# CMS 2017 pp Luminosity Precision

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## CMS PAS: LUM-17-004

### CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV

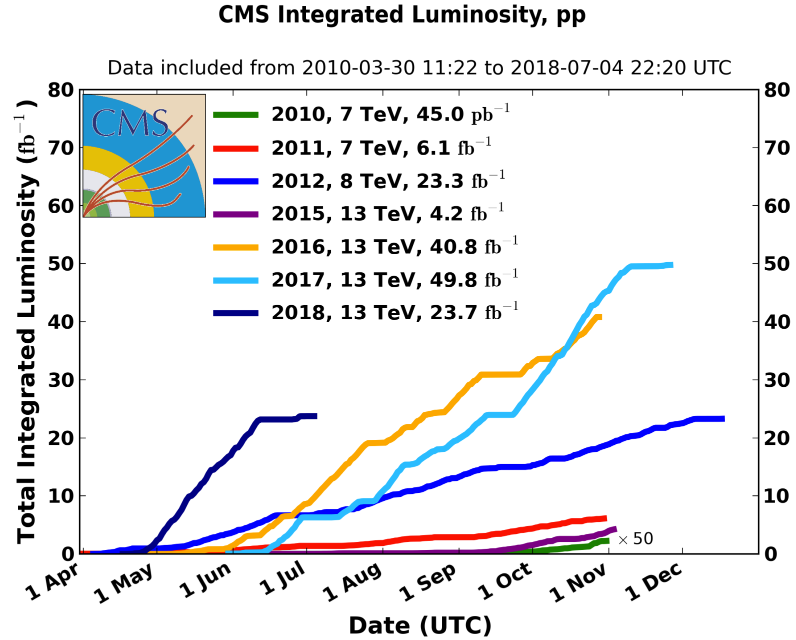
The CMS Collaboration

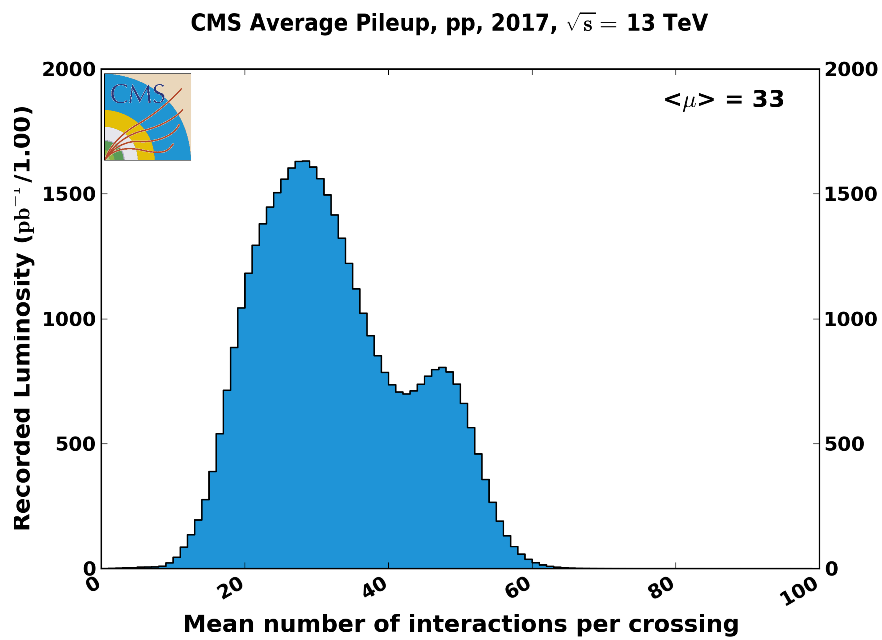
**Abstract**

The calibration for the luminosity measurement by the CMS experiment for the 2017 proton-proton LHC run at $\sqrt{s} = 13$ TeV is described. The principal calibration is derived from the analysis of the van der Meer scan program in CMS taken during LHC fill 6016. In addition, the performance and stability of the CMS luminometers are also evaluated using emittance scans taken throughout the course of the year. The systematic uncertainty in the absolute calibration from the van der Meer scan is derived with a precision of 1.5%, with the dominant contributions arising from the $x$-$y$ correlations of the beam shape and the scan to scan variation. The total systematic uncertainty, including terms from stability and linearity effects, is 2.3%. The uncertainty for the special low-pileup run at the end of 2017 is also evaluated and found to be 1.7%.

# Overview

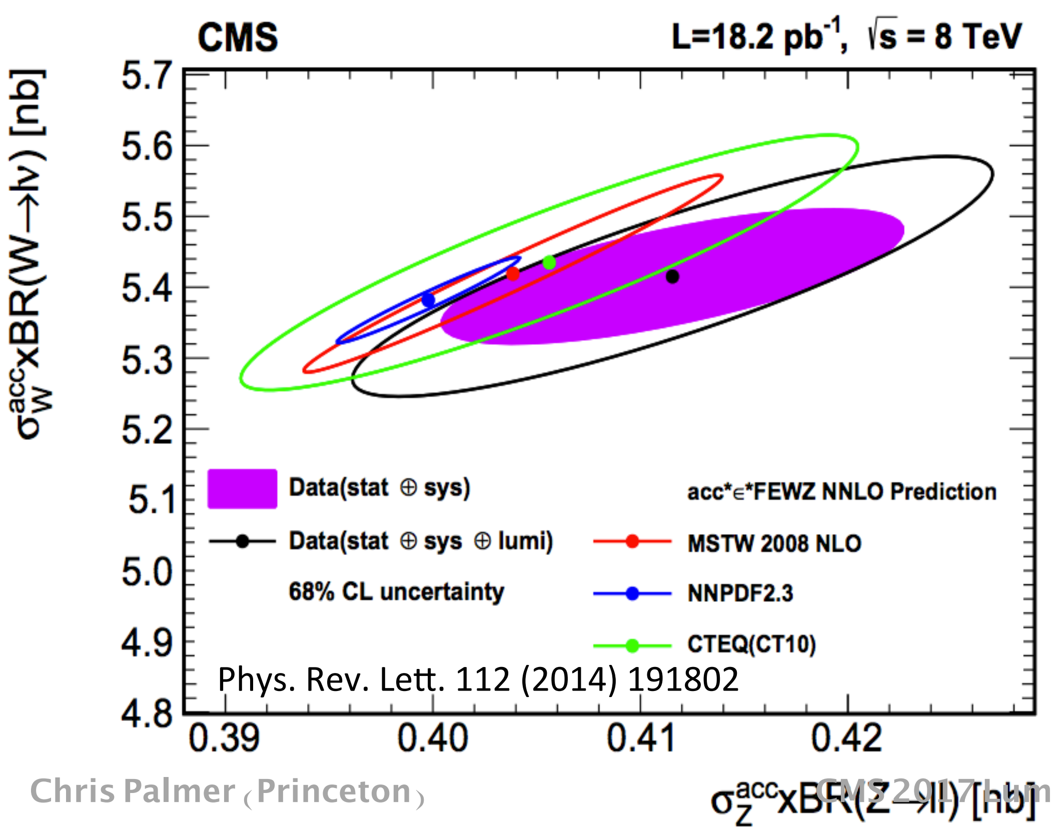
- Motivation and basic information
- CMS luminosity analysis
  - Normalization with Van der Meer scan data
  - Calibration stability
    - Efficiency
    - Correction stability
    - Linearity with pile-up uncertainty
- Emittance scan analysis (NEW!)
  - LHC scans for estimating beam shape
  - With marginal adjustments CMS analyzed these data as VdM throughout 2017
  - Poster A_7: "CMS emittance scans for 2017 luminosity calibration"

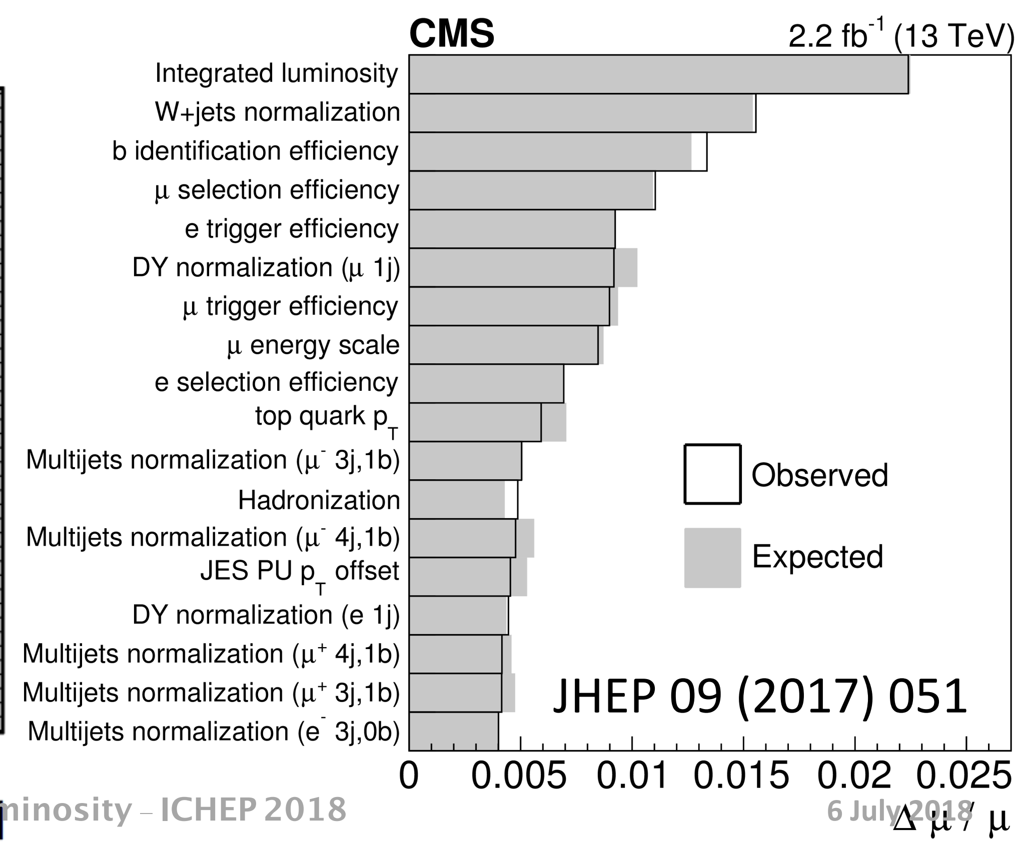


# Luminosity Precision Motivation

- While luminosity precision is a systematic for almost all searches and measurements, it is particularly important for measurements with well-controlled systematics.
  - Typically cross sections involving 1 or 2 muons or electrons.
  - E.g W, Z and top pair decays
  - Order 1% precision would be ideal.



