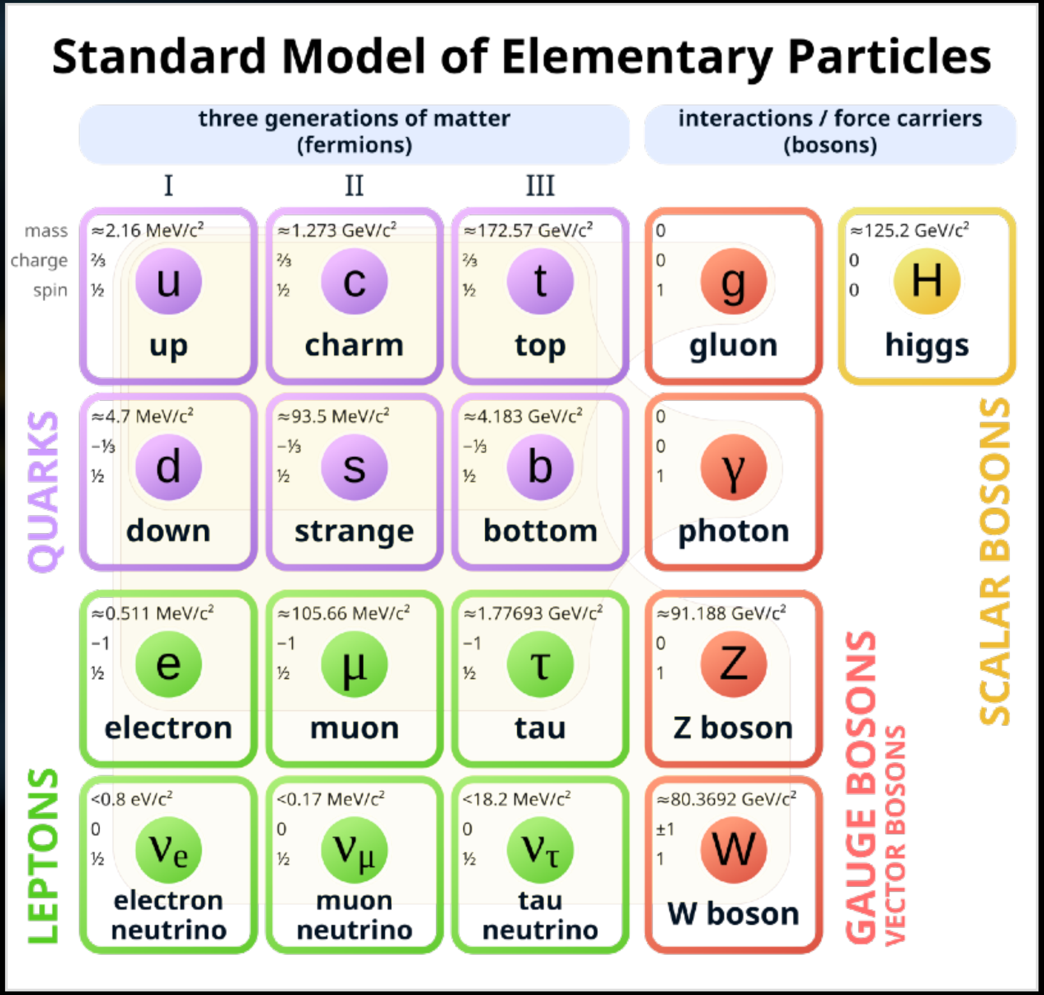
CMS's Full Run 2 Precision Luminosity Measurement

Chris Palmer
Queen Mary University London
HEP Seminar Series
October 6th, 2025

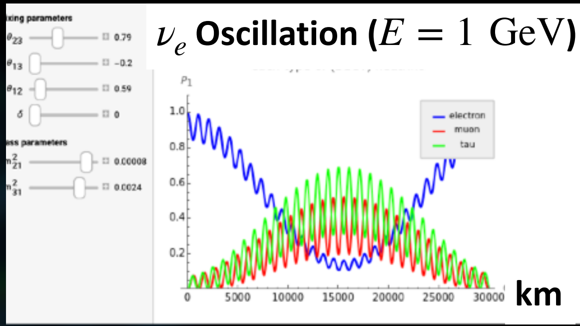
The Standard Model

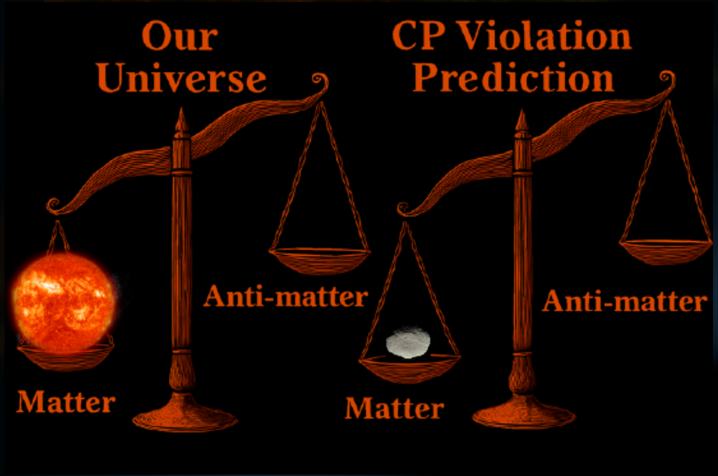
- One quantum field theory that describes the weak, strong, and electromagnetic forces.
  - Both elegant and accurate.
- All the particle predictions (particularly Z and Higgs bosons in electroweak sector) have been observed.

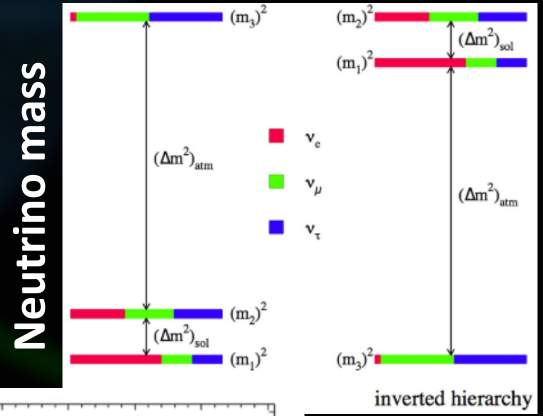


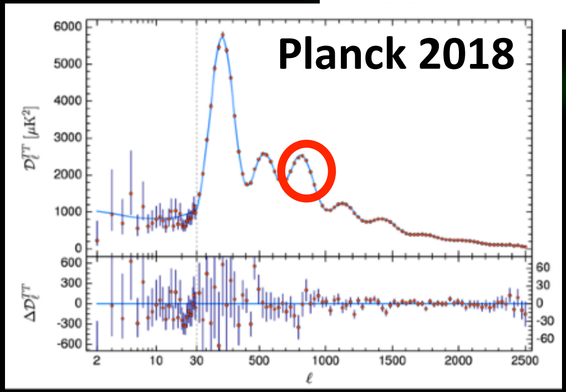
The Standard Model

- Ignores gravity.
- Lacks electroweak+strong unification.
- No dark matter particle predicted.
- Oscillation and mass of neutrinos are not predicted.
- Known CP violation is too weak to explain our matter-dominated universe.
- Accelerating expansion of the universe (dark energy)???
    - SM: “not my problem”
- Higgs hierarchy/extreme fine tuning with Planck mass.









