Overview of the CMS Run-2 luminosity determination and calibration methodology

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on behalf of CMS

Lumi days 2019
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Overview

<u>Summarizing in this talk:</u> CMS-PAS-LUM-15-001 (2015), CMS-PAS-LUM-17-001 (2016), CMS-PAS-LUM-17-004 (2017), CMS-PAS-LUM-18-002 (2018)

vdM → Normalization

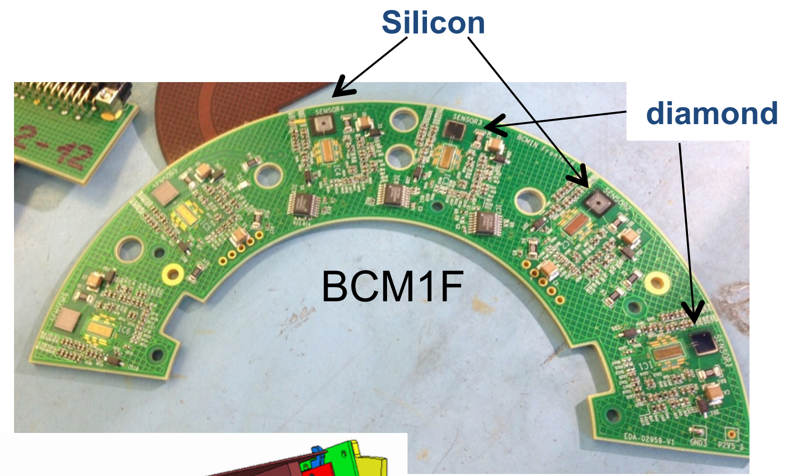
data taking → Integration

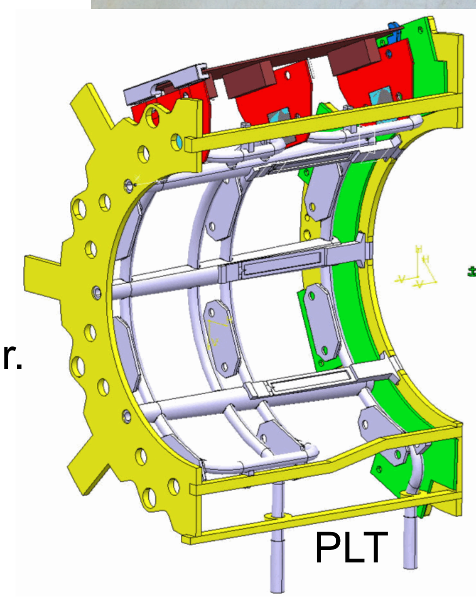
2018	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	—	0.5
	Background subtraction	0 to 0.8	0.1
Integration	Afterglow (HFOC)	0 to 4	$0.1 \oplus 0.4$
	Cross-detector stability	—	0.6
	Linearity	—	1.1
	CMS deadtime	—	<0.1
	Total		2.5

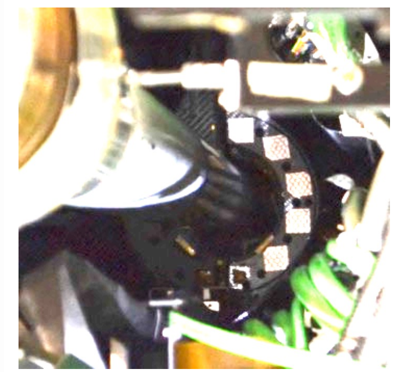
Luminometers and detector effects

CMS luminosity instruments

- Only bunch-by-bunch measurement
  - ~1.45 s (2^{14} LHC turns) granularity
  - ~1% precision / BX / s
- <u>Hadron Forward calorimeter</u>
  - Quartz fibers in Steel absorber.
  - Dedicated lumi back-end.
  - Two algorithms: Zero counting (**HFOC**), transverse energy sum (**HFET**)
- <u>Pixel Luminosity Telescope (**PLT**)</u>
  - Three phase-0 CMS Pixel planes in telescope arrangement.
  - Tipple coincidences of detector module fast-or.
- <u>Fast Beam Condition Monitor (**BCM1F**)</u>
  - Pad detector with fast analog front end.
  - Hit counting with 6.25 ns time resolution.
- One of these systems provides Luminosity to LHC.

