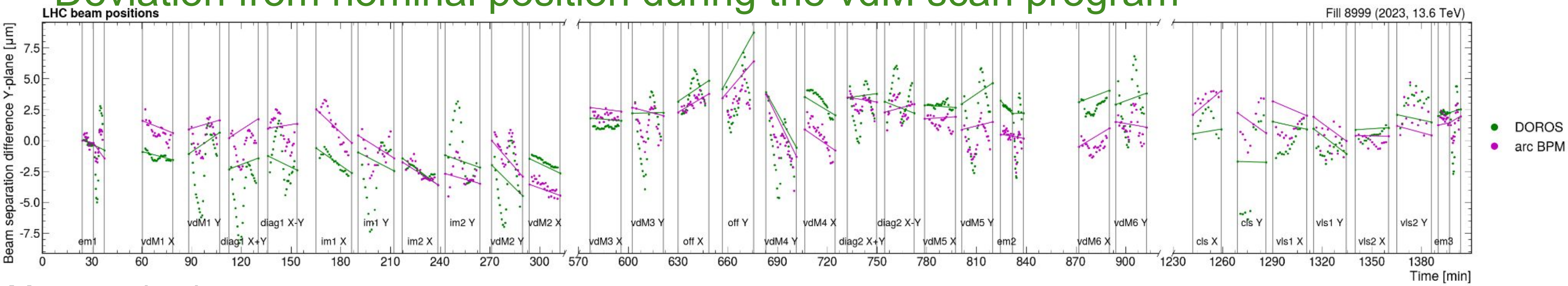


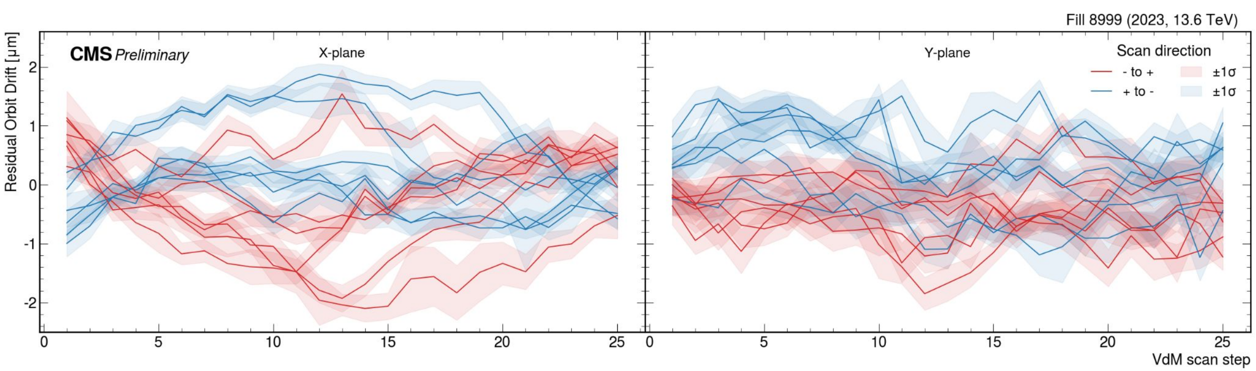
Measured using

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

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

Contributes:

- ❖ Orbit drift
- ❖ Beam-beam deflection (partial effect from Bassetti-Erskine formula)
- ❖ Residual effects ← clear difference based on scan direction:

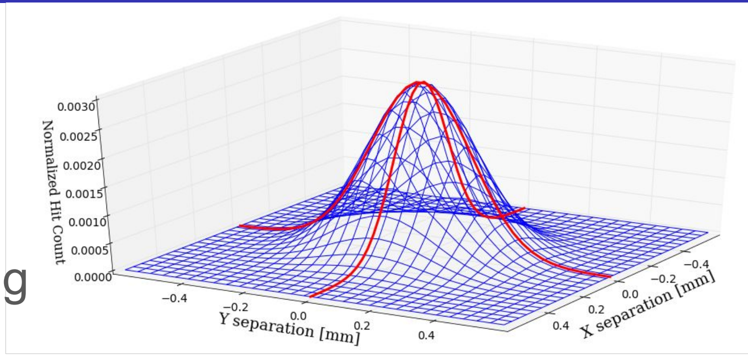


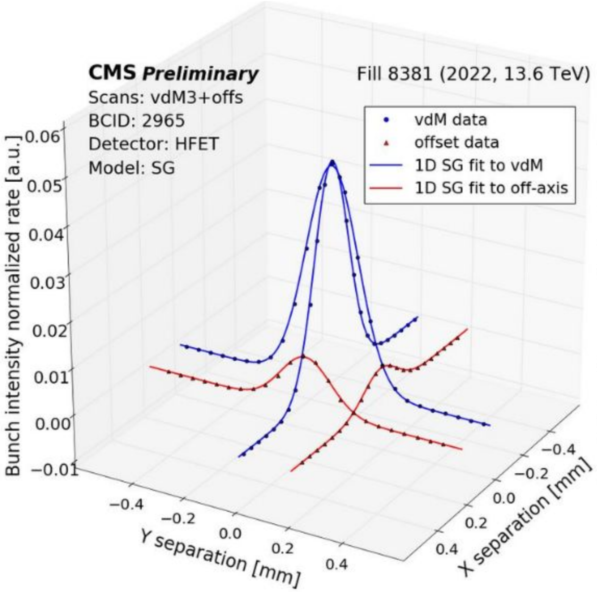
Non-factorisation

Multiple methods used:

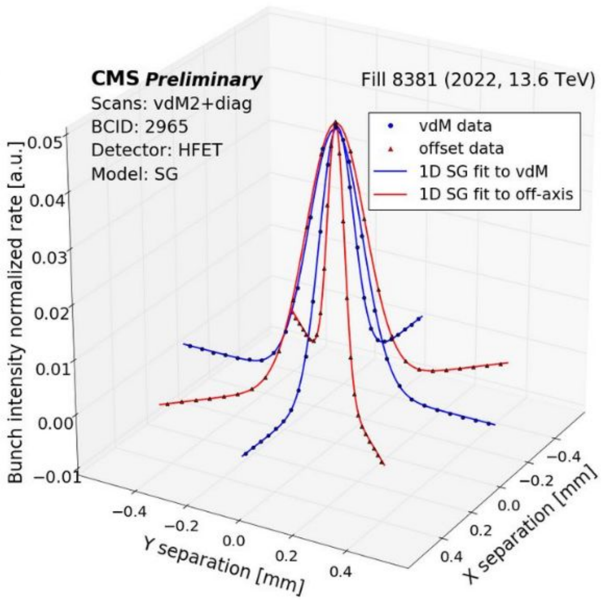
❖ **2D scans**
- Fits the bunch overlap shape directly
- Using complementary scans for off-axis sampling
- All BCIDs are used