The Standard Model

- Ignores gravity.
- Lacks electroweak+strong unification.
- No dark matter particle predicted.
- Oscillation and mass of neutrinos are not predicted.
- Known CP violation is too weak to explain our matter-dominated universe.
- Accelerating expansion of the universe (dark energy)???
  - SM: “not my problem”
- Higgs hierarchy/extreme fine tuning with Planck mass.

$$-(\delta m)^2 + m_0^2 = m_H^2$$

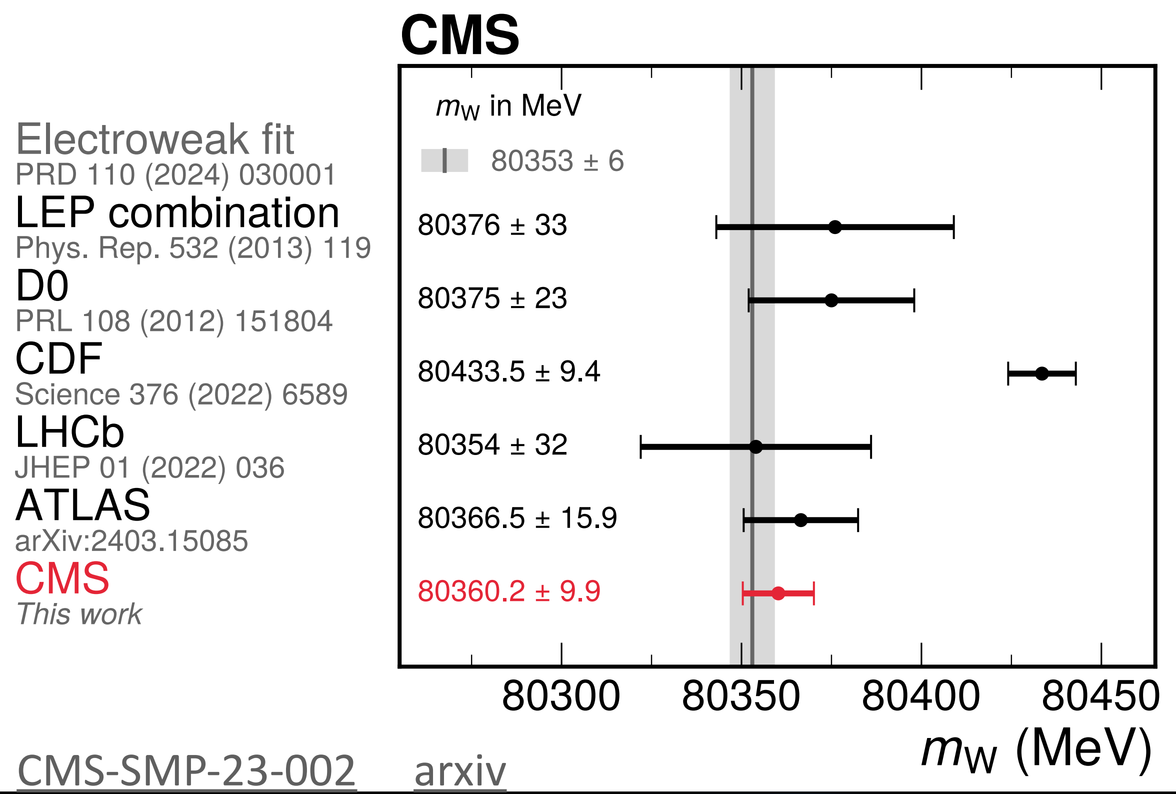
$$\delta m \sim m_{\text{Planck}} \sim 10^{19}\ \text{GeV}$$

$$-\left(10^{19}\ \text{GeV}\right)^2 + m_0^2 = \left(125\ \text{GeV}\right)^2$$

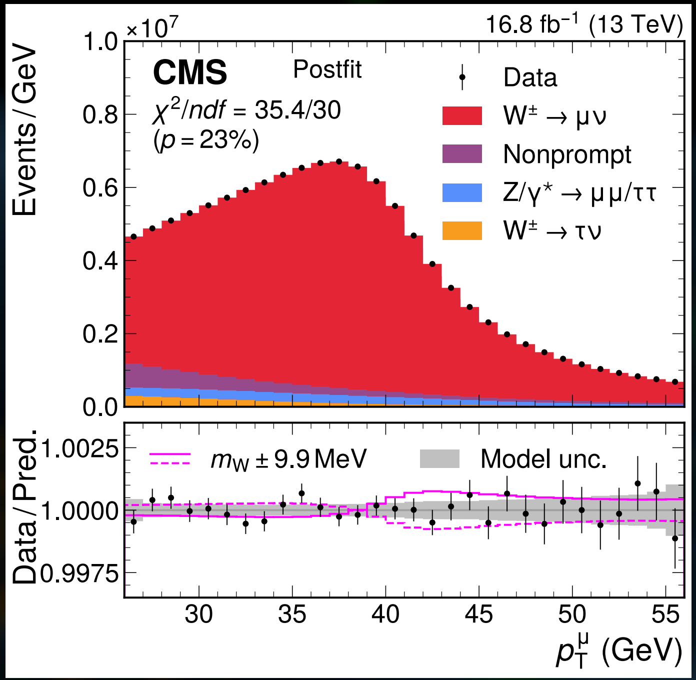
W Mass

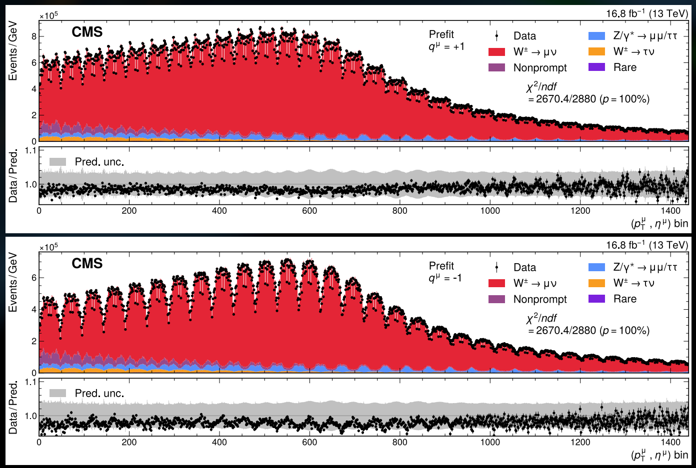
Precision in Particle Physics

- CMS' W boson mass measurement is a precise kinematic fit.
- Requires excellent simulation.



CMS-SMP-23-002 arxiv





- The electroweak fit uses other precision measurements of SM interactions and particles.
- A large deviation from the electroweak fit would be a giant hint of BSM particles.