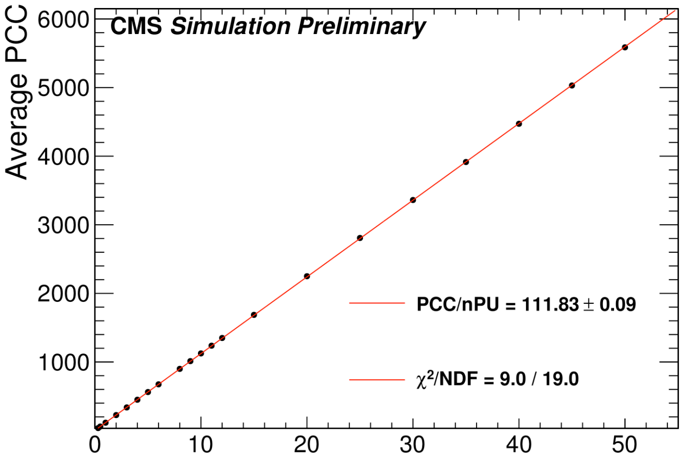






CMS luminosity instruments

- CMS Pixel cluster counting (**PCC**)
  - Triggered system
  - Available ~48 h after the fill.
- Primary **vertex counting**:
  - Used only in low pile-up.
  - Cross-check during calibration.



Number of pixel clusters is linear with pile-up

- Cross-calibrated reference systems:
  - Typically low rate, not bunch-by-bunch
    - ➢ No vdM calibration
  - Selected systems with proven stability and linearity.
    - Drift Tubes (**DT**, barrel muon chamber)
    - **Ramses** (Cavern radiation monitor)
  - Used for cross detector comparisons.

RAMSES

Online corrections

- Zero counting used by BCM1F, PLT and HFOC.
  - Compensates non-linearity due to double hits at higher pile-up.

$$\mu_{BX} = -\ln(1 - \frac{R_{BX}}{R_{\max}})$$

- Non-linear detector responses:
  - PLT: accidental triple coincidences (over efficient at high pile-up)
  - BCM1F (diamond based channels): dynamic sensor efficiency (under efficient at high rates)

➢ Quadratic term in calibration.

$$c_0 = 0$$

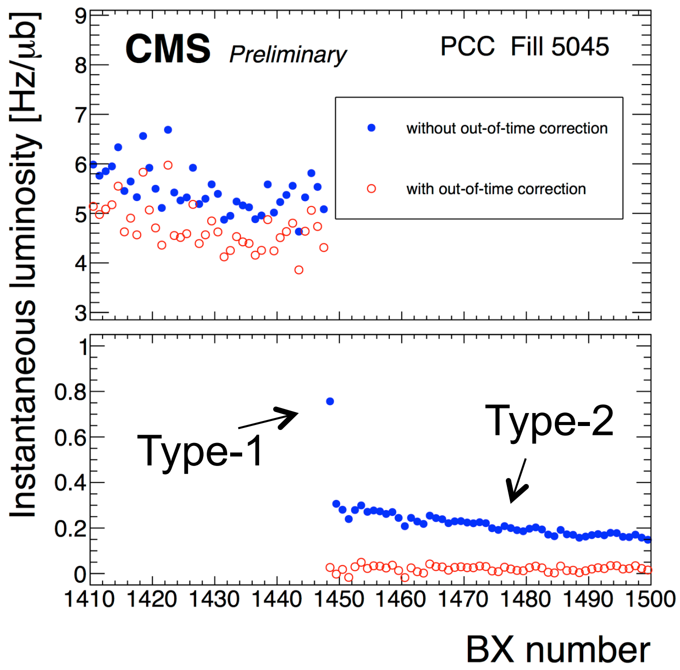
$$L_{BX} = c_2 \cdot \mu_{BX}^2 + c_1 \cdot \mu_{BX} + c_0$$

$$c_1 = \frac{f_{LHC}}{\sigma_{vis\_0}}$$

$$c_2 = -\mathrm{non\_linearity} \cdot \left(\frac{f_{LHC}}{\sigma_{vis\_0}} \right)^2$$

Out-of-time corrections

- Type-1: Detector effects on next bunch crossing
  - Magnitude non-linear: **leading and train bunches have different efficiency and non-linearity.**
  - PCC & HF: Charge spill over to next BX.
  - PLT: Fast-or dead time leads to inefficiency.
- Type-2: Late particles.
  - Late particle hits: Nuclear excitations, neutron albedo, slow particles (loopers)
  - Linear with Luminosity.
    - Iterative correction proportional to in-time luminosity
  - Affected systems: HF, PCC, BCM1F.