# Luminosity Fundamentals

- The kindergarten relationship of HEP is:

$$N_{\text{Events}} = \sigma \int L$$

- Before getting to "the" number that everyone needs for their analysis we need to determine the instantaneous luminosity over the entire data-taking period.

$$\frac{dN}{dt} = R = \sigma L$$

- For a luminosity detector we invert this relationship, convert the rate into the detector's observable, and finally we arrive at the paradigm for luminosity measurements.

$$L = \frac{R}{\sigma} = \frac{\mu f_{\text{LHC}}}{\sigma_{\text{pp, minBias}}} = \frac{\kappa \mu_{\text{vis}} f_{\text{LHC}}}{\kappa \sigma_{\text{vis}}} = \mu_{\text{vis}} \frac{f_{\text{LHC}}}{\sigma_{\text{vis}}} \quad \Rightarrow \quad L_{\text{total}} = \sum_{N_{\text{BX}}} \mu_{\text{vis}} \frac{f_{\text{LHC}}}{\sigma_{\text{vis}}}$$

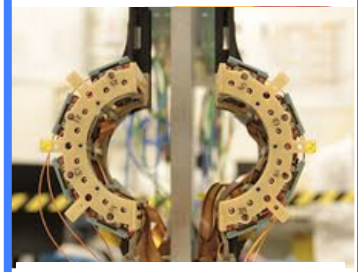
# CMS Run 2 luminosity monitors



- Detector with rate estimation algorithm constitutes a "luminometer"

**Online measurements**

**Pixel Luminosity Telescope (PLT)**

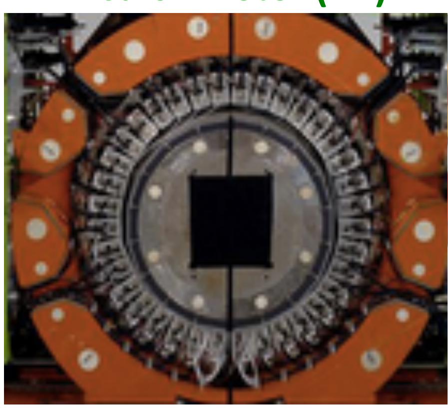


Event counting

**Fast Beam Condition Monitor (BCM1F)**

Hit counting

**Hadron Forward Calorimeter (HF)**



HFOC: hit counting

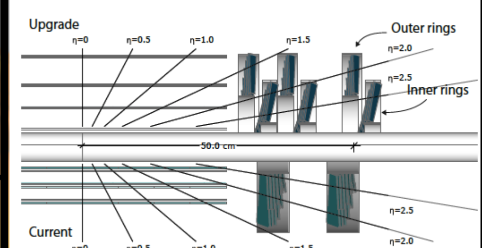
HFET: sum $E_T$

**Offline measurements**

**Muon Drift Tubes (DT)**

Rate of muon tracklet trigger primitives

**Silicon Pixel Detector**

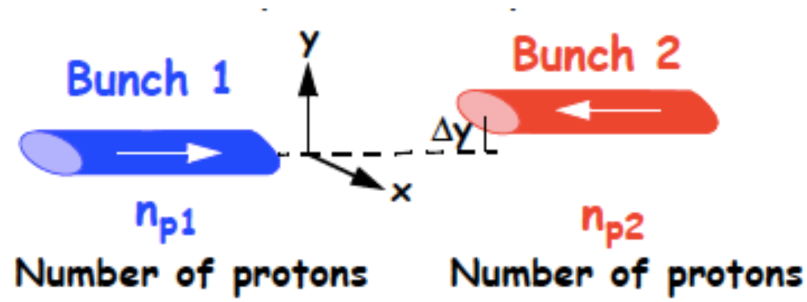



Pixel Cluster Counting (PCC)

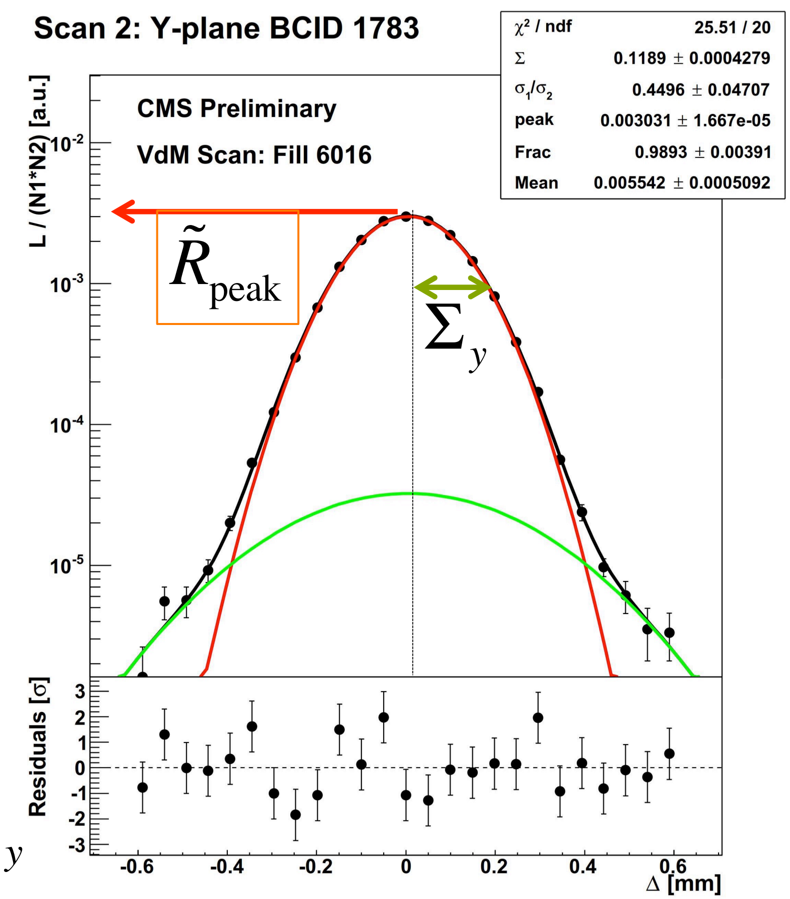
**2015/2016 based on: PCC**
**2017 based on: HFET**
**(complemented with: PCC)**

# Van der Meer Calibration

- The strategy is to measure the absolute luminosity in a pair of scans in orthogonal directions.




- Each scan consists of numerous scan points (25 scan steps, 30-second each) with varying separation in the vertical (horizontal) direction while the horizontal (vertical) separation is ~0.




$$L = f_{\rm LHC} N_{p1} N_{p2} \int \rho_{b1}(x,y)\rho_{b2}(x,y)\,dxdy$$

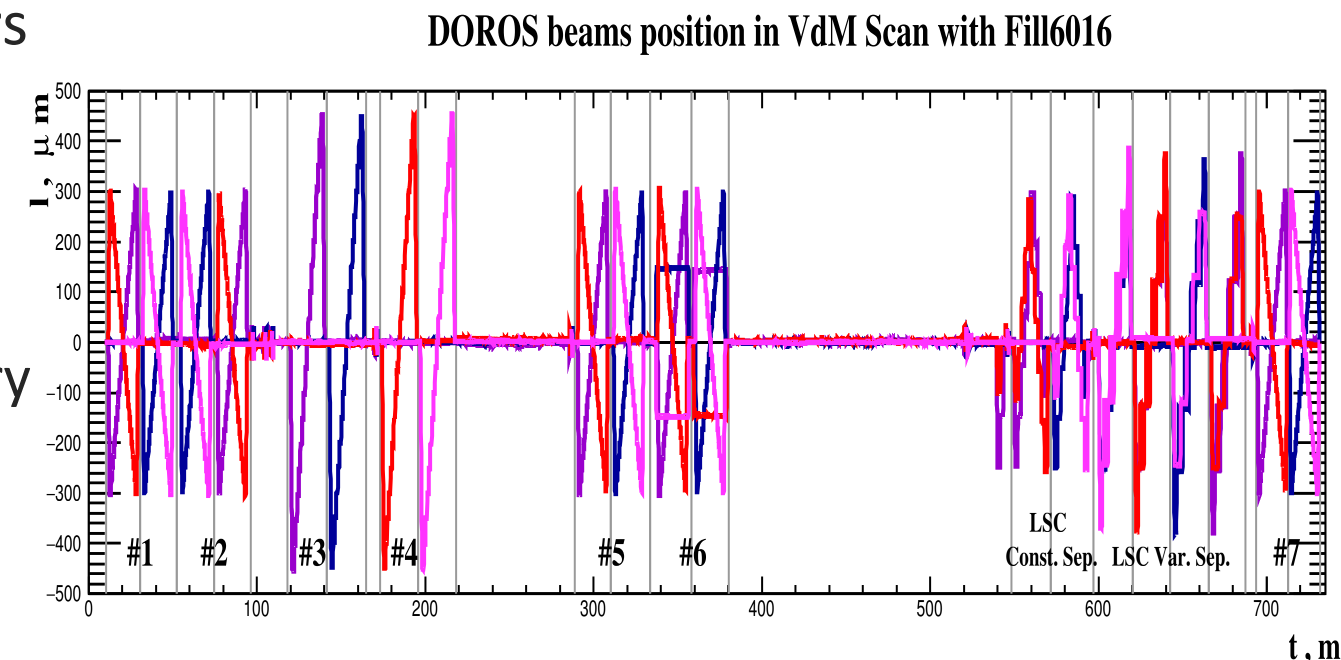
- Assuming x and y are factorizable:

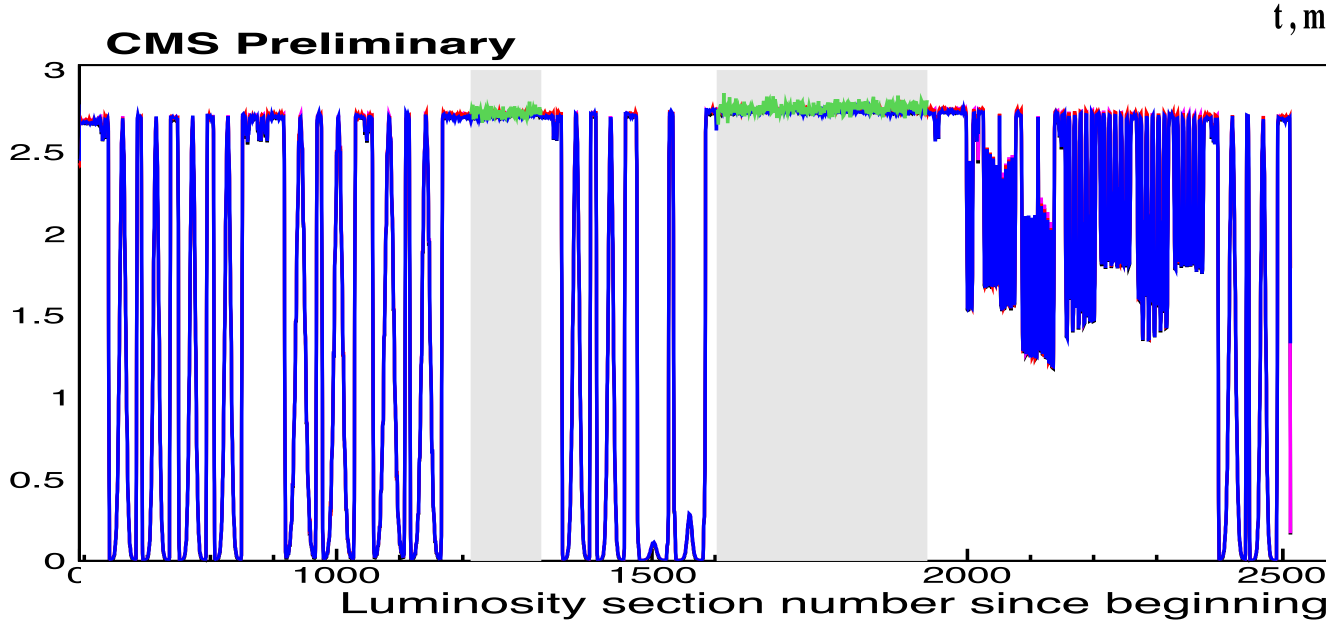
$$L_{\rm peak} = f_{\rm LHC} \frac{N_{p1}N_{p2}}{2\pi\Sigma_x\Sigma_y}$$

$$\Rightarrow \sigma_{vis} = R_{\rm peak}\frac{2\pi\Sigma_x\Sigma_y}{f_{\rm LHC}N_{p1}N_{p2}} = 2\pi\tilde{R}_{\rm peak}\Sigma_x\Sigma_y$$

# Scan Program

- Four "regular" VdM pairs
  - (1, 2, 5, 7)
- Beam imaging scans
  - (3, 4)
  - One beam is stationary or "fixed" while the other scans in both directions
  - Used to estimate impact due to non-factorization using reconstructed vertices
  - Analyzed also as VdM scans
- Length scale scans
  - Constant separation
  - Variable separation



# Calibration Systematics

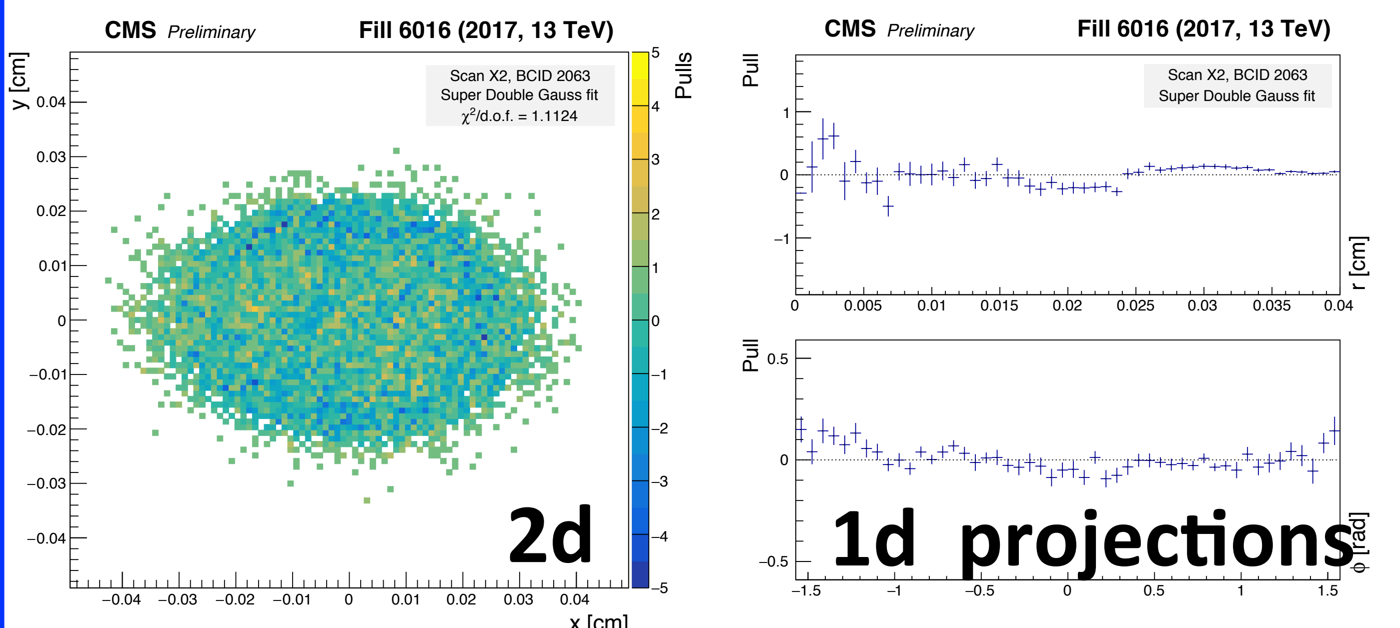
- The overall calibration uncertainty is 1.6%.
- A few previous medium to large range uncertainties were significantly reduced in this analysis:
  - Length scale, orbit drift and non-factorization
- The consistency among calibrations is now the leading source of uncertainty.

| | 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 | 0.64 |
| | Dynamic-$\beta^*$ | — | 0.5 | |
| | Beam current calibration | — | 0.3 | 0.32 |
| | Ghosts and satellites | — | 0.1 | |
| | Scan to scan variation | — | 0.9 | 1.19 |
| | Bunch to bunch variation | — | 0.1 | |
| | Cross-detector consistency | 0.4–0.6 | 0.6 | |

# Calibration Systematic: XY Correlations

- The factorization of the proton bunch probability density function (PDF) is fundamental to the analysis.
  - Not an exactly valid assumption
- Beam imaging scans keep one beam stationary or "fixed" and scan the other beam in both directions.
- The positions of reconstructed vertices are used to produce beam overlap templates (BOT).
  - Four: b1x, b1y, b2x, b2y
- Two dimensional models for each beams' PDF are constructed and fit to BOTs with and without correlations to derive correction factors per bunch crossing

Model compatibility to BOT

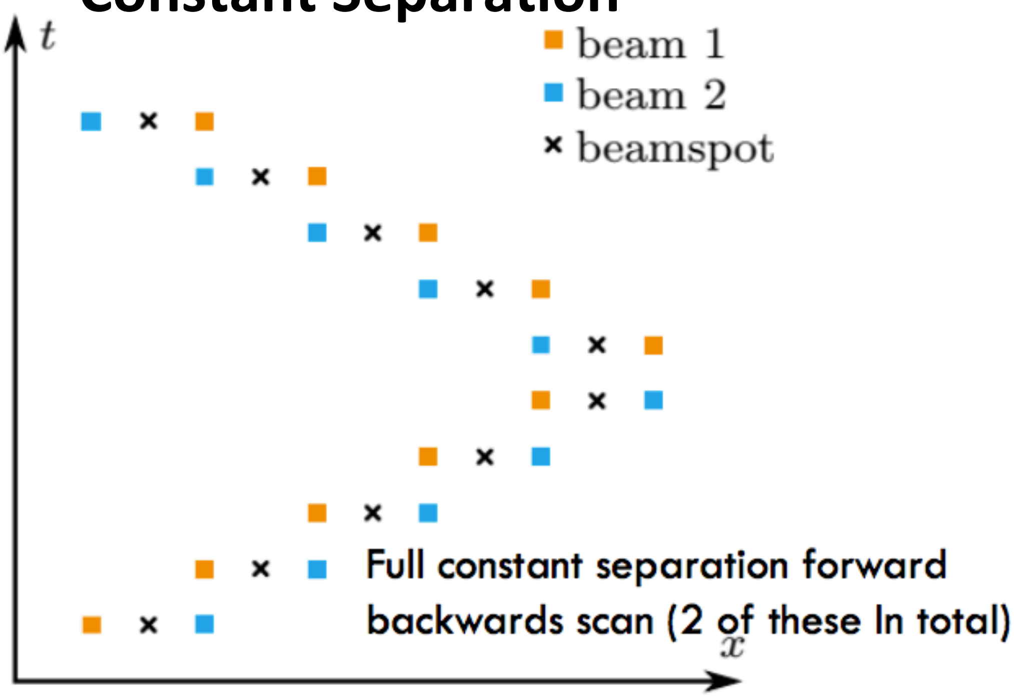



- Several models were attempted and the best produced an average correction of 0.8%.
  - No significant difference using alternative model
- Systematics (±0.8%)
  - Potential bias from MC studies
  - Statistical error estimated with MC