Muon $g-2$

Precision in Particle Physics

- Muon spin precesses in a magnetic field due to its magnetic moment.
- Muons decay more often along their spin direction.
- The oscillation in positron counts tracks spin precession.

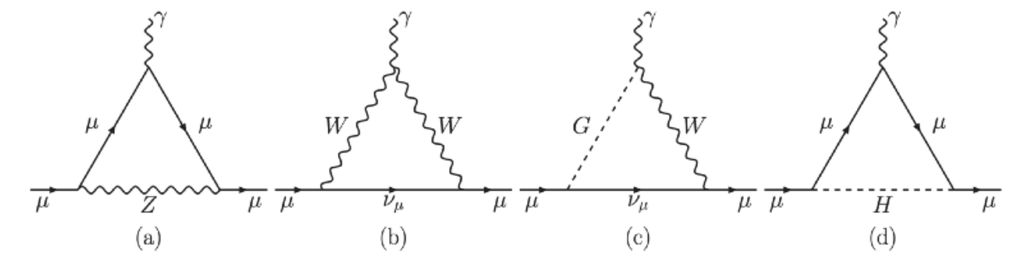


Figure 100: One-loop Feynman diagrams contributing to a_μ^{EW}.

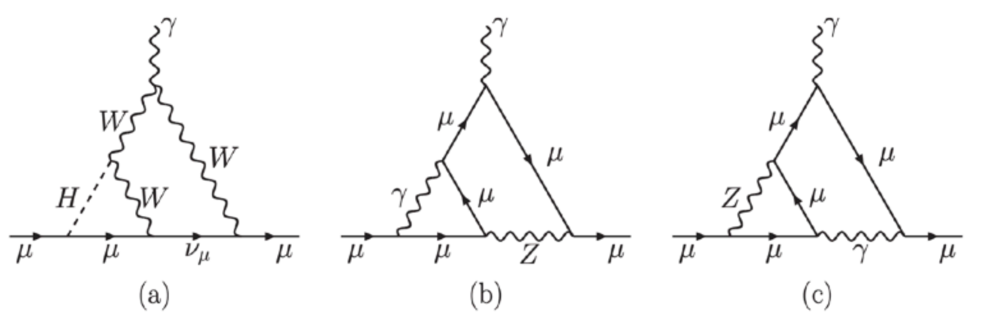
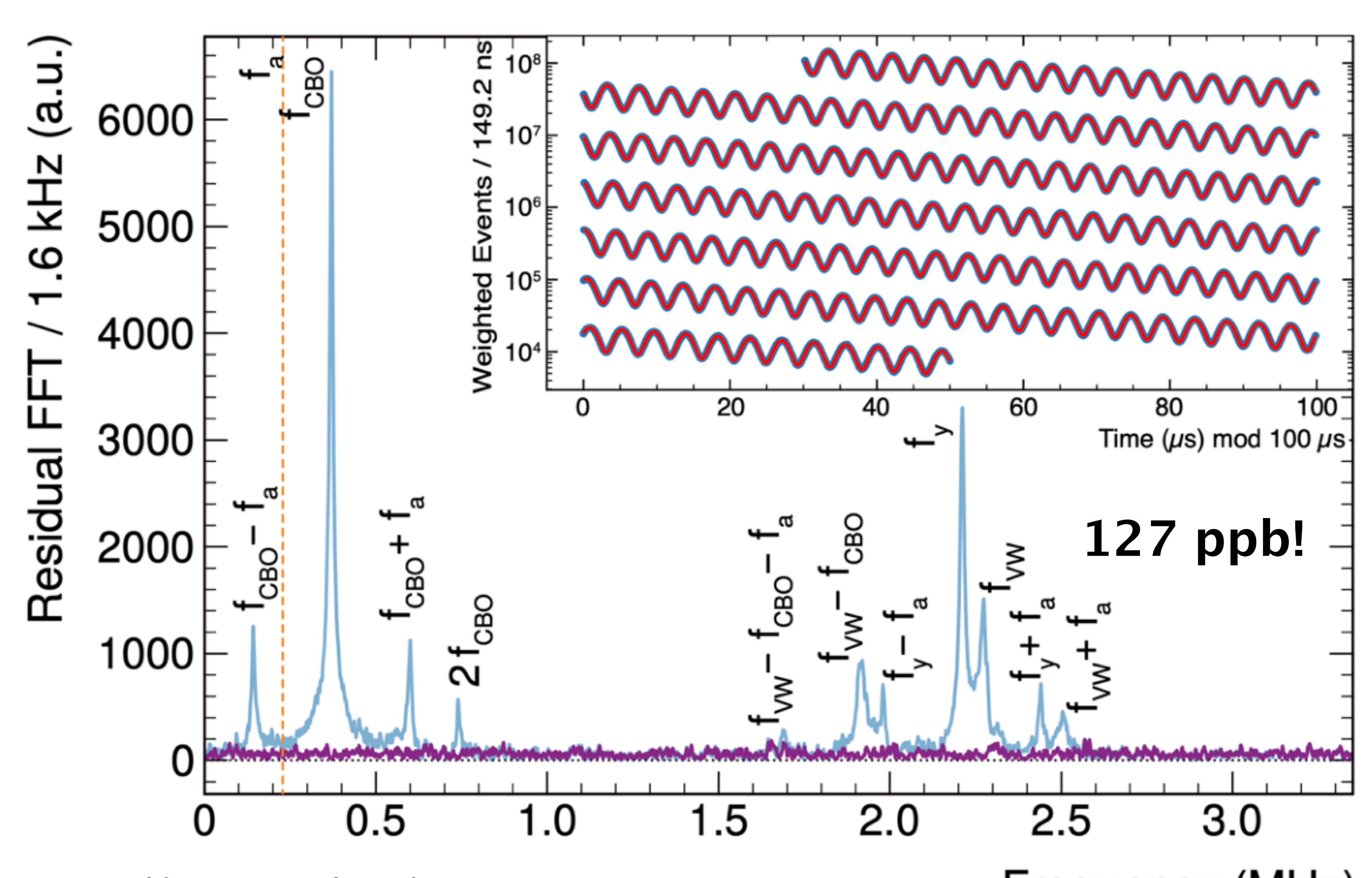


Figure 101: Sample bosonic two-loop Feynman diagrams contributing to a_μ^{EW}.

Electroweak (aka the easy ones!)



https://arxiv.org/abs/2506.03069

Phys. Rept. 887 (2020) 1-166

Muon $g-2$

Precision in Particle Physics

- Muon spin precesses in a magnetic field due to its magnetic moment.
- Muons decay more often along their spin direction.
- The oscillation in positron counts tracks spin precession.