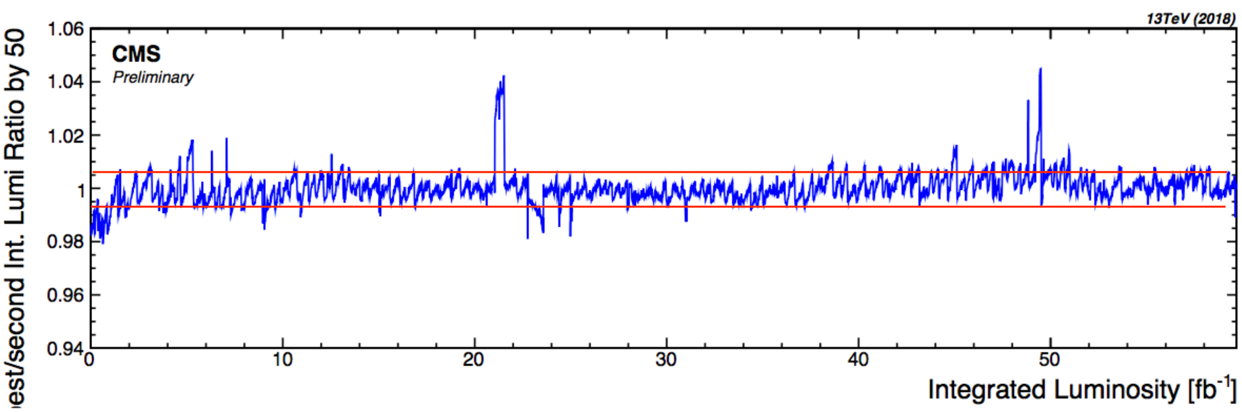


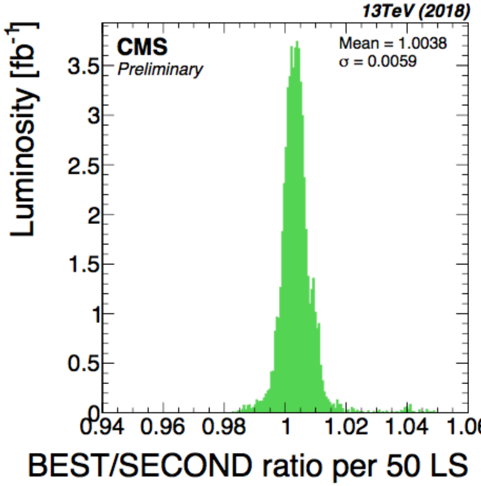
- Corrections are applied to compensate those effects
  - Magnitude of correction: PCC 7 - 16 %, HF 0 - 4 % (filling scheme dependent)

Stability and linearity

Dedicated talk by O. Karacheban, tomorrow 11:15

- Absolute measurement: Emittance scans.
  - Short vdM-like scans during nominal operations at start and end of scan
  - Corrections applied: Beam beam deflection, peak position, FBCT train effect.
  - Used to estimate correction on stability and linearity.
- Relative study: Detector comparisons.
  - No absolute measurement. Several agreeing systems provide confidence.
  - Comparison of at least 3 systems shows inconsistencies.
  - Used to estimate error on stability and linearity.





Detector effects uncertainties

- Detector uncertainties estimated for the system used as main luminometer for the offline luminosity for a given year.
  - 2015/16: **PCC**
  - 2017/18: **HF**

- Out of time effects uncertainties: **~0.4 %**
- Stability uncertainty: **0.5 - 1 %**
- Linearity uncertainty: **0.6 - 1.5 %**

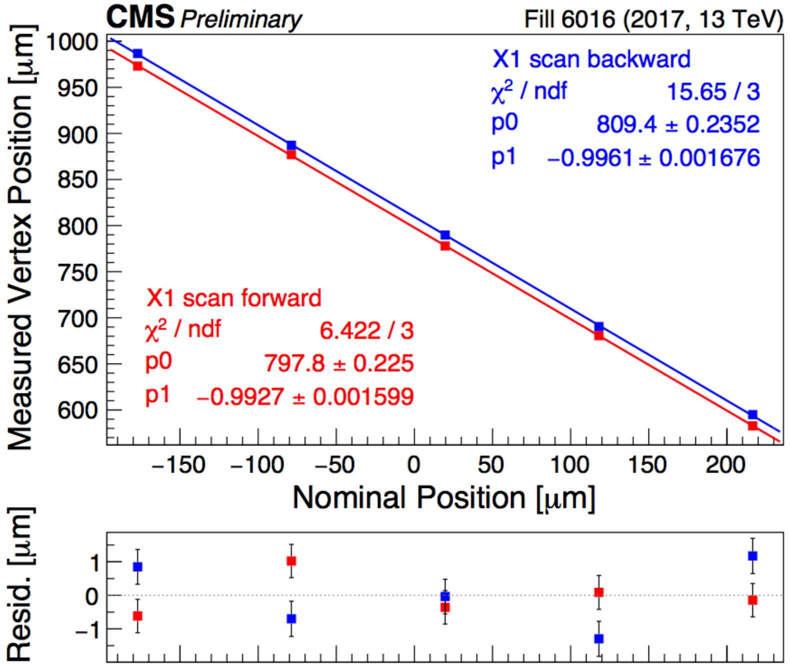
- CMS dead time uncertainty: **< 0.1%** (on recorded luminosity only)
  - In 2015: **0.5 %**