❖ Luminous region analysis



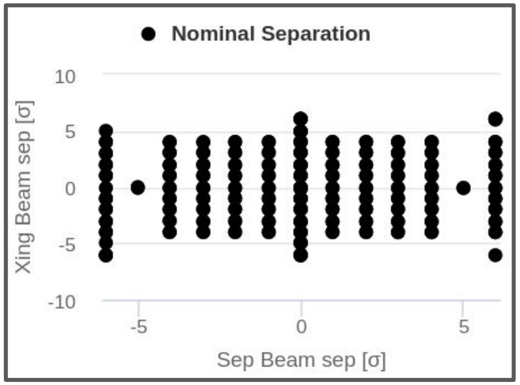


offset scan



diagonal scan

New in 2024 vdM



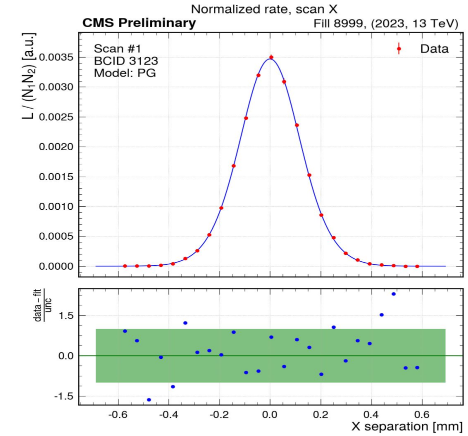
grid scan

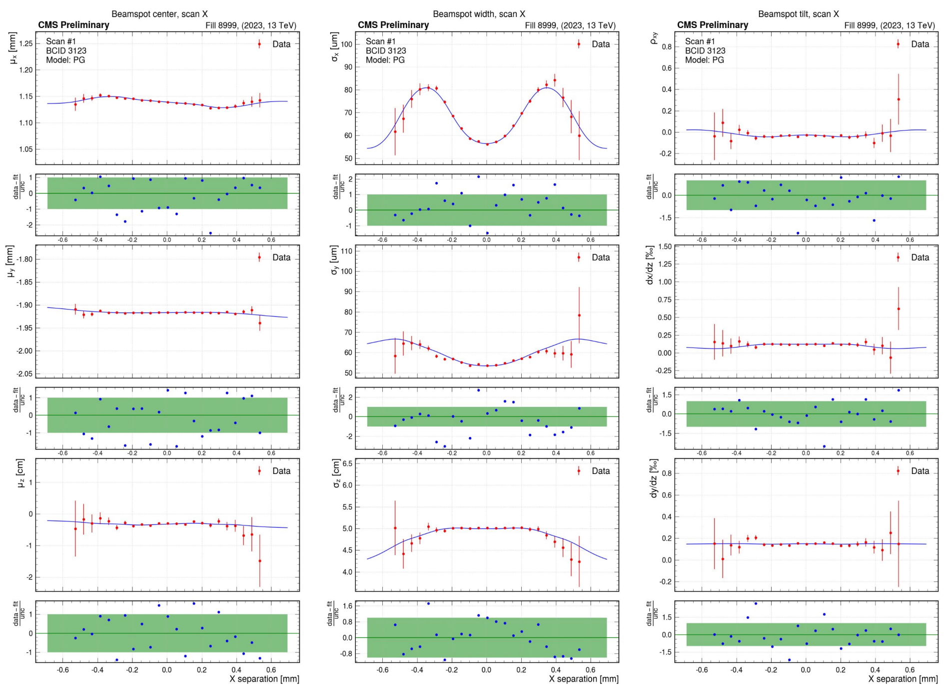
Non-factorisation

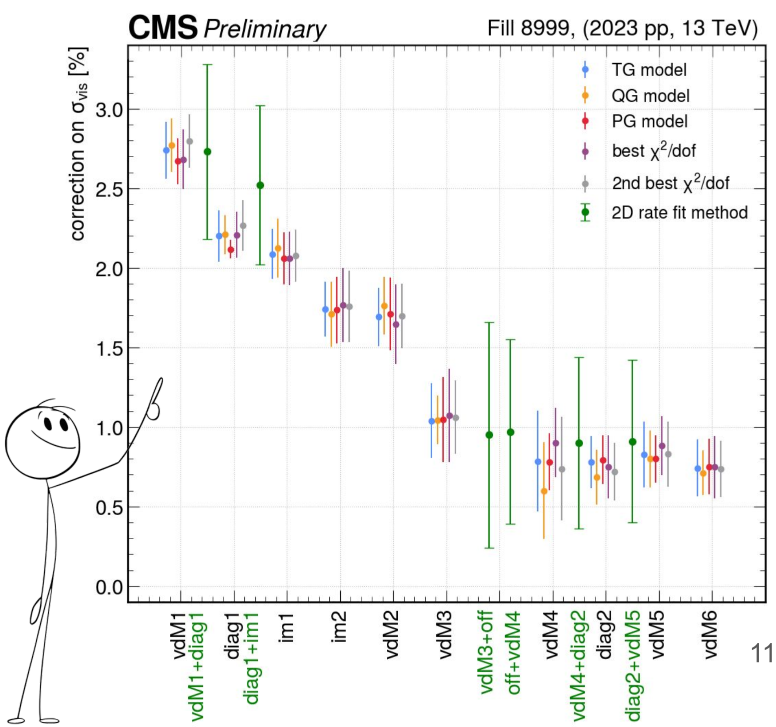
Multiple methods used:

- 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

Non-factorization uncertainty:
2022 (prelim): 0.8%
2023 (prelim): 0.7%

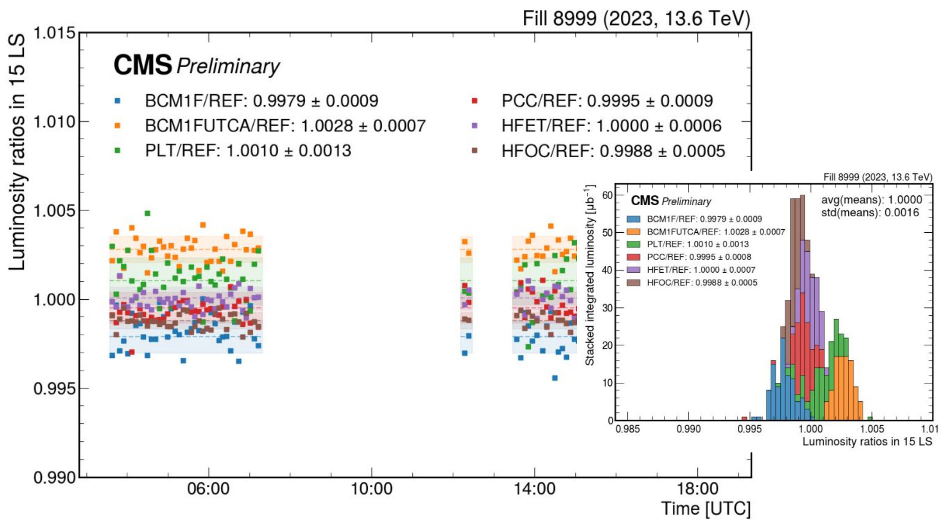


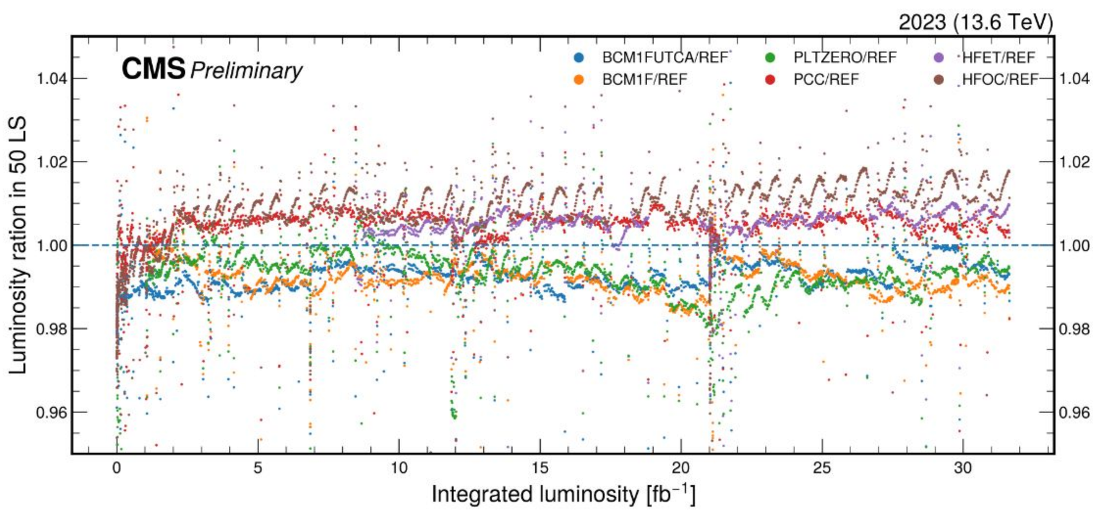


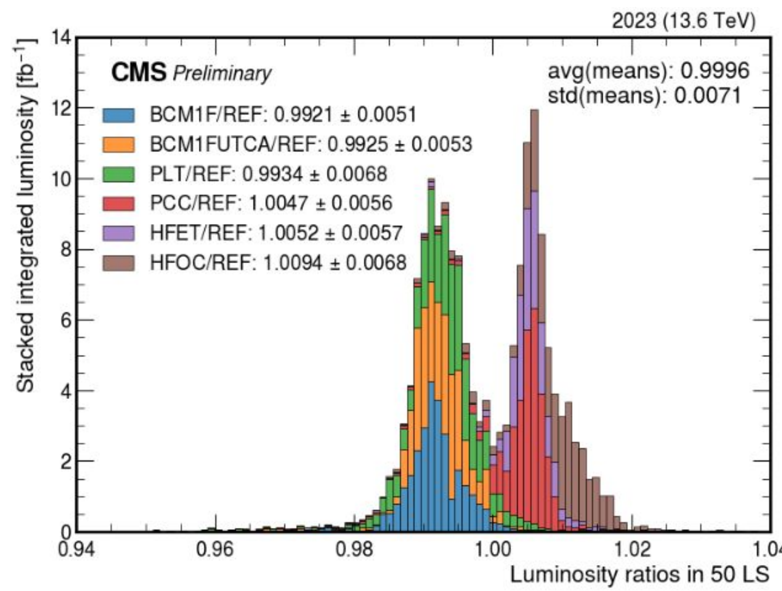


Consistency, stability

- Closure of detectors checked in the vdM fill
- Efficiency of applicable detectors is tracked and corrected for independently using emittance scans
- Spread of detectors is tracked throughout the whole year
  - Uncertainty derived from the RMS the mean of all histograms



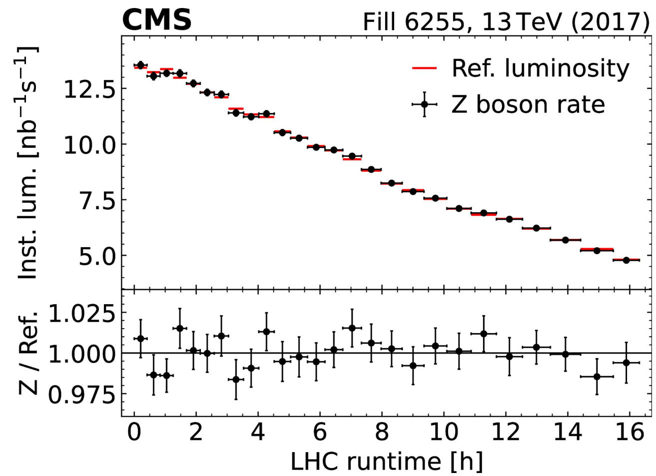


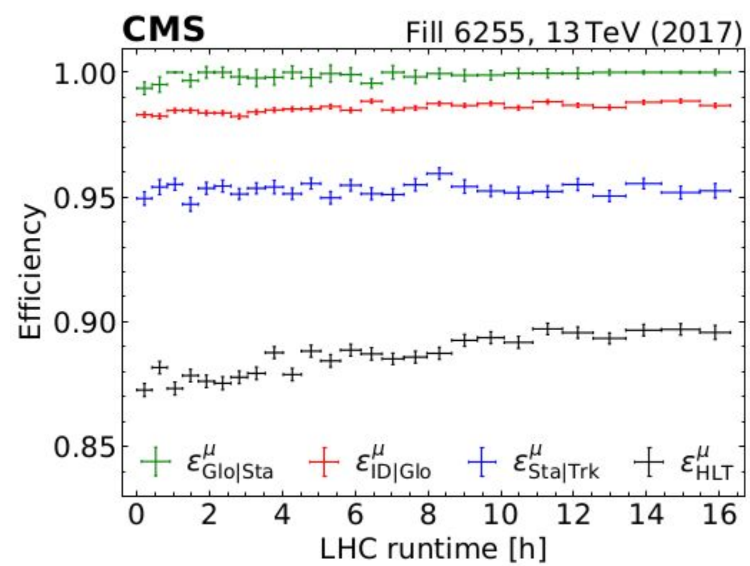


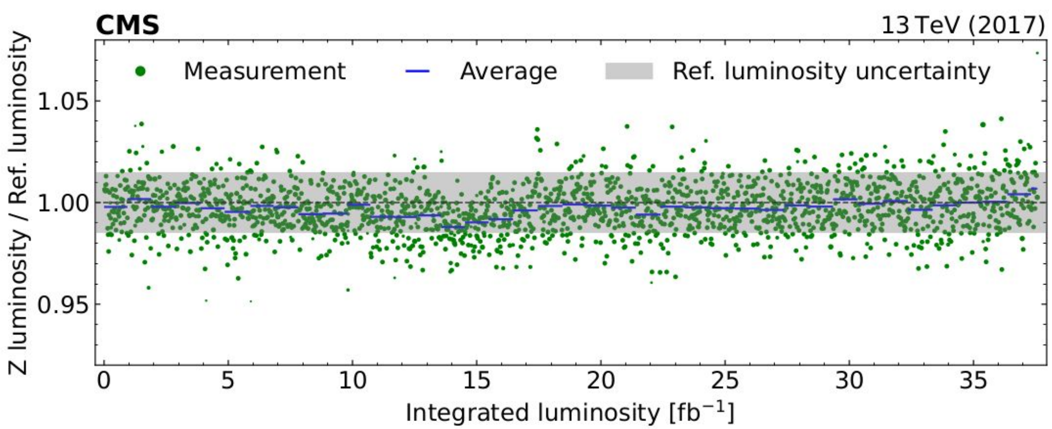
Z counting

- Z→μμ has
  - ➢ a clean signature
  - ➢ large cross section
- Trigger and selection efficiencies are measured in situ every 20/pb
- Main goal: anchoring the measurement at low PU
  → extrapolate to high PU

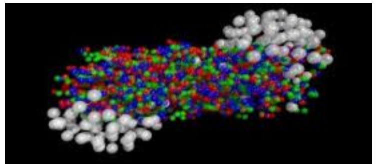
$$\mathcal{L}_{\text{highPU}} = \frac{N^{Z}_{\text{highPU}}}{N^{Z}_{\text{lowPU}}} \mathcal{L}_{\text{lowPU}}.$$