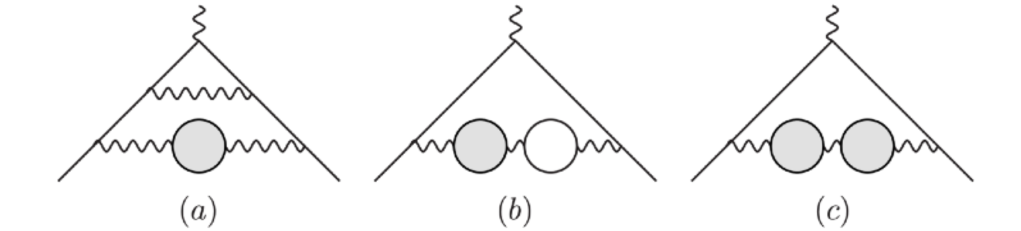


Figure 33: Higher-order insertions of HVP at NLO. The gray blobs refer to HVP, the white one in diagram (b) to leptonic VP.

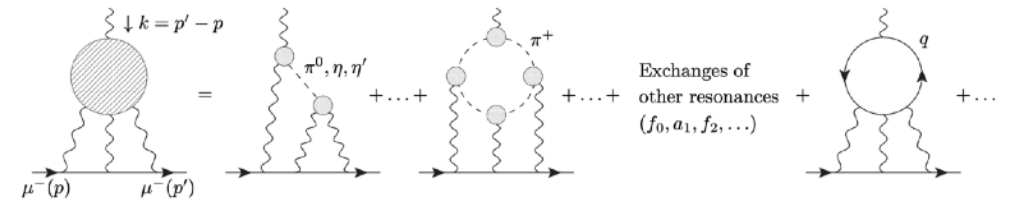
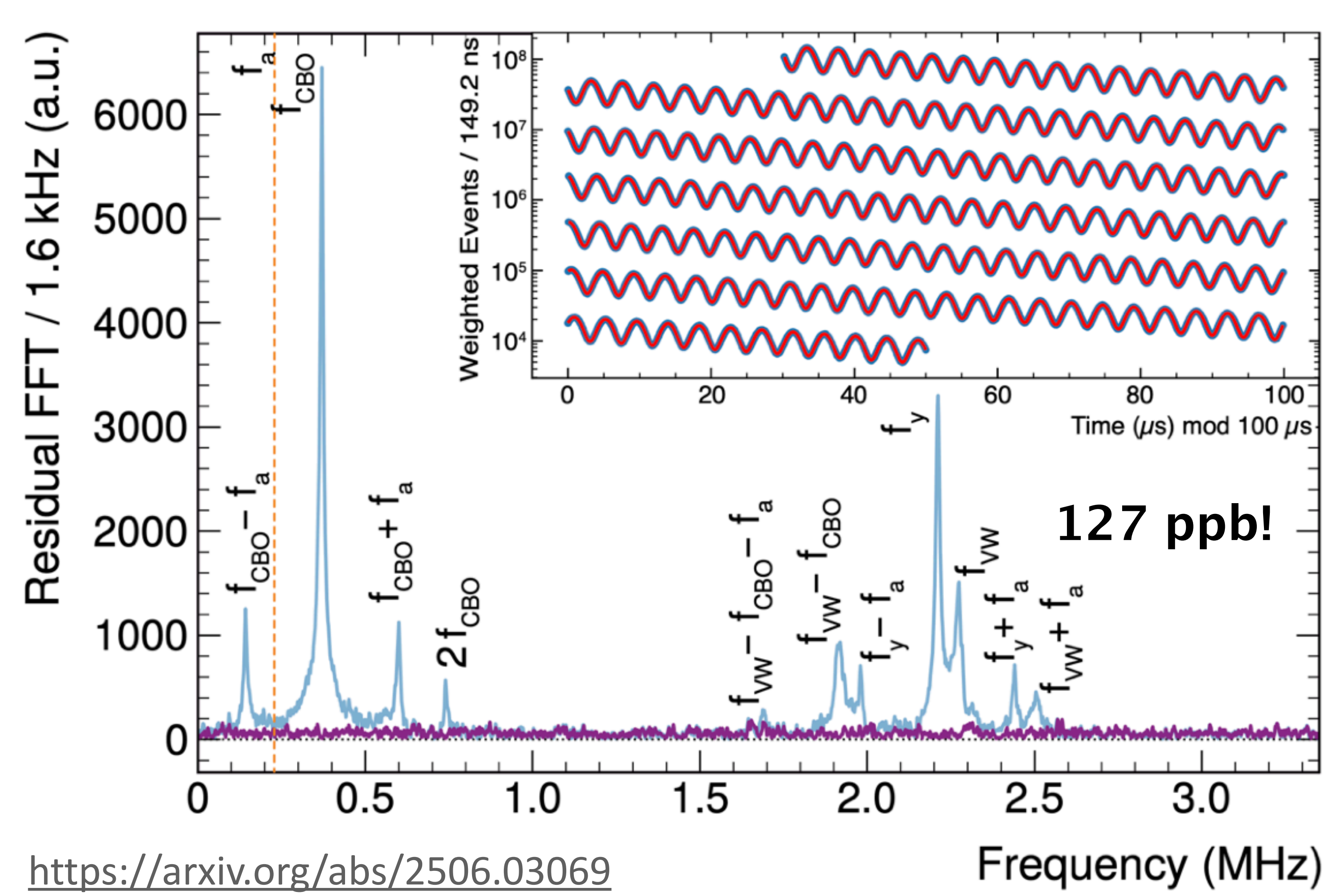


Figure 48: HLbL in the muon $g-2$ in model calculations. The blobs on the right-hand side of the equal sign are form factors that describe the interaction of photons with hadrons. Adapted from Ref. [471].

Hadron-photon interactions (or calculations that give me nightmares)



https://arxiv.org/abs/2506.03069

Measuring and using luminosity

- Computing event yield (and MC weighting):

$$N_{\text{expected},pp\to X} = \sigma_{pp\to X}\mathscr{L}_{\text{int}}$$

- Instantaneous luminosity: measure of collision rate
  - $R(t)$ measured (and $\mathscr{L}(t)$ inferred) continuously and in real time.
  - Needed by CMS and LHC control rooms to ensure continuous data-taking.

$$\mathscr{L}(t) = \frac{1}{\sigma_{vis}}R(t)$$

- Integrated luminosity: computed in the same way as instantaneous with integration of the rate.