VdM corrections

Uncertainties shown here are from proton-proton at 13 TeV

Length scale calibration

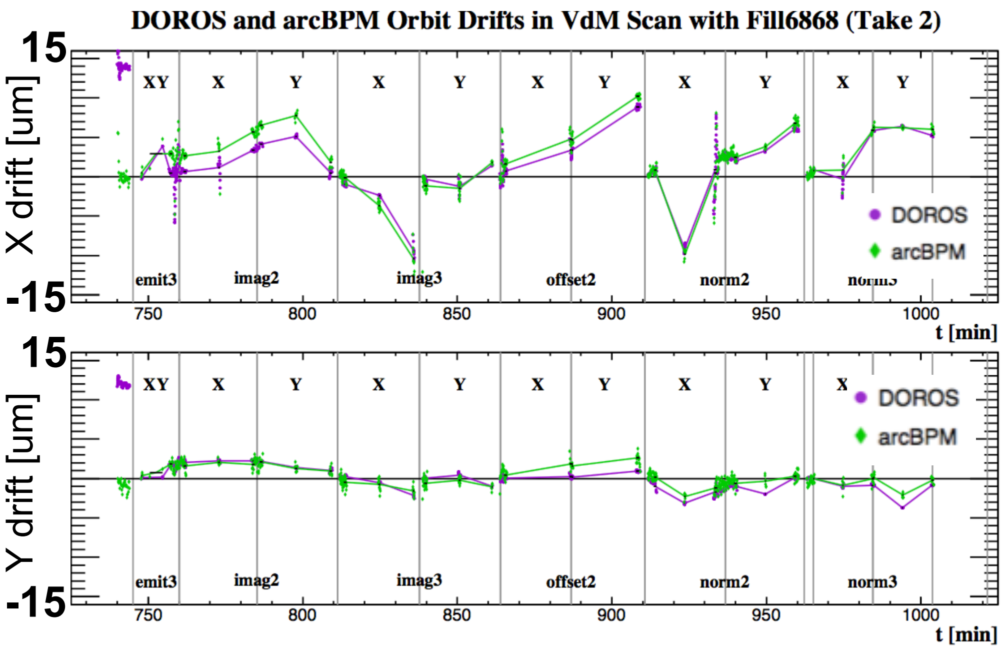
- Correction of nominal beam position with actual position measurement from vertex locations.
- Constant separation scan (hobbit scan):
  - Beams are kept at 1 Cap-sigma distance (highest sensitivity to drift)
  - Vary position along X and Y axis to map the scanning range, in both directions to measure a potential hysteresis.
- Variable separation scan:
  - Similarly the location to be measured is moved along axis.
  - Each position is measured in a 3 point scan. -> optimization of real position.
  - Calibrate both beams independently.



Magnitude of effect:
correction: **0.5 – 1.6 %**
uncertainty: **0.2 – 0.8 %**

Orbit drift

- Measurement using arcBPMs and DOROS.
- Relative position to zero (defined after optimization).
- Only head on positions are considered (start, middle and end of scan)
  - Interpolation during separated beams.
- The beam positions used in the vdM fitting are corrected.
  - Improves scan to scan variations.
- The uncertainty from the impact on the vdM result when using only DOROS or arcBPMs.