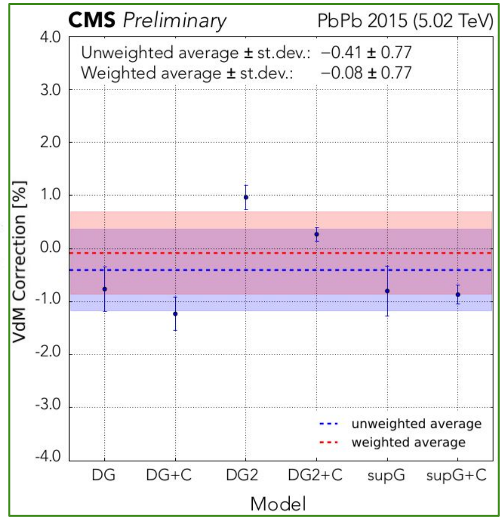
Run2 PbPb results

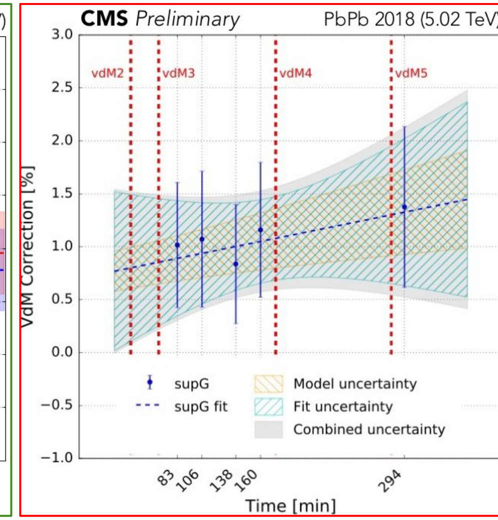


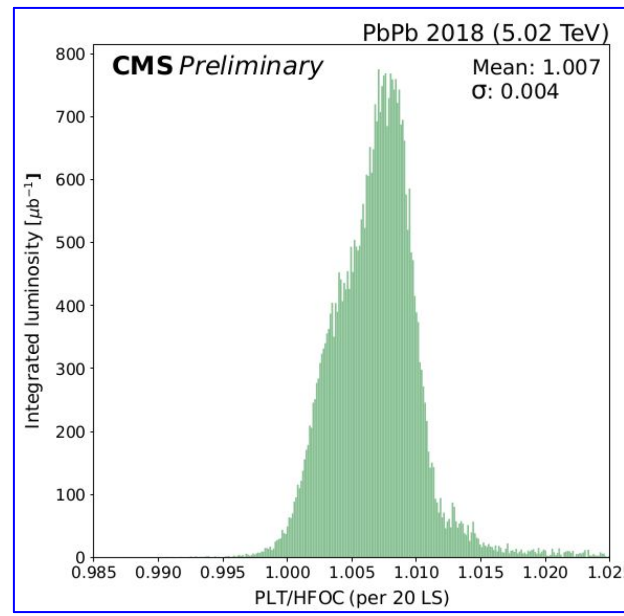
New for ICHEP

Source	2015 [%]	2018 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.3	0.5	Yes
Beam current calibration	0.2	0.2	Yes
Noncolliding bunches			
Noncollision rate	0.5	0.2	No
Beam position monitoring			
Random orbit drift	0.5	0.1	No
Systematic orbit drift	0.2	0.2	Yes
Beam overlap description			
Length scale calibration	0.5	0.5	Yes
Beam-beam effects	0.2	0.3	Yes
Transverse factorizability	1.1	1.1	No
Result consistency			
Cross-detector consistency	2.5	0.4	No
Scan-to-scan variation	—	0.5	No
Statistical uncertainty	0.2	0.1	No
Integration uncertainty			
Detector performance			
Cross-detector stability	0.7	0.8	No
Noncolliding bunches			
Noncollision rate	0.1	0.1	Yes
Total normalization uncertainty	2.9	1.5	
Total integration uncertainty	0.7	0.8	
Total uncertainty	3.0	1.7	

year	Recorded luminosity [nb^{-1}]	Uncertainty correlated	Uncertainty uncorrelated	Total uncertainty [%]
2015	0.43 ± 0.01	0.7%	2.9%	3
2018	1.7 ± 0.1	0.8%	1.5%	1.7
Combined Run 2	2.132	$0.003\,nb^{-1}$ (2015) $0.014\,nb^{-1}$ (2018)	$0.028\ nb^{-1}$	1.5







Proton-proton luminosity calibration results

pp 13.6 TeV

New for ICHEP

Source	Uncertainty (%)
Calibration	
Beam current	0.20
Ghosts & satellites	0.10
Orbit drift	0.02
Residual beam positions	0.16
Beam-beam effects	0.34
Length scale	0.20
Factorization bias	0.67
Scan-to-scan variation	0.28
Bunch-to-bunch variation	0.06
Cross-detector consistency	0.16
Integration	
Cross-detector stability	0.71
Cross-detector linearity	0.59
Calibration	0.89
Integration	0.92
Total	1.28