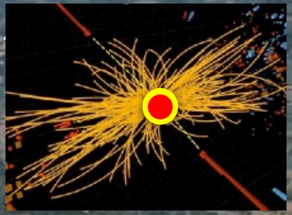
$$\mathscr{L}_{\text{int}} := \int \mathscr{L}(t)\,dt = \frac{1}{\sigma_{\text{vis}}}\int R(t)\,dt$$

- Critical component of cross section measurements.

$$\sigma_{pp\to X} = \frac{N_{\text{measured}}}{\mathscr{L}_{\text{int}}}$$

Large Hadron Collider (LHC)

CMS



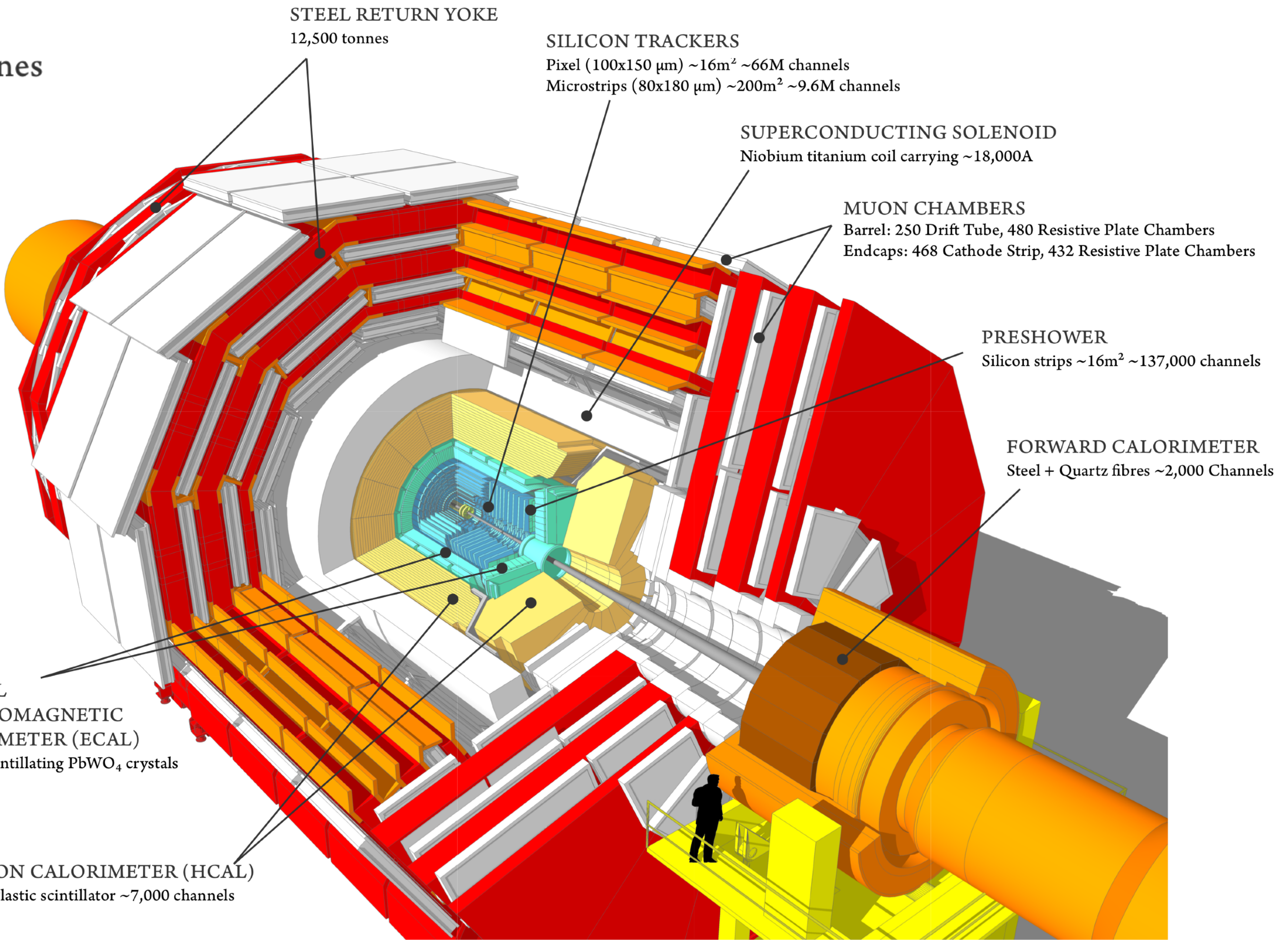
- Proton beams circulate 11,245 times/sec
- 100’s of billions of protons per proton bunches
  - Colliding only about ~60 per crossing in Run 3
- Collisions are a billion times hotter than the center of the sun and create new particles ($E = mc^2$)

CERN

Photo credit: Lucas Taylor, 2012

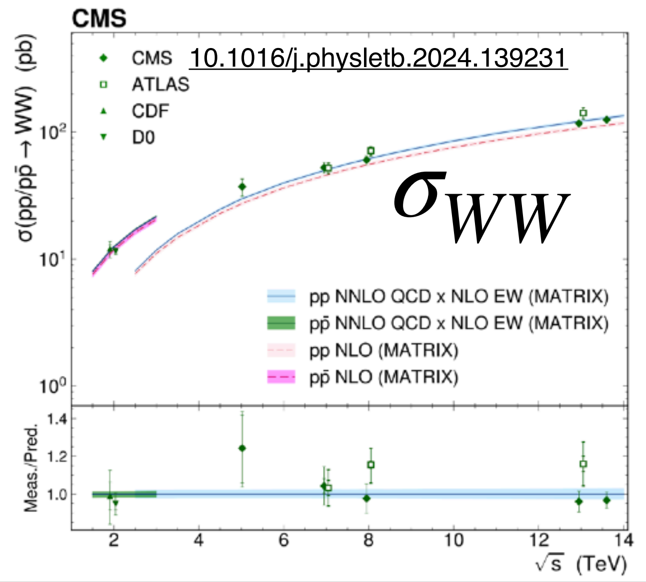
CMS DETECTOR

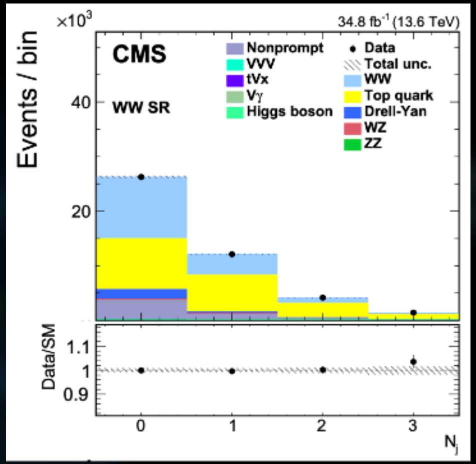
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



Why luminosity matters now!

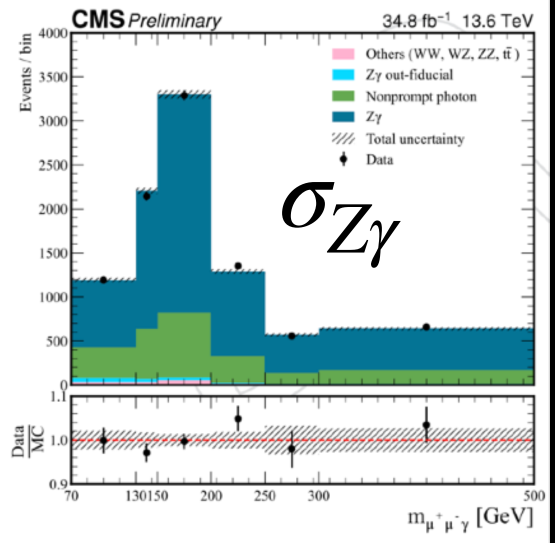
- A new era of precision measurement opportunities are opening up at the LHC.
- CMS has collected over $400\ fb^{-1}$ of pp collision data.
- Luminosity uncertainty is often one of the leading systematic uncertainties in precision cross-section measurements.
  - Typically in lepton/photon final states!
- Precision can also aid searches where better modeling of large-cross-section backgrounds are important.