Magnitude of effect:
correction: **none – 0.2 %**
uncertainty: **0.1 – 0.4 %**

Additional information in talk by W. Kozanecki, today 15:20

Charge calibration

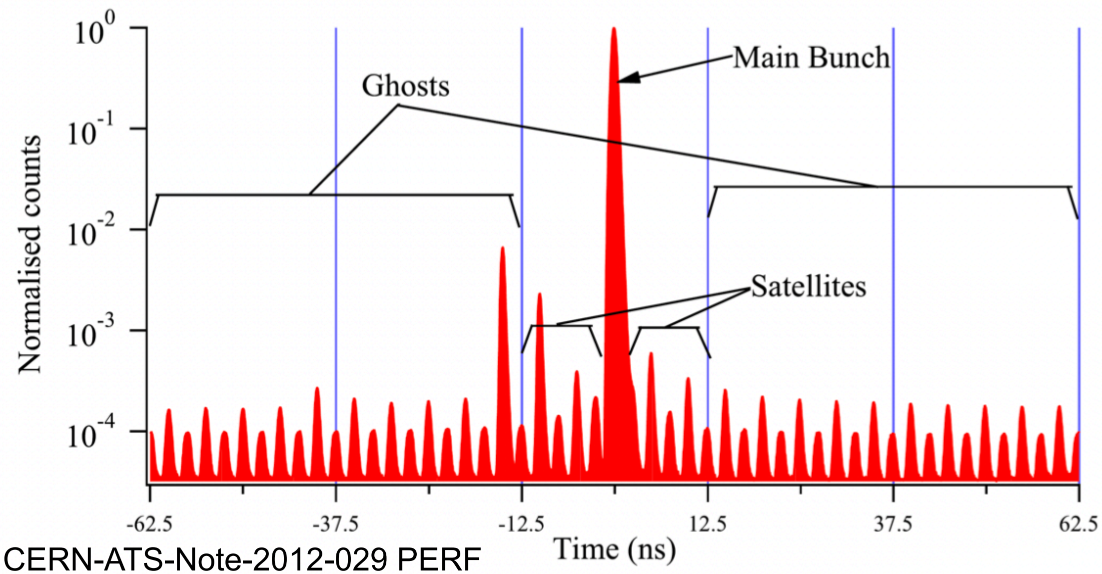
Ghost and satellite

- Bunch-by-bunch current measurement by FBCT used in vdM normalization
- Absolute calibration of FBCT using DCCT (in 2018: 2.3% correction)
- Ghost and satellite charge as measured by LDM are taken into account

Satellite charge subtracted from FBCT measurement

$$n^j = \frac{n^j_{\mathrm{FBCT}}\left(1 - f^j_{\mathrm{sat}}\right)}{\sum_k n^k_{\mathrm{FBCT}}} N_{\mathrm{DCCT}}\left(1 - f_{\mathrm{ghost}}\right)$$

Calibration using ghost subtracted DCCT

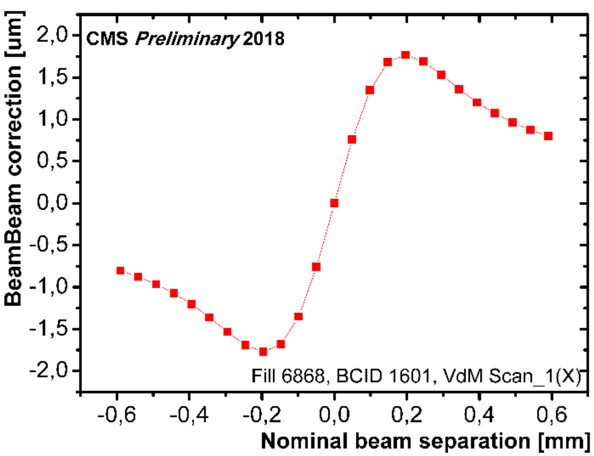


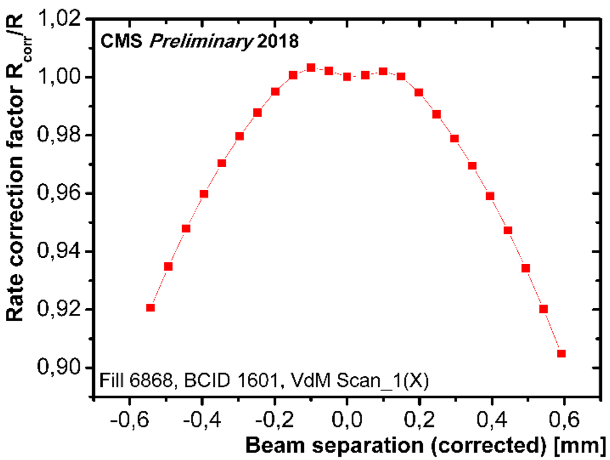
CERN-ATS-Note-2012-029 PERF

Magnitude of effect:
correction: **none – 0.4 %**
uncertainty: **0.2 – 0.4 %**

Beam Beam & dynamic β

- Beam beam deflection leads to a deviation from nominal position.
  - ➢ Correction on position.
- Beam beam force leads to a focusing effect.
  - Magnitude changes with separation.
  - ➢ Correction on rate
- Calculated from established models.
  - CERN-ACC-NOTE-2013-0006, CERN Yellow Report CERN-2014-009.431
- Uncertainty on correction mostly originates from uncertainty on β*
- Are there uncertainties on the model itself?