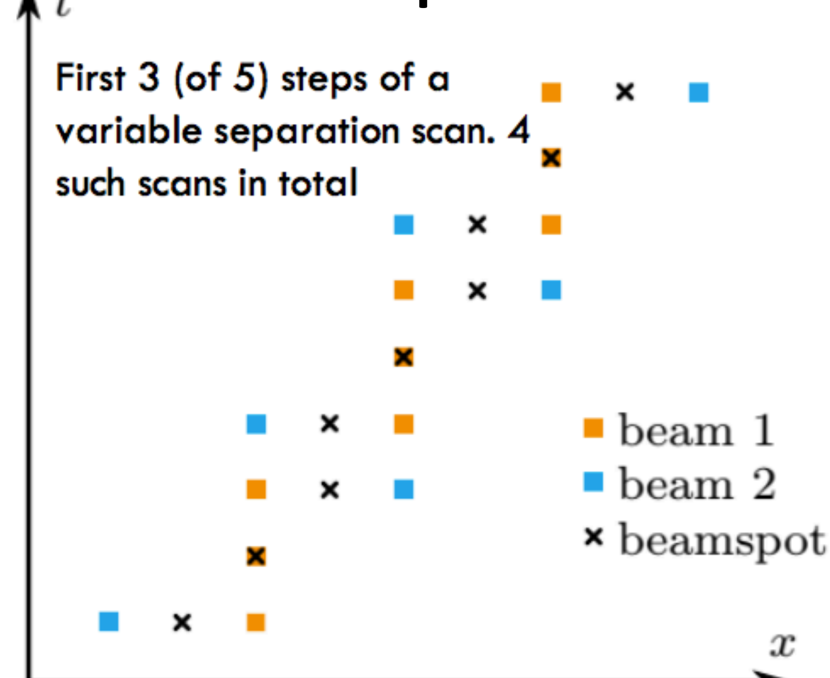
# Calibration Systematic: Length Scale

- The accuracy of beam positions given by LHC must be verified and corrected if necessary.
  - LHC beam positions are estimated using current in steering magnets.
- Length scale scans are tests of systematic bias in LHC reported positions.
  - In 2017 CMS employed **two** scan methods (NEW!)

**Constant Separation**




**Variable Separation**

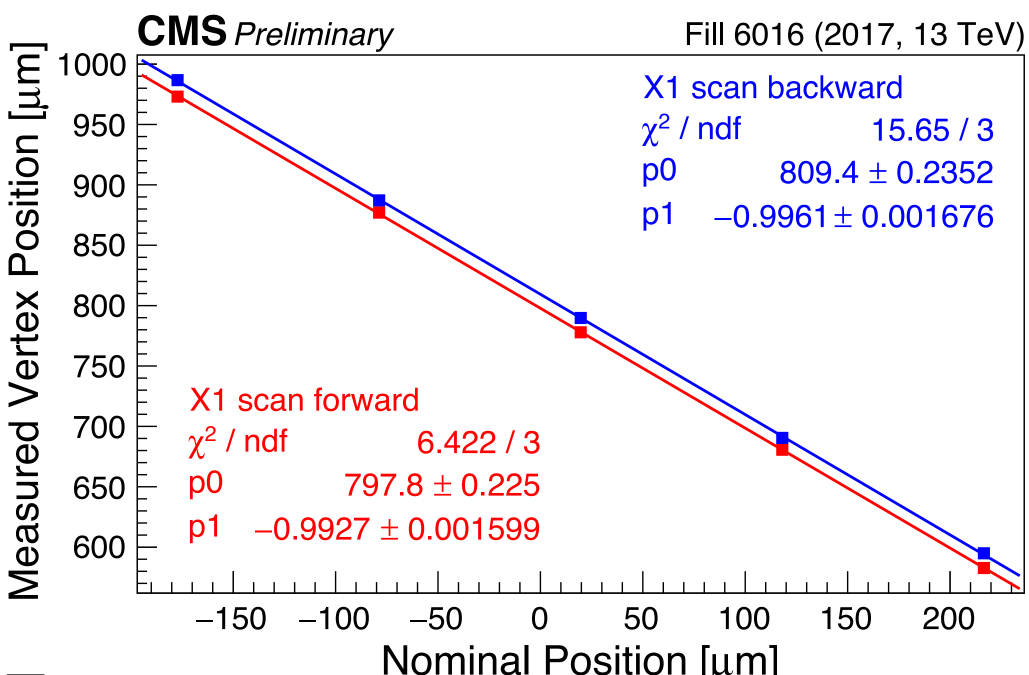


# Calibration Systematic: Length Scale

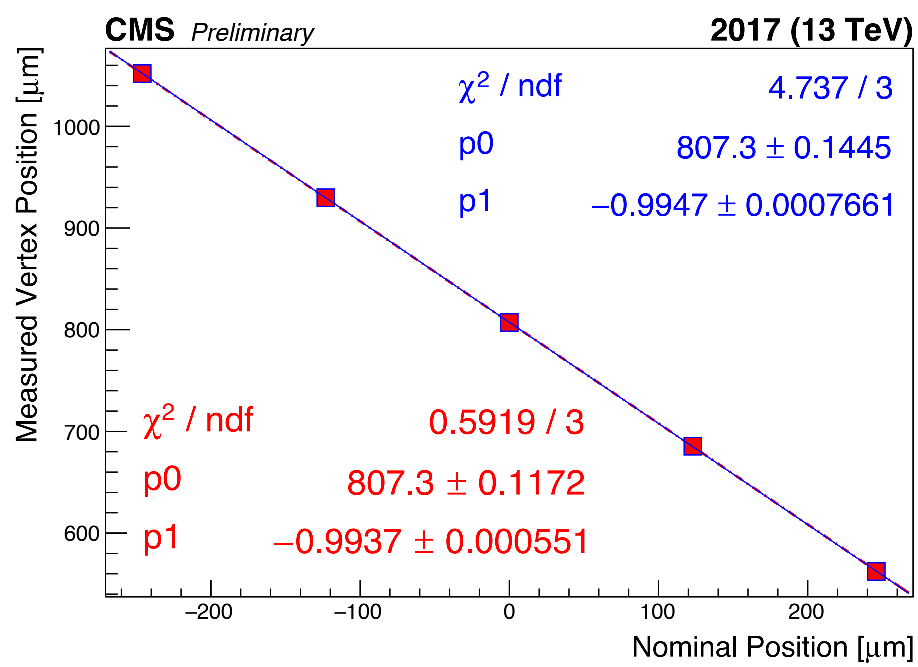
- The two scans give amazingly consistent results.
  - Within 0.1%!
- The two sets of results are combined assuming no correlation and 100% correlation.
  - Both round up to 0.3% combined uncertainty.

| Method | Uncertainty |
|---|---|
| Constant | 0.5% |
| Variable | 0.3% |
| Combined | 0.3% |