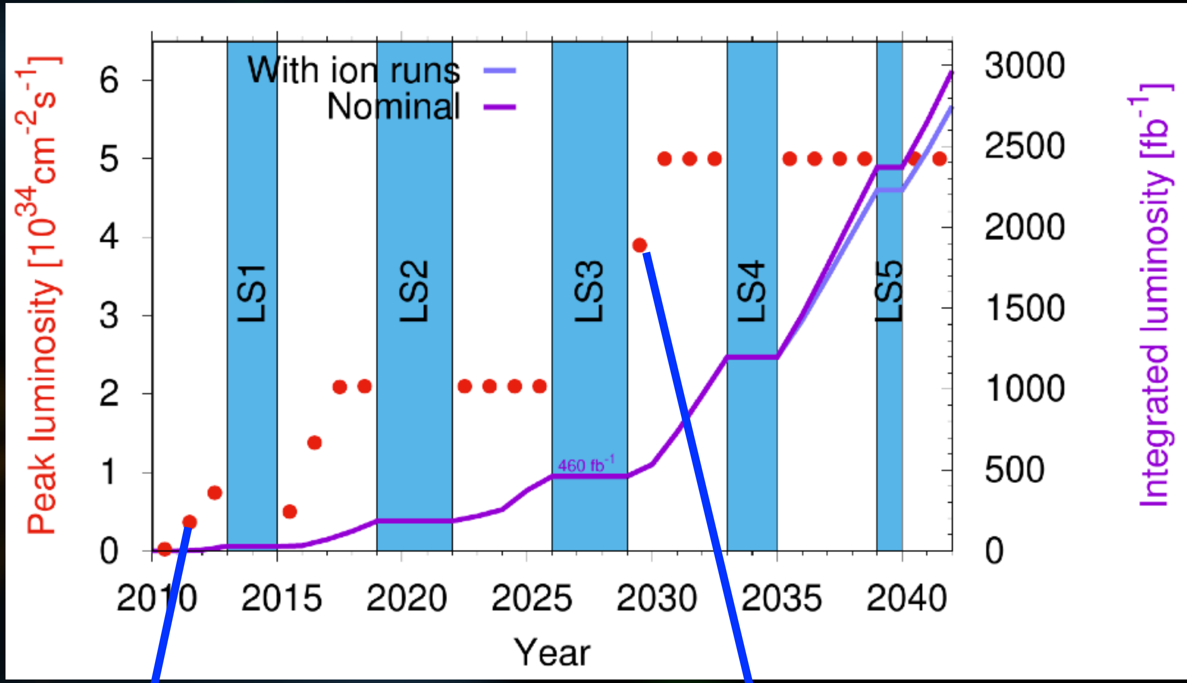
Uncertainty source	$\Delta\mu$
Integrated luminosity	0.014
Lepton experimental	0.019
Jet experimental	0.008
b tagging	0.012
Nonprompt background	0.010
Limited sample size	0.017
Background normalization	0.018
Theory	0.011
Statistical	0.018
Total	0.044

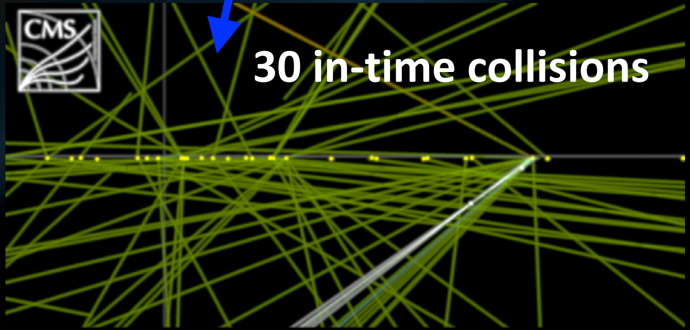
SMP-24-002

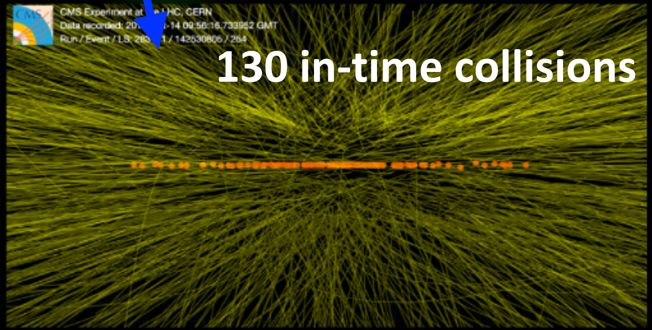


Why luminosity matters at HL-LHC!

- At High Luminosity LHC, the in-time collision rate will be 3-4 times larger.
- HL-LHC physics goals:
  - Precision Higgs boson coupling measurements.
  - Measurements of two boson final states (e.g., WZ, WW) to search for anomalous couplings.
  - Top physics: mass, couplings, and rare decays.
- Luminosity target for HL-LHC: ~1%.