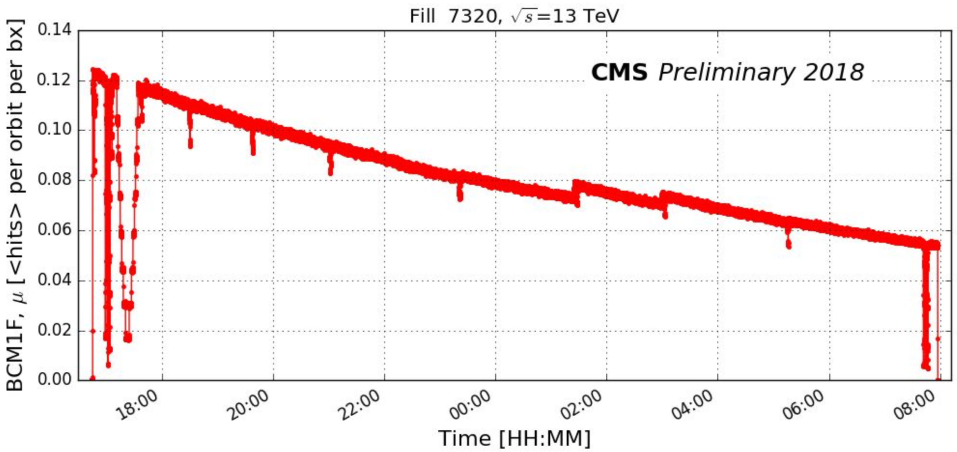
Similar uncertainties in int. & cal.

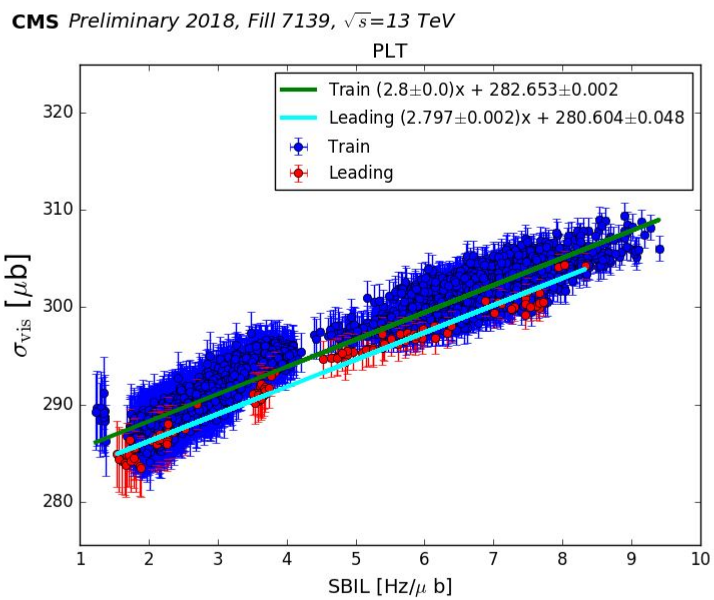
2015	1.6%	Published paper	
2016	1.2%		
2017	2.3%	prelim	Paper in preparation
2018	2.5%	prelim	
2022	1.4%	prelim	Paper in future
2023	1.28%	prelim	Paper in future

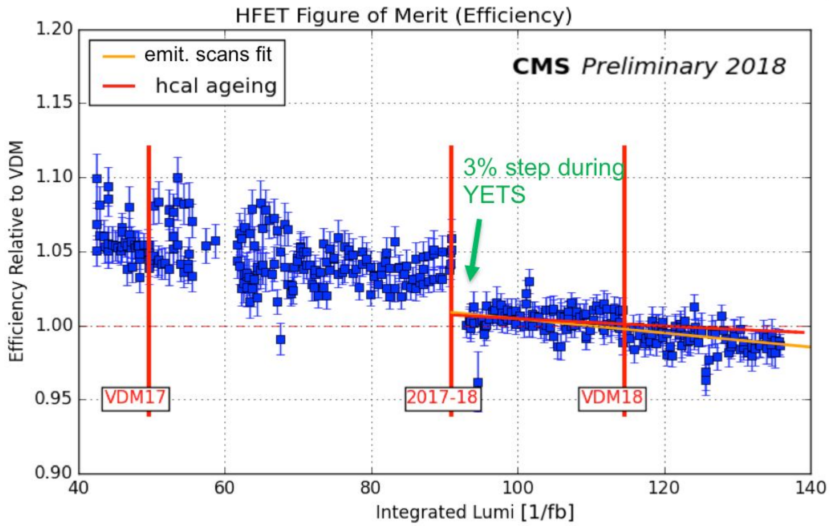

Thank you!