## Constant Separation

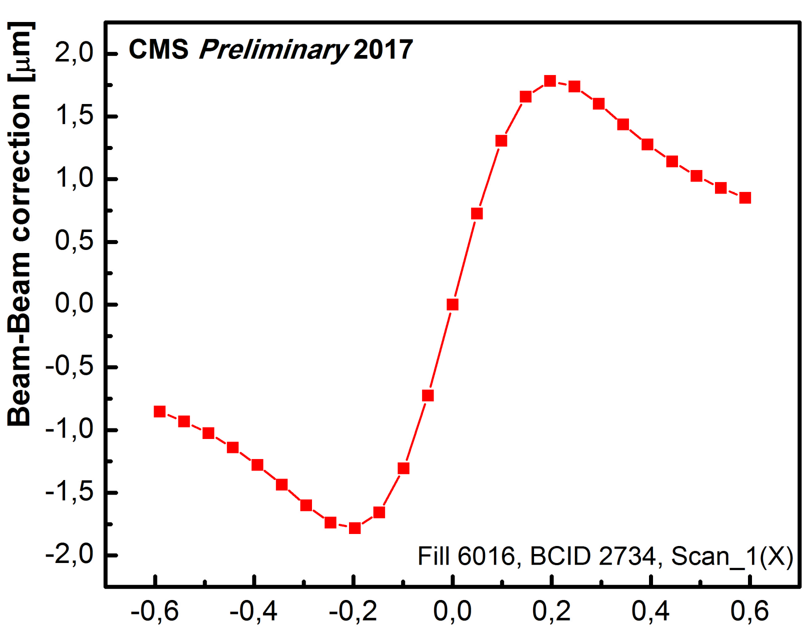


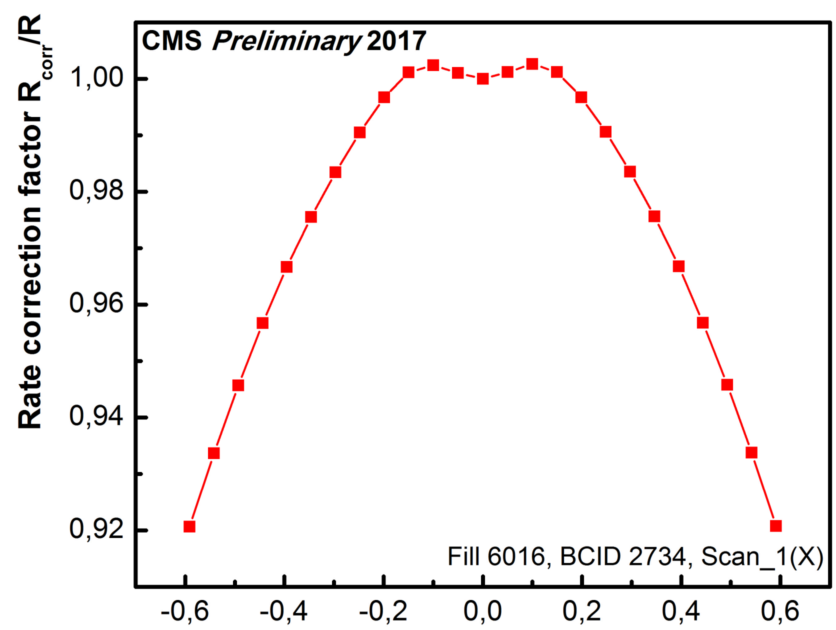

## Variable Separation



# Calibration Systematic: Beam-Beam

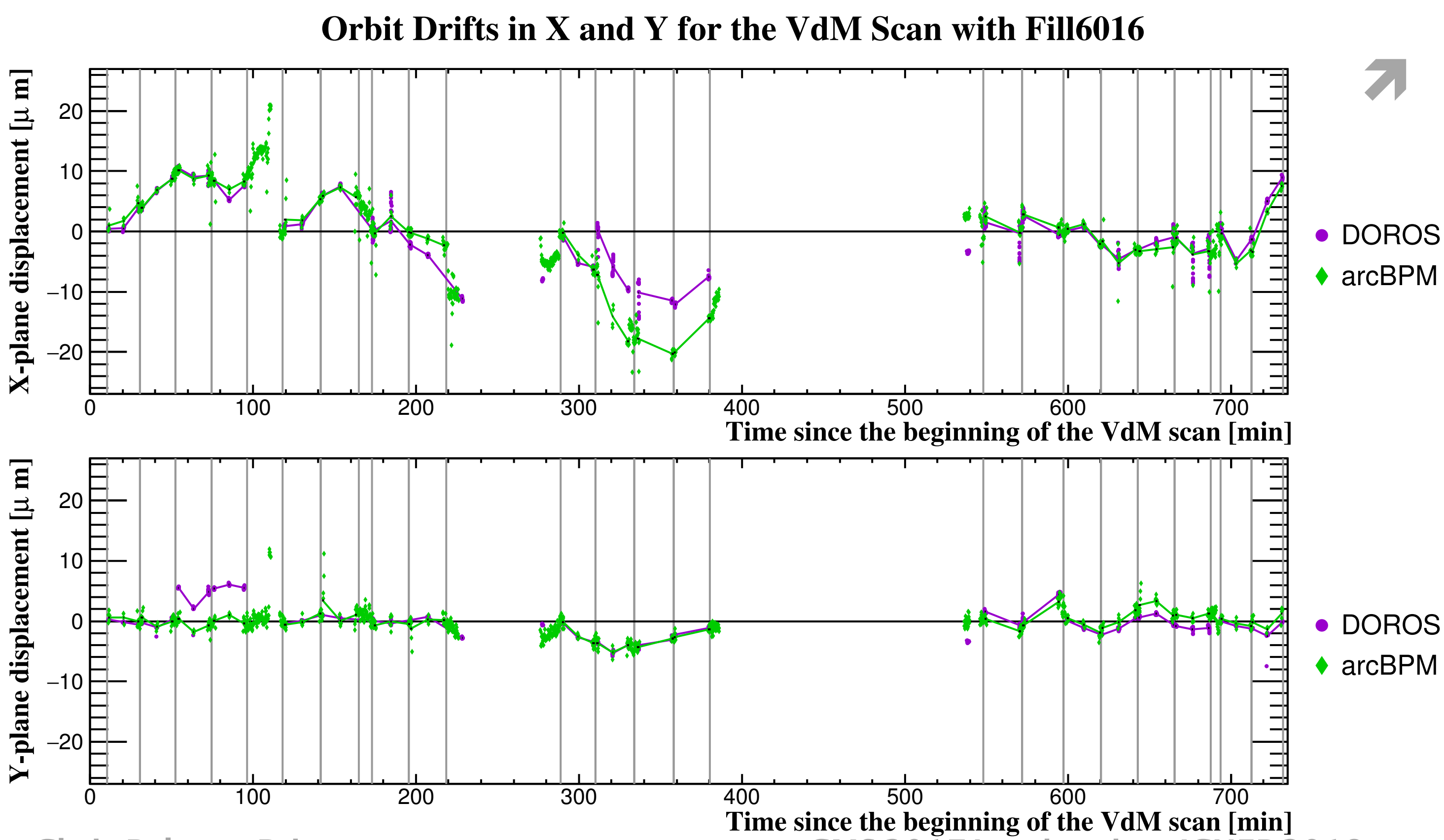
- Electromagnetic charges push beams apart (BB-deflection).
  - A correction derived analytically from classical EM.
  - The correction is proportional to β*.
  - β* uncertainty of 20% is assumed.
  - Correction = 1.6 ± 0.4%
- The bunch shape itself is morphed by the EM field produced by the passing bunch.
  - The rate is reduced because of this distortion.
  - Up to 0.5% bias is estimated using model from MAD-X simulation.
  - Bias is uncorrected and taken as uncertainty.



# Calibration Systematic: Orbit Drift

- Two alternative sources of beam positions considered for estimating drift in nominal beam positions.
- The difference between nominal and alternative positions just before (after) the scan and at the head-on value in the scan are used to derive a linear correction.




- The full (small) difference between uncorrected and corrected is taken as the uncertainty: 0.15%.

# Calibrations Consistency (1/2)

- After all corrections are applied the results are examined per scan (6 in total) and per bunch crossing.
- While most scans yielded very consistent results, the final scan deviated significantly.
- Half the fractional difference between the largest and the smallest visible cross sections was taken as a systematic uncertainty.
  - Averaged over all five of the calibrated luminometers.
  - This is 0.9%.

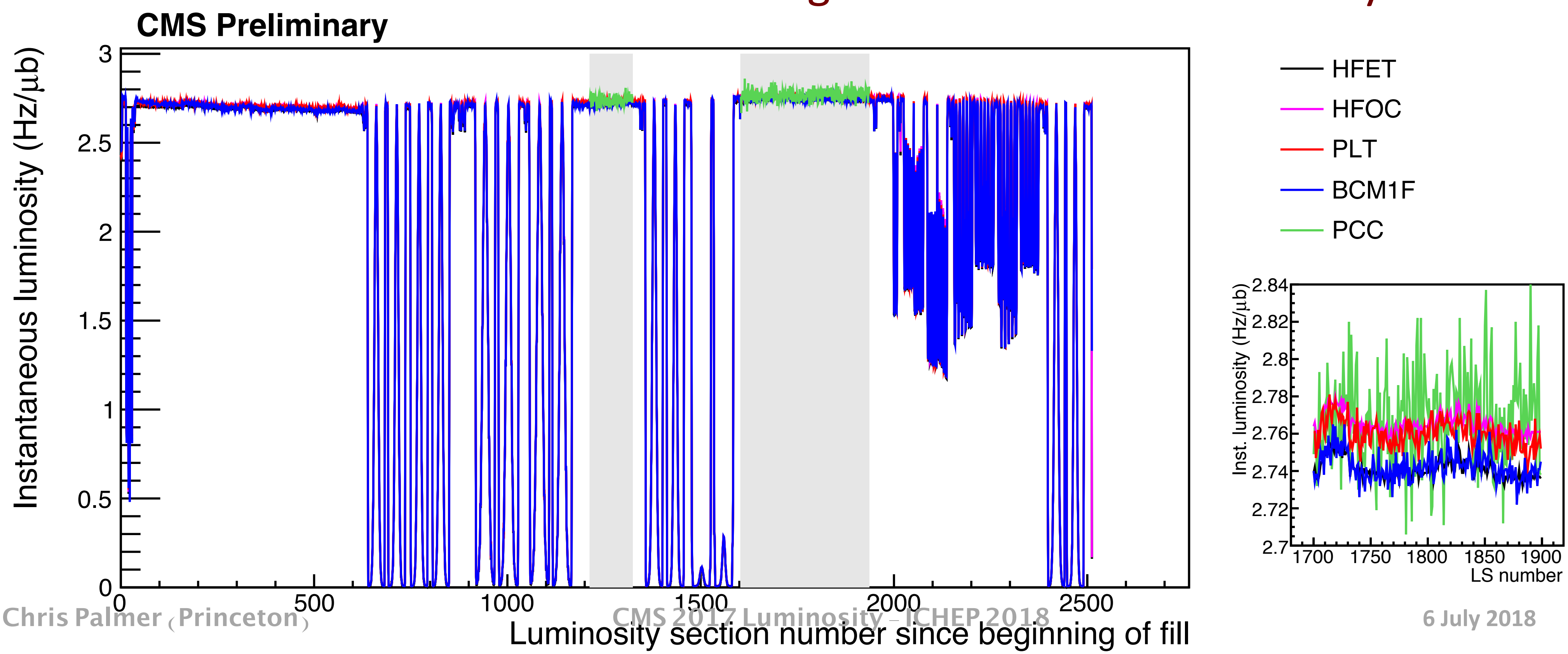
| | | | |
|---|---|---|---|
| Scan to scan variation | — | 0.9 | 1.19 |
| Bunch to bunch variation | — | 0.1 | |
| Cross-detector consistency | 0.4–0.6 | 0.6 | |

# Calibrations Consistency (2/2)

- Luminosity was measured with each luminometer in non-scanning periods of the VdM fill.
- The closure was not perfect and the average luminosity in the validation data was used to set the final scale.

| Luminometer | Difference from average |
| --- | --- |
| HFET | -0.6% |
| BCM1F | -0.4% |
| PLT | — |
| HFOC | +0.3% |
| PCC | +0.5% |

Largest difference is taken as systematic.