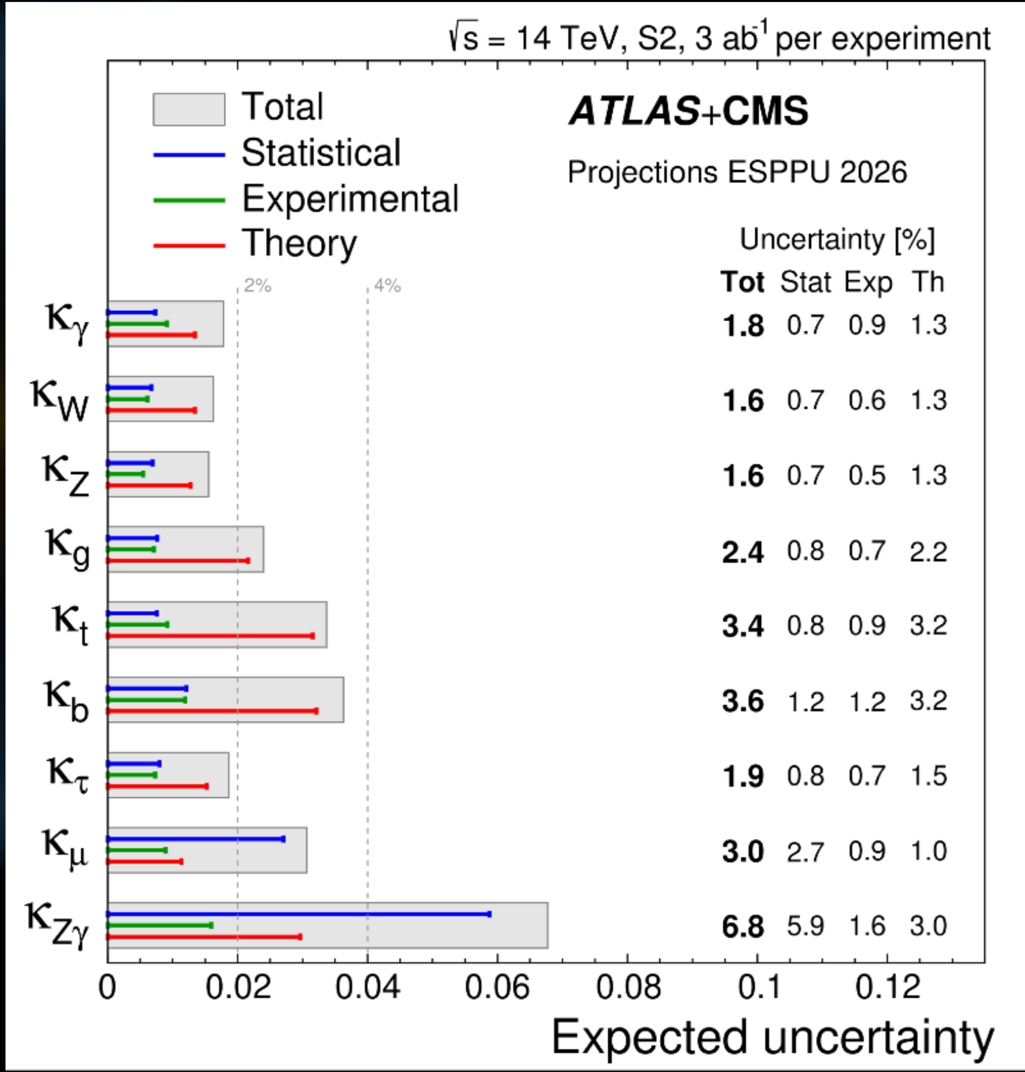






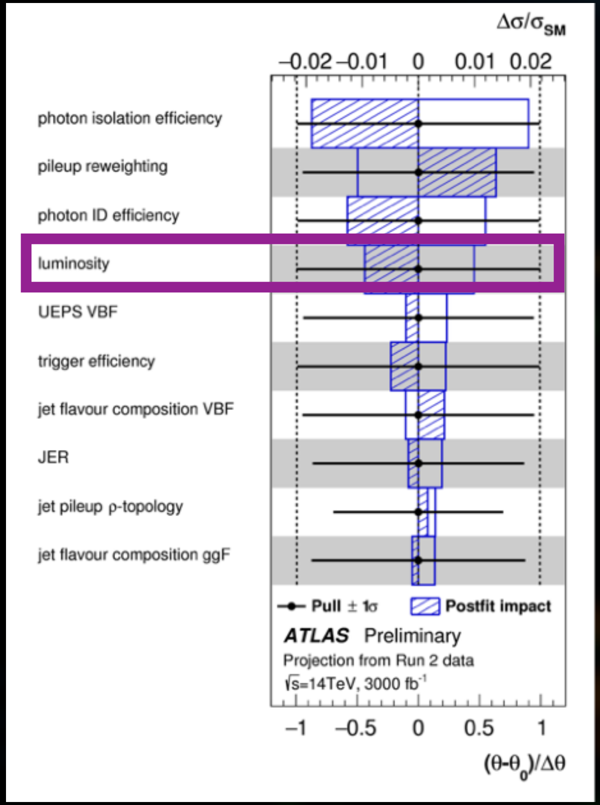
Why luminosity matters at HL-LHC!

- At High Luminosity LHC, the in-time collision rate will be 3-4 times larger.
- HL-LHC physics goals:
  - Precision Higgs boson coupling measurements.
  - Measurements of two boson final states (e.g., WZ, WW) to search for anomalous couplings.
  - Top physics: mass, couplings, and rare decays.
- Luminosity target for HL-LHC: ~1%.

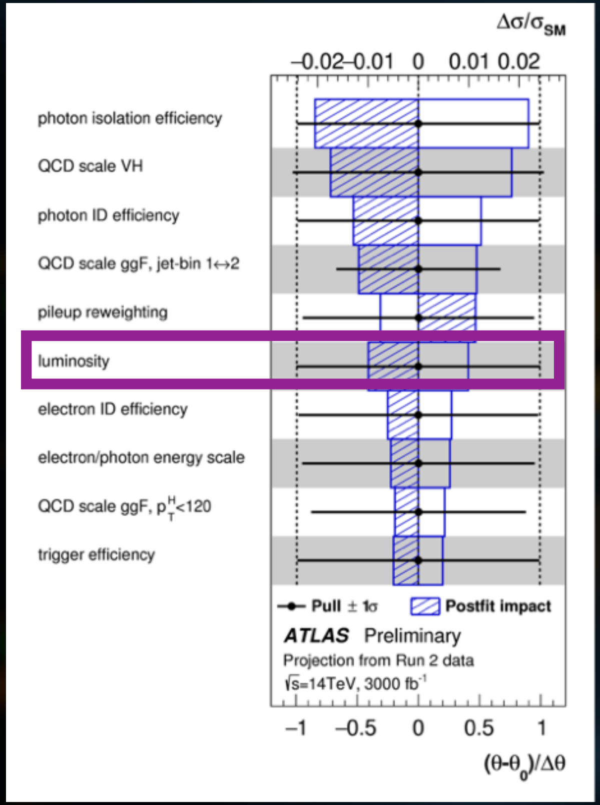


HL-LHC Higgs Physics

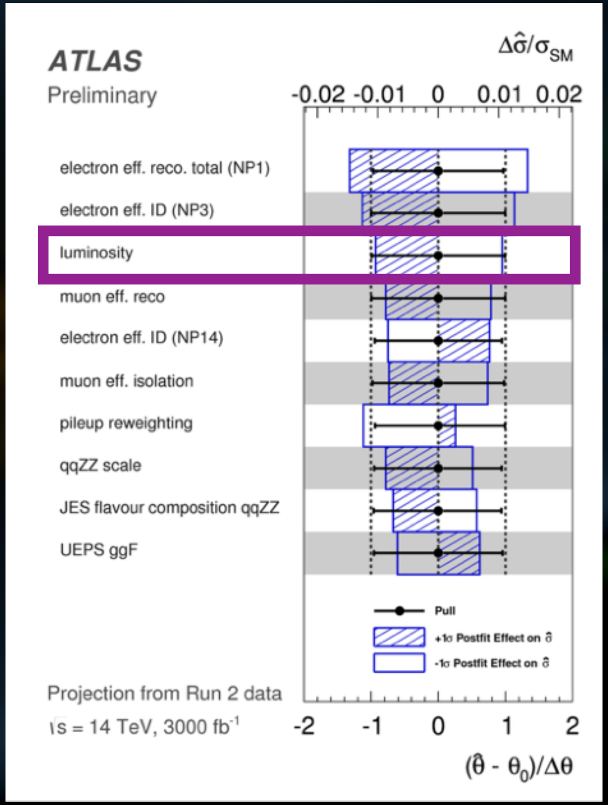
- ATLAS systematic impacts in HL-LHC projections