Emittance scans

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

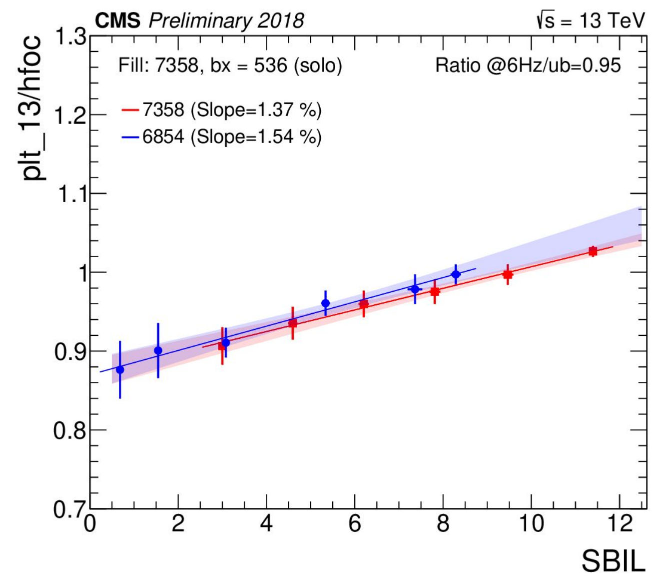


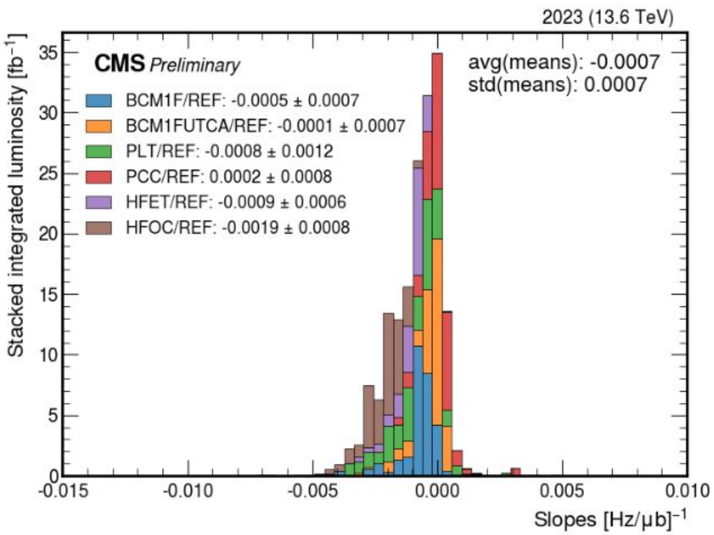


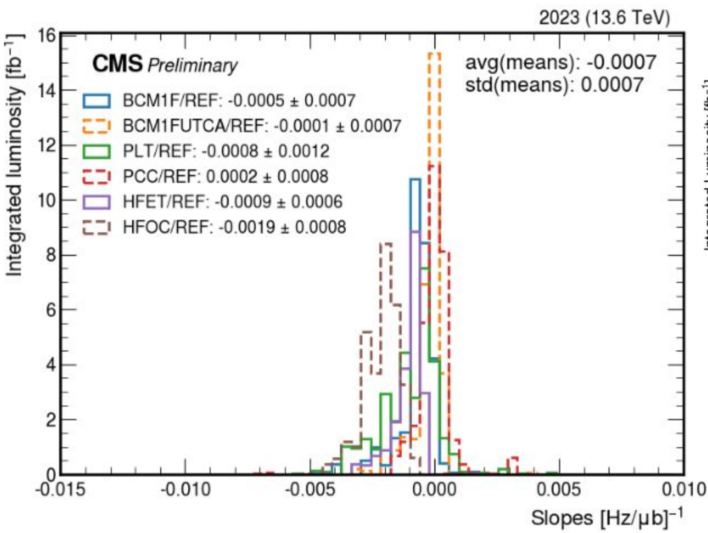


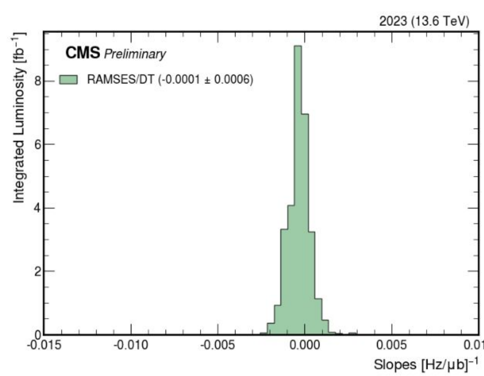
Linearity

- ❖ 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)

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  - **Variable separation LS scan**
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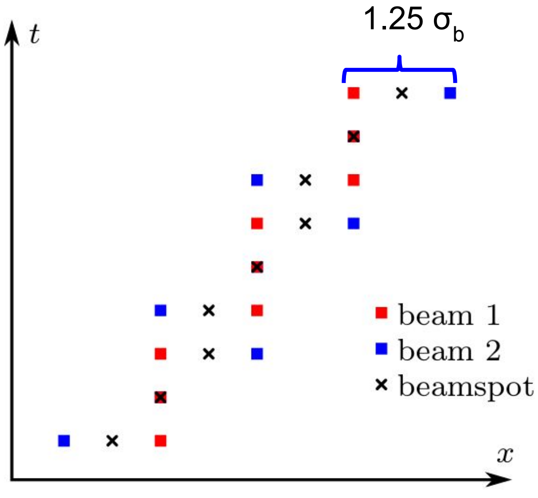
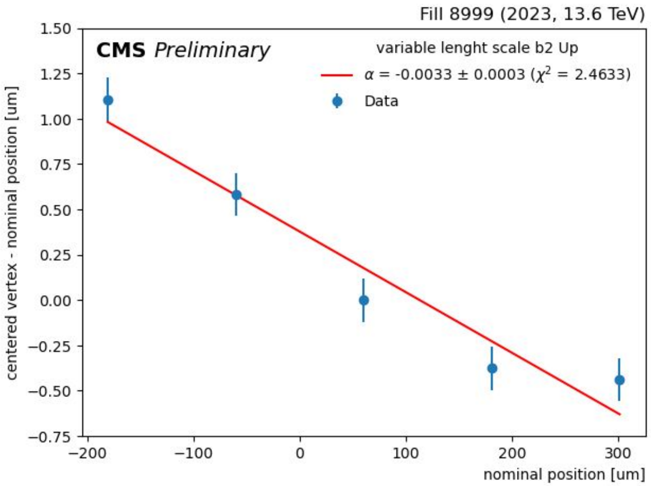
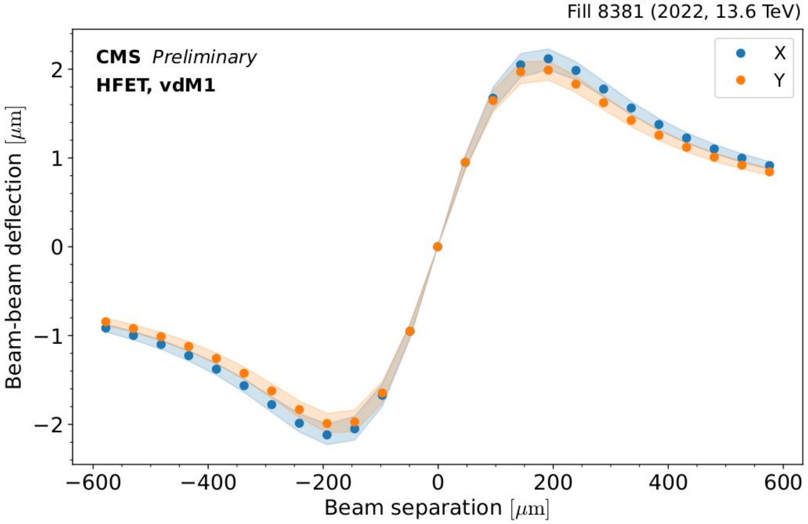
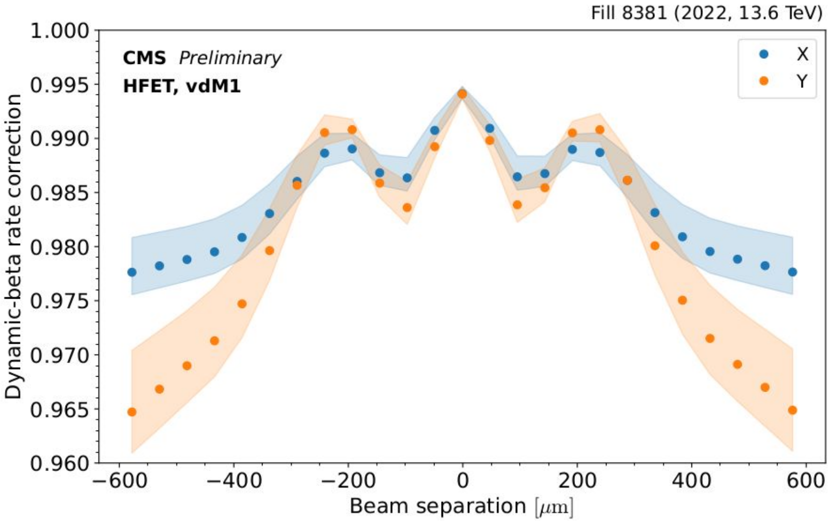