# Detector Stability

- There are three main sources of "instability" in luminosity measurements

1. Extrapolating from VdM program's very low PU to high PU (linearity)
2. Inaccuracy in correcting for non-luminosity sources of luminometer rate (afterglow)
3. Changing luminometer efficiency over time

- Main strategies for estimating these effects.

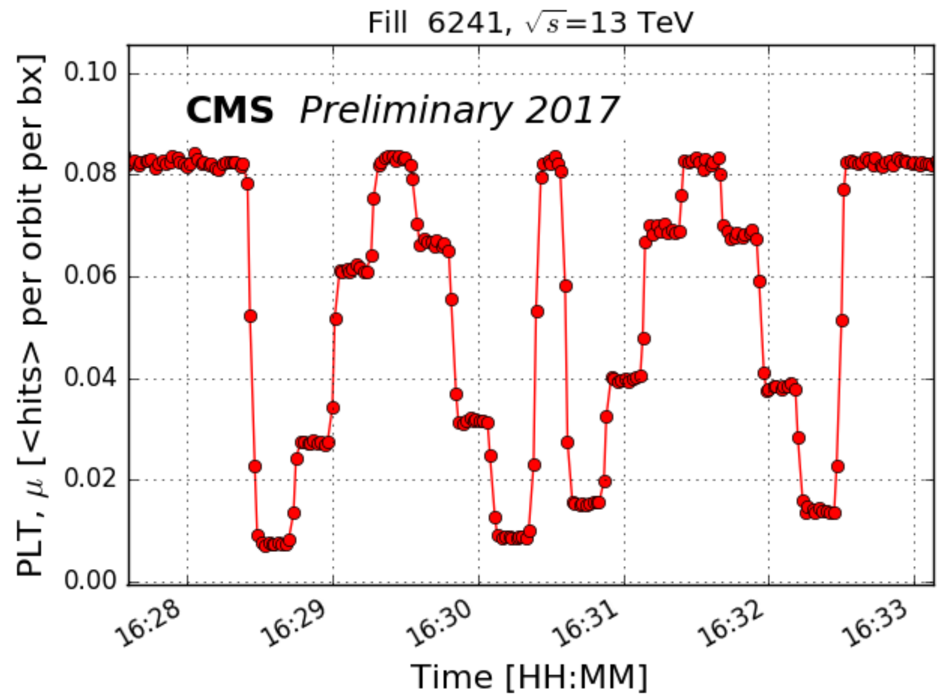
1. Comparing luminosity A to luminosity B after calibrations and all known corrections are applied in various ways and taking the differences as systematics
2. NEW! Using fast scans used by LHC to estimate bunch size (emittance) performed in each LHC fill (usually beginning and end) to study long-term trends.

| | | | |
|---|---|---|---|
| Integration | Afterglow (HF) | — | 0.2⊕0.3 |
| | Cross-detector stability | — | 0.5 |
| | Linearity | — | 1.5 |
| | CMS deadtime | — | 0.5 |

**1.7%**

# Emittance Scans

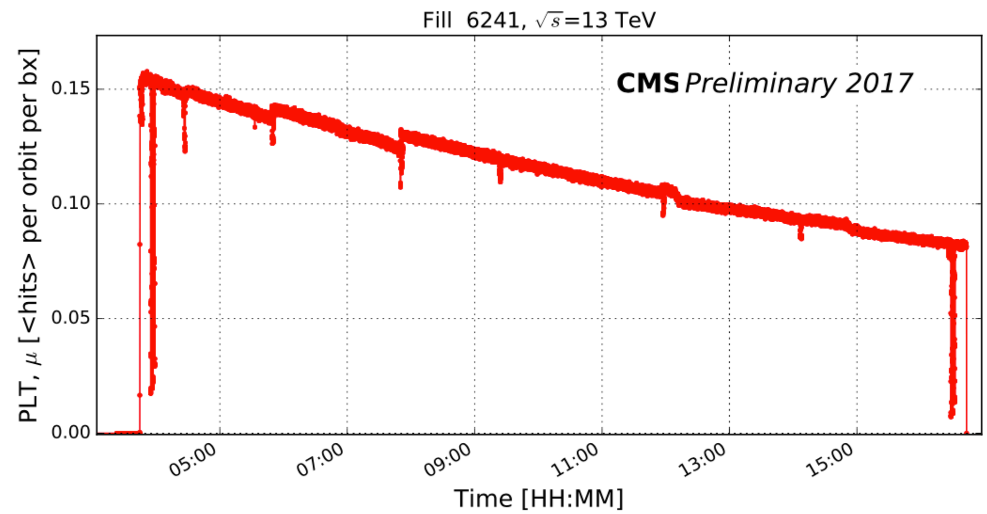
- When emittance scans are performed in vertical, horizontal pairs, they can be analyzed as VdM scans.
  - Only seven (later nine) scan points, 10 seconds per point
- The fit shapes are limited and the calibrations cannot be used for absolute calibration with VdM precision.
- However, trends over time and trends over pile-up can be observed and corrections can be verified or derived.

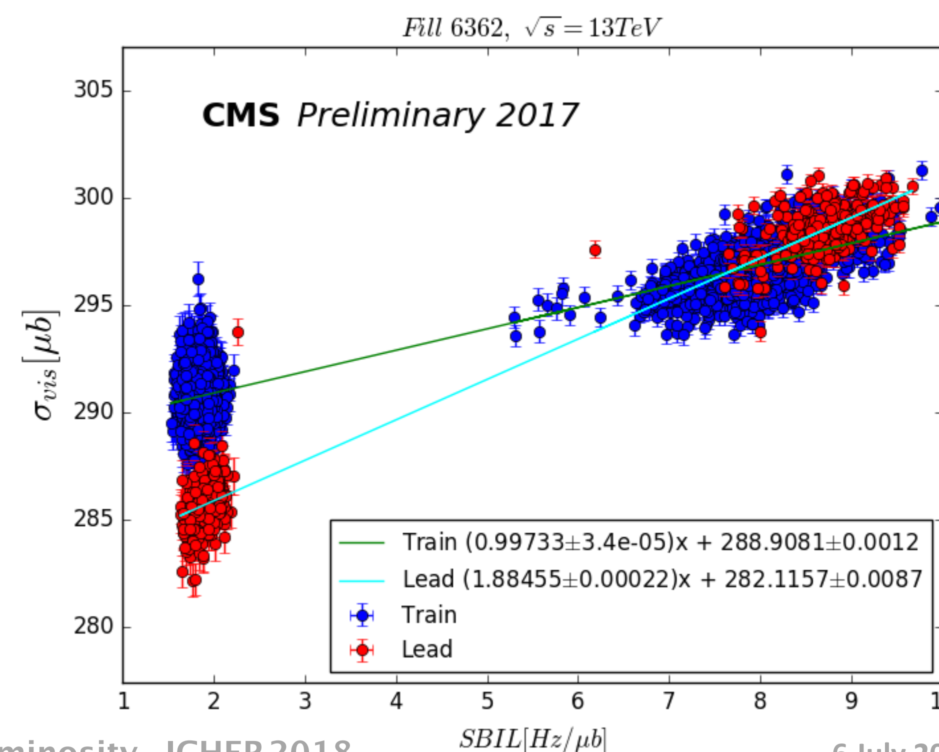



- This analysis was not performed for PCC because it requires an unreasonable bandwidth.
- Currently we are working on an alternative strategy for PCC that estimates only the peak value from the data before and after the scan.

# Extracting Linearity Corrections

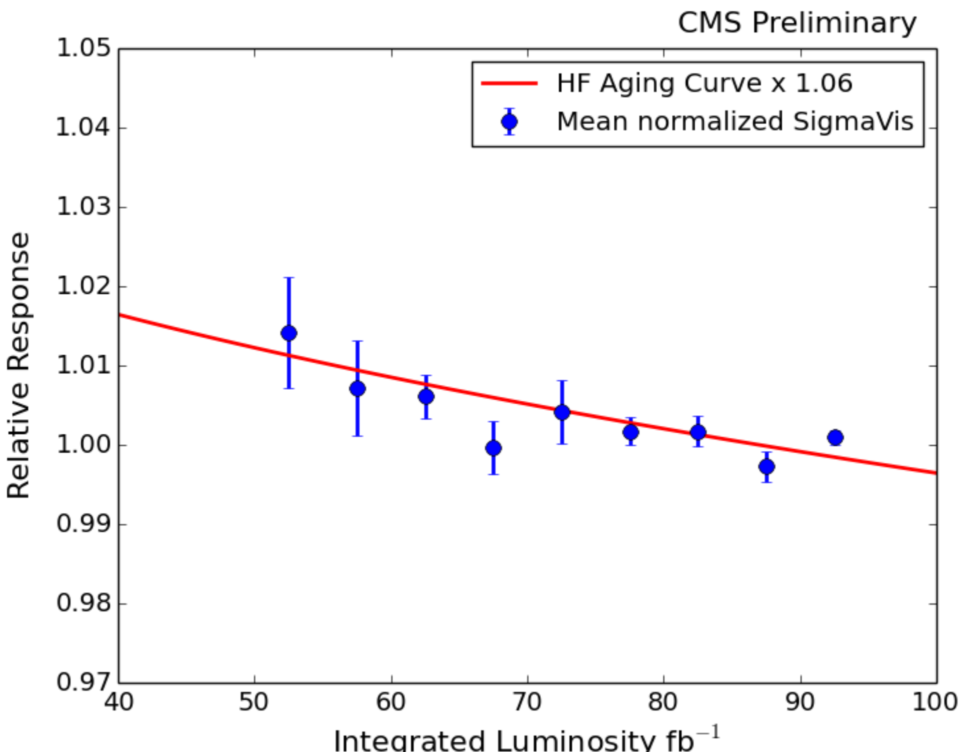
- Emittance scans at the beginning and end of fills
  - Very different PU!
- Among our first observations of this data was that the linearity of the leading bunches and other bunches in trains were different.
- For HFET (primary source) linearity estimates were performed in early data and used for the entire dataset.
  - A linear combination of leading correction and in-train corrections were derived based on bunch train length.