Magnitude of effect:
correction: **1 – 1.8 %**
uncertainty: **0.2 – 0.6 %**

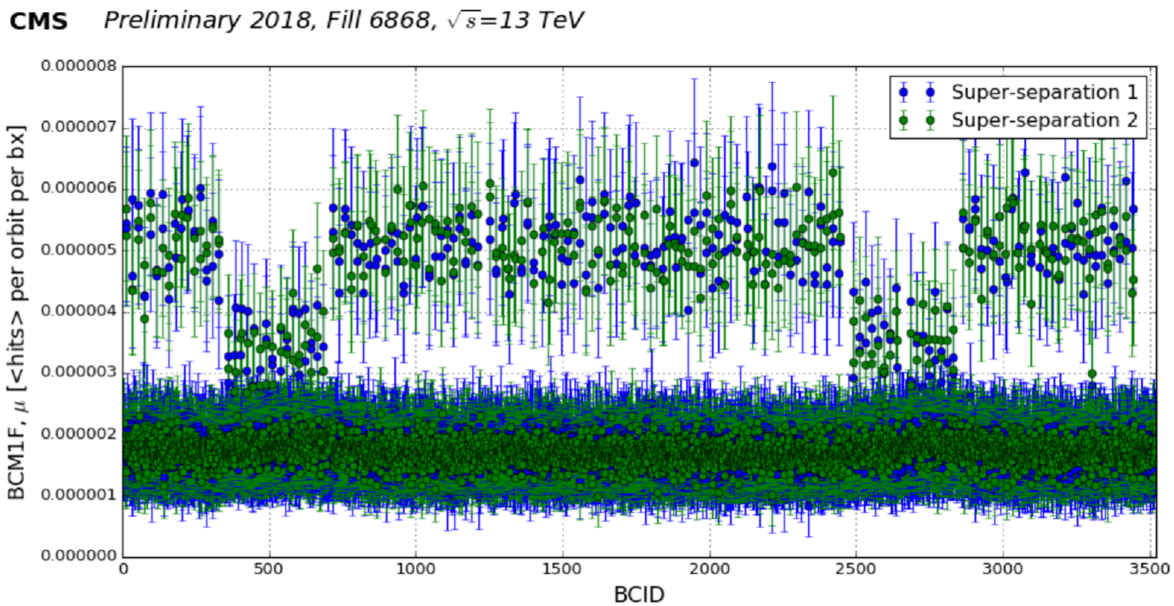
Additional information in talk by T. Pieloni, tomorrow 9:55.

Background subtraction

- **Intrinsic noise** in some detectors, not negligible in the vdM fill.
- Wide beams result in low rates, beam intensity and hence **beam induced background** (BIB) similar to nominal conditions. -> Background to Lumi fraction much higher in vdM.
- Constant detector rates treated with **constant term in vdM fit** in the past:
  - Constant value not well estimated, can deteriorate fit quality.
- **New strategy: Measure and remove background**: non-colliding bunches (2017, 2018), super separation (2018).
  - Both methods showed comparable results

➢ Significant improvement of fit-convergence.

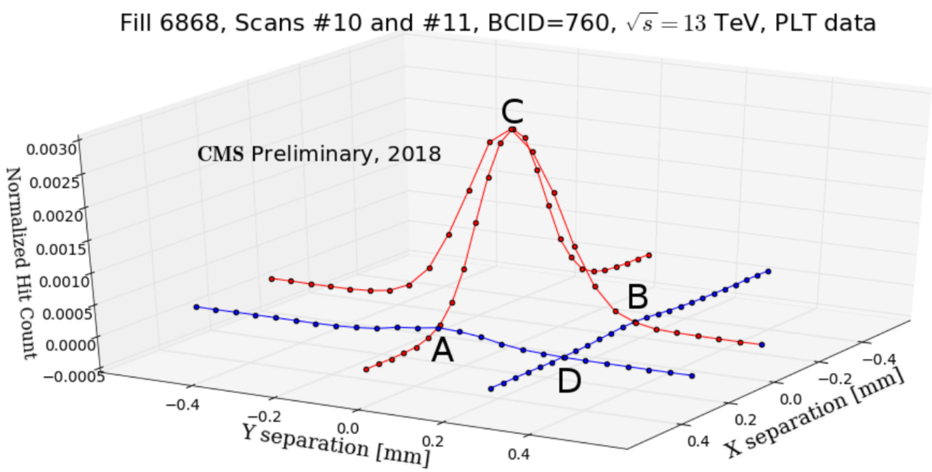
Magnitude of effect:
correction: **0 – 0.8 %**
uncertainty: **0.1 %**