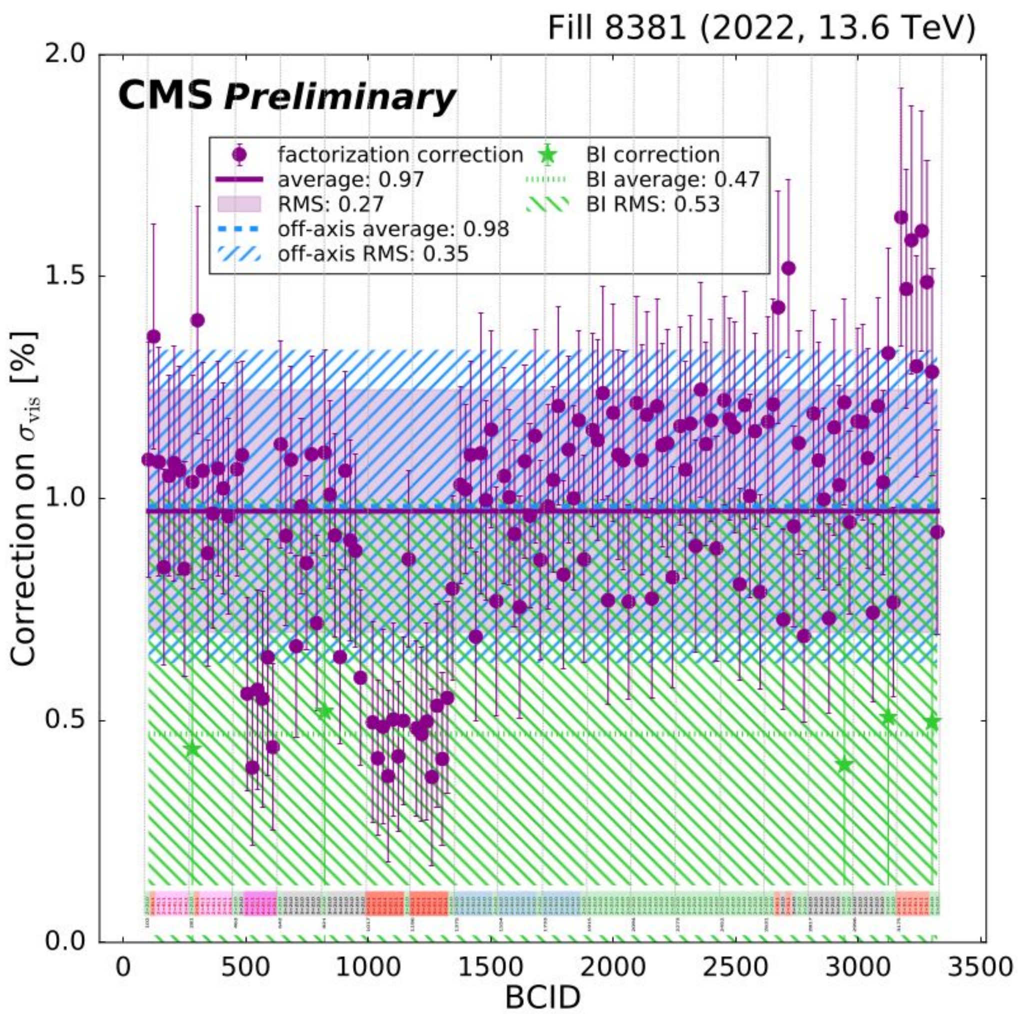


Beam-Beam effects





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