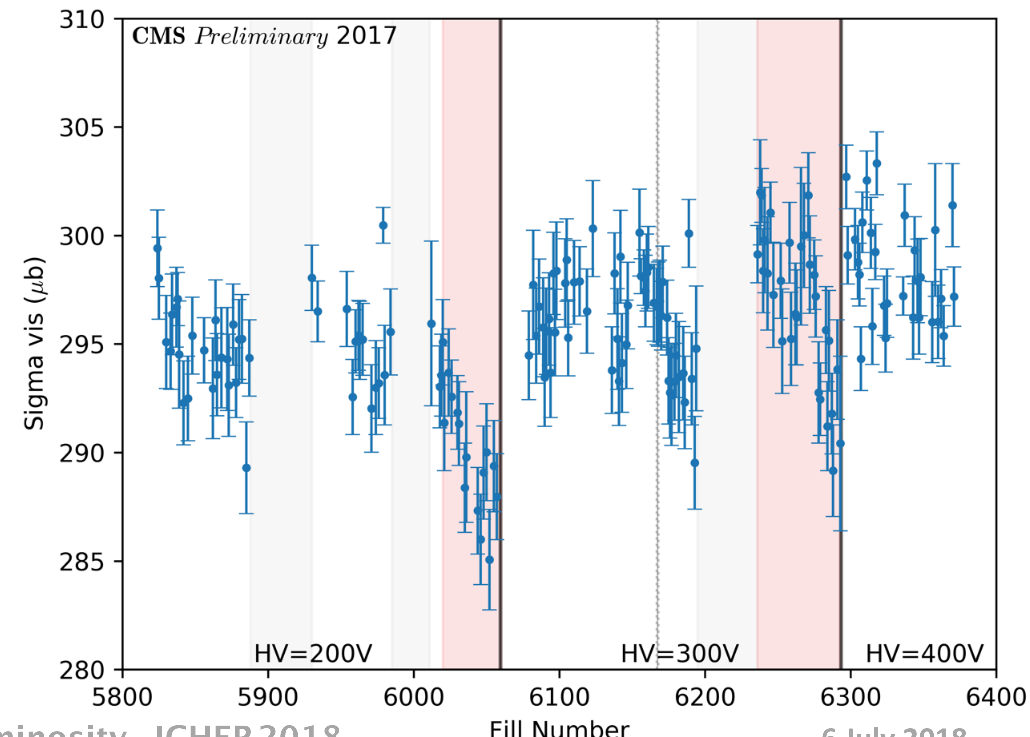


# Extracting/Estimating Efficiency

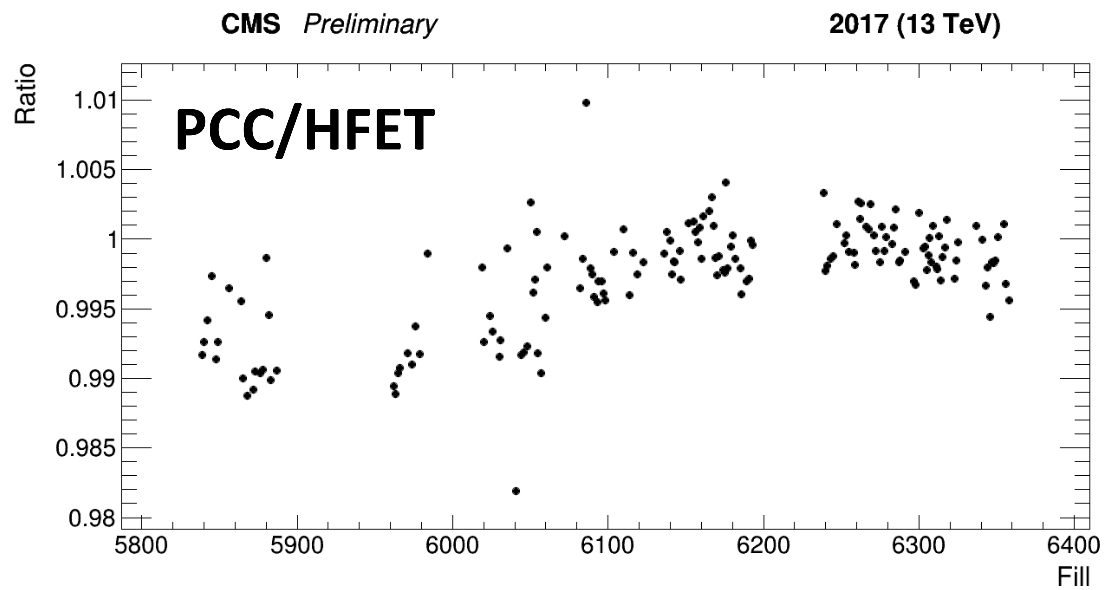
- Aging (reduced efficiency) is expected as a function of integrated luminosity for the HF.
  - The plot below shows the model in red following well the trend observed in uncorrected emittance scan sigma visible over the course of 2017.
- The PLT also experienced periods of inefficiency in 2017.
  - These data were used to derive corrections and verified that adjusted HV settings recovered the reduced efficiency.

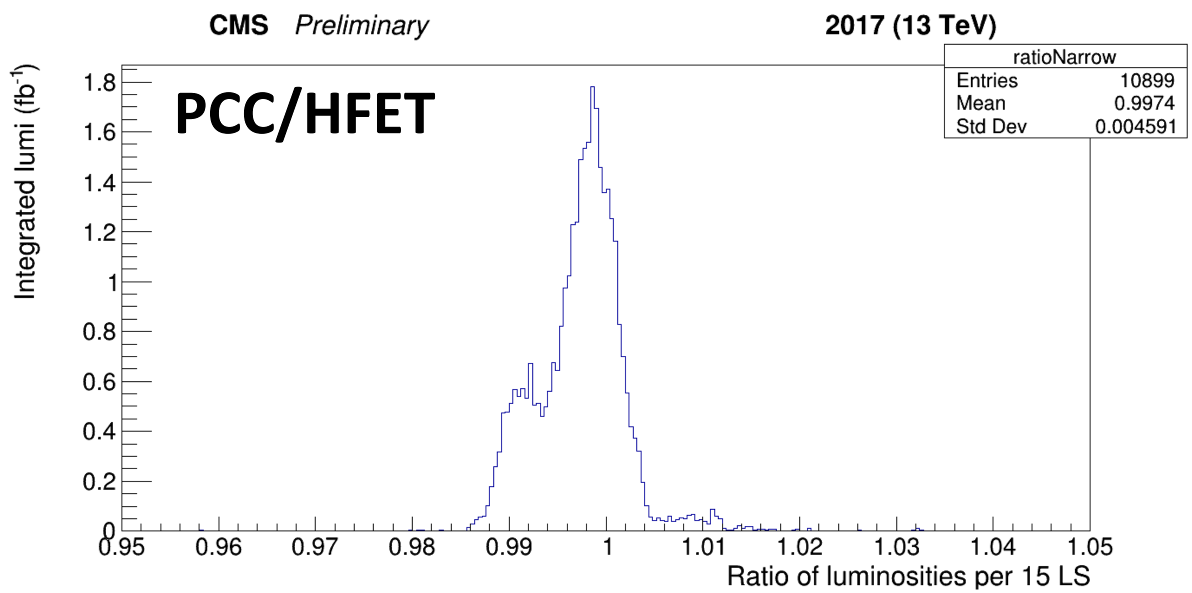


# Cross-detector comparison

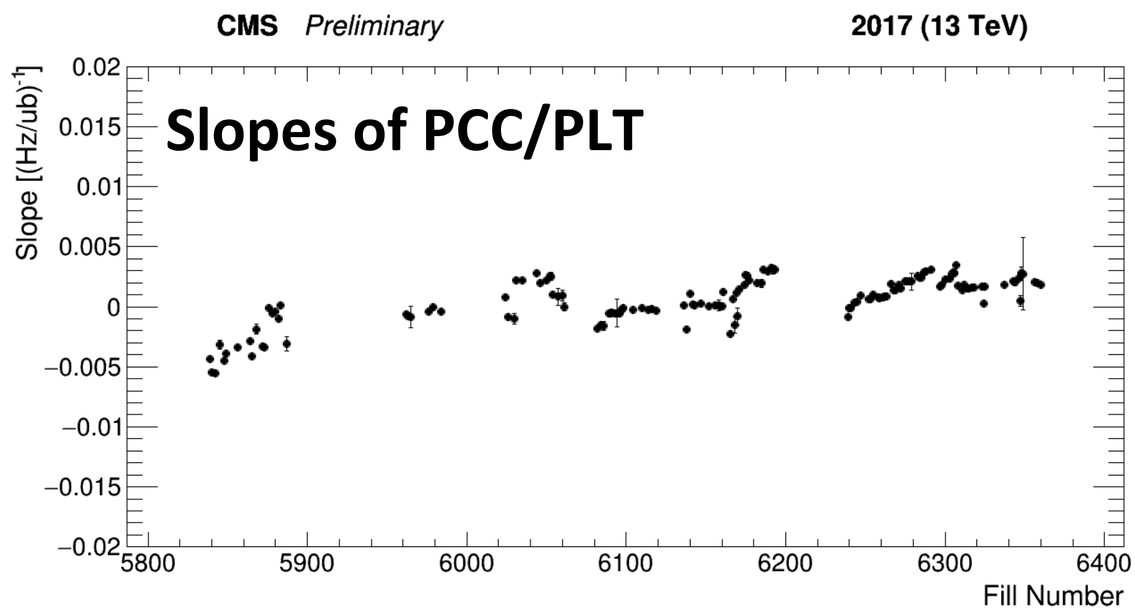
- The three best sets of luminosity data for 2017 were: HFET, PCC and PLT.
  - This hierarchy was selected because of the observed stability of the detectors.
- PCC and HFET in particular are highly correlated despite independent corrections and separate DAQ systems.
- The RMS of the ratio of PCC/HFET is taken as the stability estimate (0.5%).