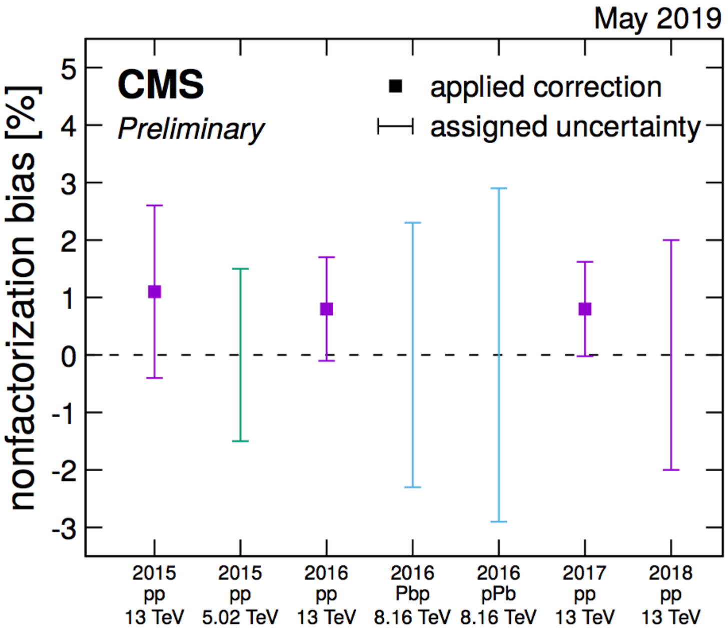


X/Y-correlations

Dedicated talk by J. Knolle, today 16:50

- Observation: Width of the beam overlap transversal to scanning direction not constant.
- Measurement methods to estimate:
  - **Beam Imaging scans**: One beam is used to probe the shape of the other beam. Beam shape reconstructed from vertex data.
  - **Offset scans**: 2D correlated Gaussian fit to luminometer data.





Run-2 uncertainties overview

Year	Total [%]	Normalization [%]	Integration [%]
2015	**2.3**	1.8	1.5
2016	**2.5**	1.5	2
2017	**2.3**	1.5	1.7
2018	**2.5**	2.1	1.3

- Driving uncertainties: X/Y-correlation, stability, linearity.
- Recent improvements: orbit drift, noise/BIB treatment.

2015/2016 Luminosity paper in internal review: Expect significant improvement.

Special runs and HI

- Stability and linearity less problematic, normalization not as thoroughly performed.
- pPb: **3.5 %**, pp reference (2015): **2.3 %**

Run-3 prospects

- Online systems:
  - PLT front end will be completely re-furbished.
    - Improved data treatment with per-channel calibrations
  - BCM1F will be replaced with upgraded design.
    - Dedicated A/C-coupled silicon sensors.
  - HF with established performance
  - Fast trigger rate monitoring being developed by CMS. Potential for luminosity under investigation.
- VdM calibration:
  - Driving uncertainty still X/Y-correlations -> Alternative methods being investigated.
  - Can the uncertainty on β* be improved at ~19 m ?
  - Is there a more optimal β* to reduce the overall uncertainty?
- Stability and linearity using emittance scans
  - Significantly increased understanding, see dedicated talk.
  - Effect of non-linearity might increase, if higher pile-up is used.

Summary

- Several systems with different systematics are employed:
  - Three reliable online luminometer.
    - Stable operation: Almost no blind moments.
  - Offline systems and low rate reference systems.
  - Addition of several luminometers compared to Run-1 giving increased confidence.
- Improvements to vdM calibration made and planned
  - Treatment of constant term.
  - Treatment of orbit drift.
  - Different methods for length scale calibration
  - Ongoing work to quantify X/Y correlations.
  - In depth treatment of beam beam effects will be crucial.
  - Year to year correlation study will improve global Run-2 uncertainty.

Backup

Full uncertainties

2015

	Systematic	Correction (%)	Uncertainty (%)
Integration	Stability	-	1
	type 1	7 – 9	0.6
	type 2	0 – 4	0.7
	CMS deadtime	-	0.5
	Dynamic Inefficiency	-	0.4
Normalization	XY-Correlations	1.1	1.5
	Beam current calibration	-	0.3
	Ghosts and satellites	-	0.2
	Length scale	-0.5	0.5
	Orbit Drift	-	0.4
	Beam-beam deflection	1.8	0.4
	Dynamic-β	-	0.5
	Total		2.3

2016

Source	correction (%)	uncertainty (%)
Integration		
Internal stability	-	0.5
Linearity	-	0.6
Cross detector stability	-	1.5
Dynamic Inefficiency	0 – 1	0.3
Type 1 correction	7 – 12	0.7
Type 2 correction	0 – 4	0.5
CMS deadtime	-	0.5
Normalization		
XY-Correlations	+0.8	0.9
Beam current calibration	-	0.3
Ghosts and satellites	-	0.4
Length scale	-1.6	0.8
Orbit Drift	-	0.4
Beam-beam deflection	+1.5	0.4
Dynamic-β	-	0.5
Statistical	-	0.3
Total		2.5

2017

	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	-0.9	0.3
	Orbit drift	—	0.2
	x-y correlations	+0.8	0.8
	Beam-beam deflection	+1.6	0.4
	Dynamic-β^*	—	0.5
	Beam current calibration	—	0.3
	Ghosts and satellites	—	0.1
	Scan to scan variation	—	0.9
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	0.4–0.6	0.6
Integration	Afterglow (HF)	—	$0.2\oplus0.3$
	Cross-detector stability	—	0.5
	Linearity	—	1.5
	CMS deadtime	—	0.5
	Total		2.3

2018

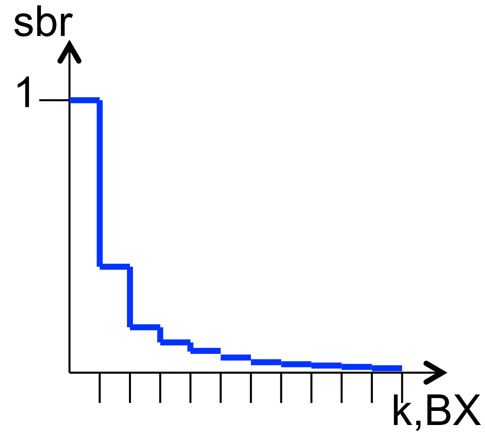
	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	—	0.5
	Background subtraction	0 to 0.8	0.1
Integration	Afterglow (HFOC)	0 to 4	$0.1\oplus0.4$
	Cross-detector stability	—	0.6
	Linearity	—	1.1
	CMS deadtime	—	<0.1
	Total		2.5

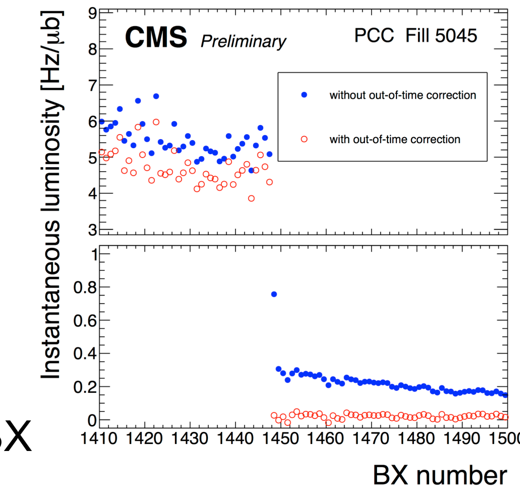
Out of time uncertainty determination

- Correction of single bunch response.

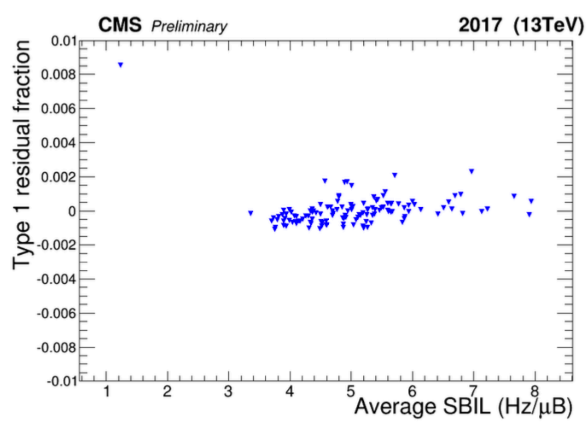
$$L_{corr}(n+k) = L_{uncorr}(n+k) - \alpha(k)\cdot L_{corr}(n)$$

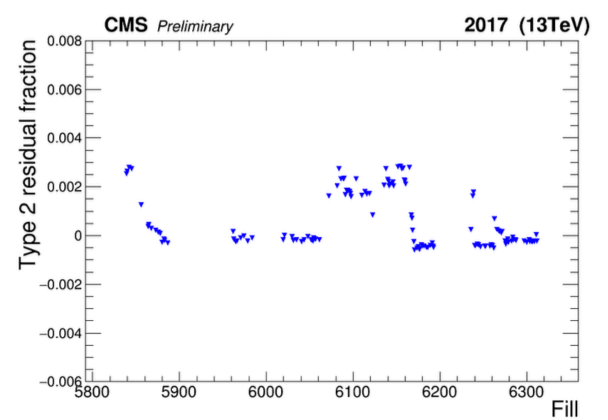
$$\alpha(k): \text{Single bunch response}$$





- First BX after train is used to study residual type-1 effect and checked for SBIL dependence.
- 30 BX after train is used to study residual type-2 effects and verify stability over the year.
- Variations in residuals are taken as uncertainty





Additional uncertainties

- Scan to scan and bunch to bunch variation in vdM.
- Consistency check between different luminometers