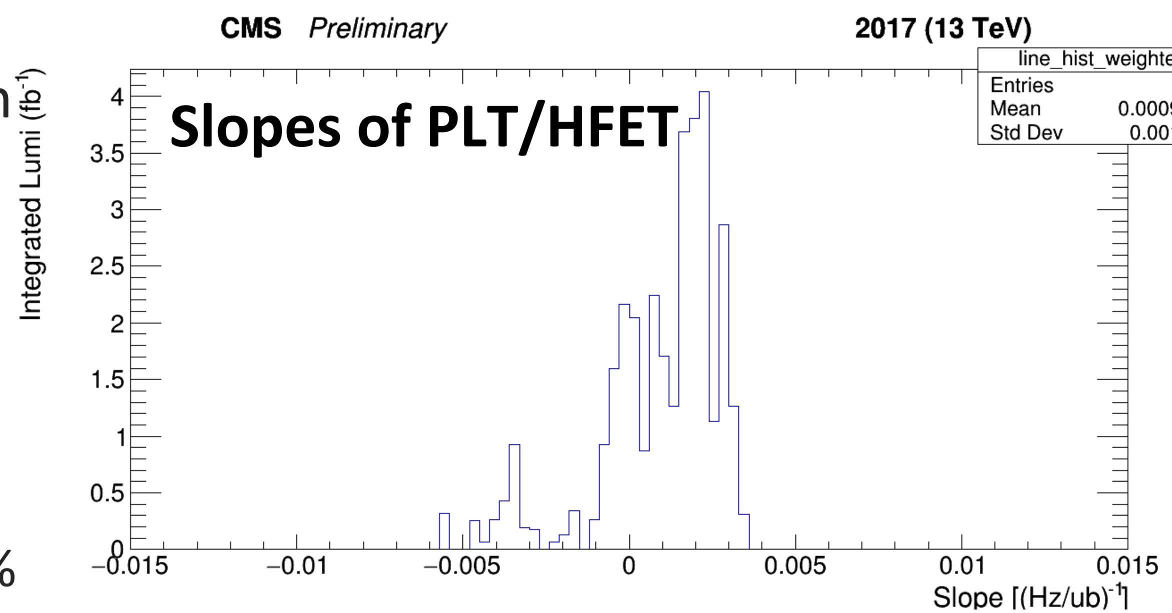


# Cross-detector linearity comparisons

- In a similar fashion relative non-linearity between two detectors can be tracked throughout 2017.
- The largest standard deviation among the slopes is 0.3%/(avg inst lumi).
- Propagating such a correction of this amount onto the data would yield a 1.5% difference in the total integrated luminosity which is taken as the systematic error due to linearity.
- Special low PU (2-3) dataset at the end of 2017 has negligible impact from linearity (0.2%).
  - Dedicated total precision: 1.7%



# Conclusions

- The first, preliminary 2017 precision of 2.3% has been described.
  - Sources almost exactly evenly divided between stability and calibration.
- Numerous systematics have been significantly reduced wrt previous results.
  - XY-correlations, orbit drift and length scale.
- First use of emittance scans as a stability monitor.
- Areas where analysis can improve:
  - Understanding some differences/variations in calibrations. (1.2%)
  - Reduce uncertainty on linearity (1.5%)
- Linearity is the big ticket item to understand as we approach HL-LHC.
  - 1.5% effect in Run 2 can easily become a 6% effect at HL-LHC (where the target is 1%).
- Detailed poster on these results at E_39

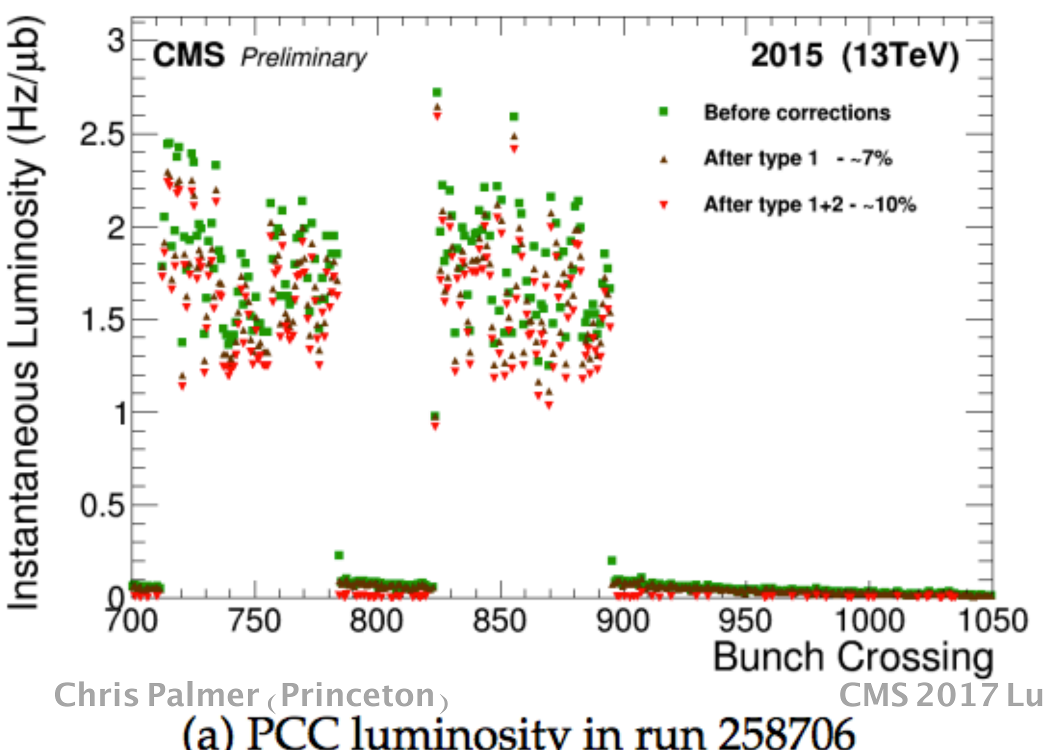
# BACKUP

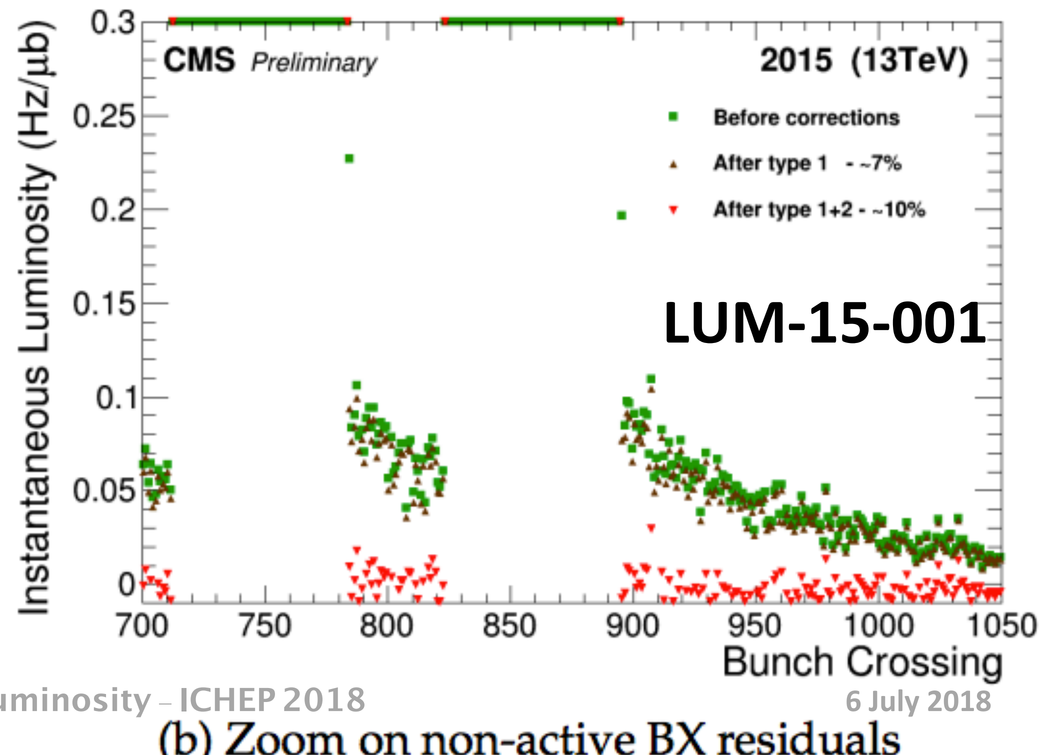
# Full Systematics Table

| | 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-$\beta^*$ | — | 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) | — | $0.2 \oplus 0.3$ |
| | Cross-detector stability | — | 0.5 |
| | Linearity | — | 1.5 |
| | CMS deadtime | — | 0.5 |
| | Total | | 2.3 |

# What is afterglow?

- Non-collision rate caused by bunch crossing N and observed in bunch crossing N+J.
- Type 1: electronic spillover
  - Mostly only in next bunch crossing
- Type 2: material activation
  - Radioactivity in or near the detectors cause real extra hits.



# Afterglow Correction Uncertainty

- For HFET, HFOC and PCC, a single bunch response model is used to correct afterglow.
  - That is, we assume that each active bunch has the same response (proportional to the luminosity of that bunch) on top of real luminosity in all following bunches.
- While all models are tuned separately per luminometer, the method for tuning and evaluating systematic error is common.
  - After corrections are made, average residual activity is computed in non-active bunches following trains.