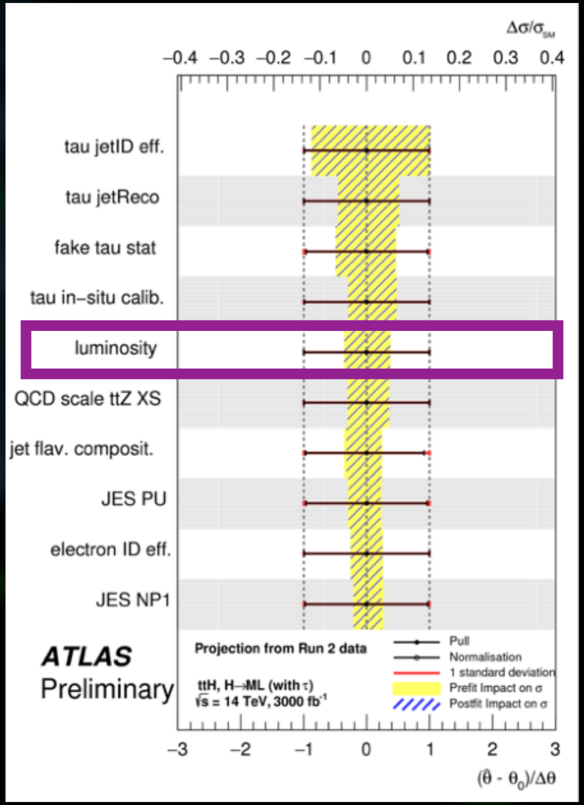
$ggF, H \to \gamma\gamma$



$VH, H \to \gamma\gamma$



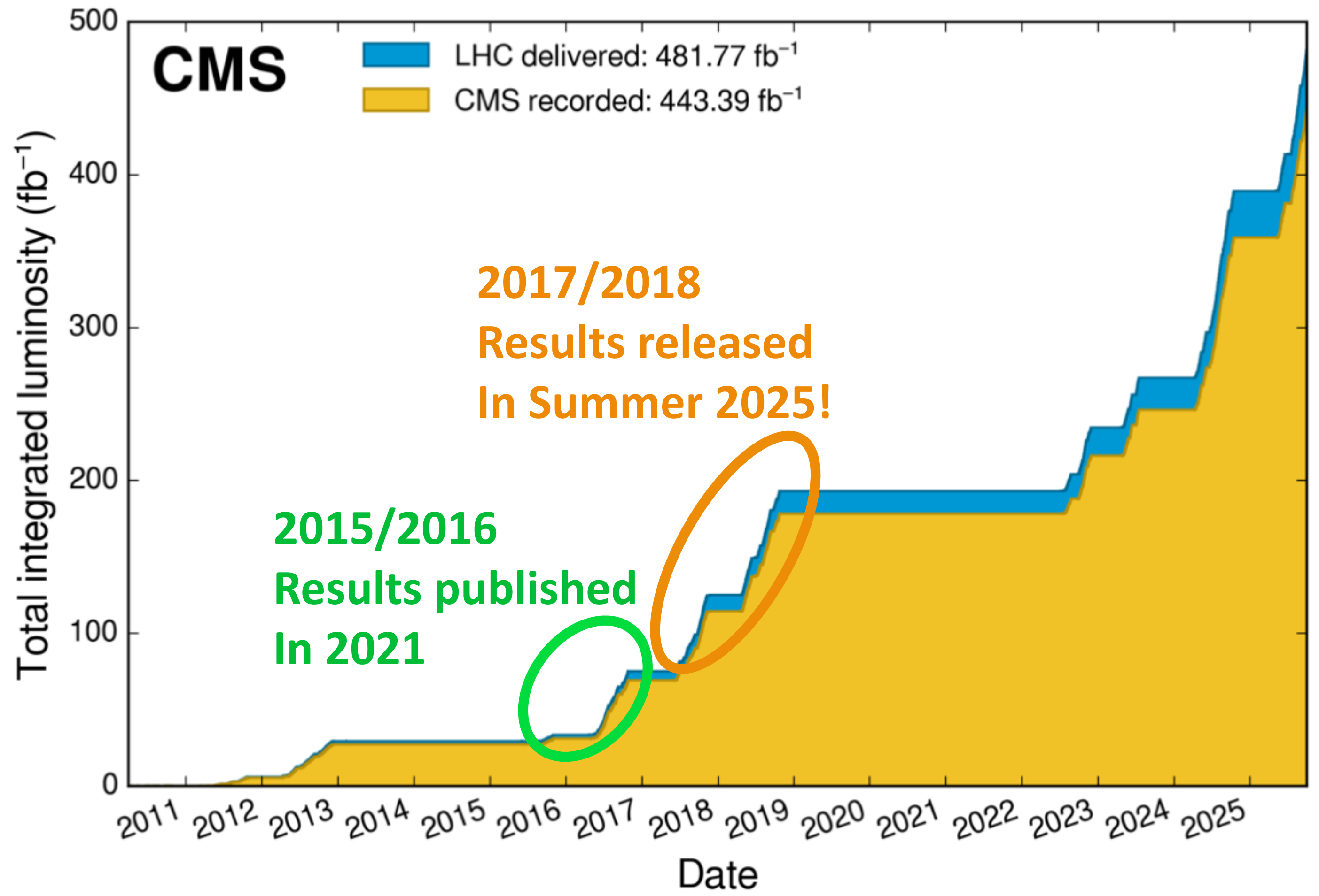
$ggF, H \to ZZ \to 4\ell$



$ttH, H \to$ multi leptons

Overview

- LHC has delivered impressive, historic datasets.
    - Thank you!
- CMS Run 2, pp, 13 TeV NEW
    - 2017/2018/Run 2 update
    - Full talk dedicated to these results



Why is this hard?

- These measurements have two main areas of uncertainty:
  - Calibration (via van der Meer scans)
  - Luminometer stability, linearity
- The precision in luminosity measurements at the LHC has tended to be in the 1-4% range, with a couple of sub-percent measurements.
  - LHCb, 1.16% for Run 1; ATLAS, 0.83% for Run 2.
- The precision achieved in the luminosity measurement for the CMS Run 2 proton-proton data (0.73%) is the lowest achieved yet at any bunched hadron colliders reached to date.

Final 2016 Results $\mathcal{L}_{\text{int}} = \frac{1}{\sigma_{\text{vis}}} \int R dt$

- The reanalysis of this data halved the precision (2.5%->1.2%).
  - Released in 2021.
  - A lengthy saga about beam-beam effects distorting the beams' shapes delayed the results about a year.
- Diligent work has continued in the meantime, so the precision of the reanalysis of 2017 and 2018 data is even better!

Source	2015 [%]	2016 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.5	0.2	No
Integration uncertainty			
Out-of-time pileup corrections			
Type 1 corrections	0.3	0.3	Yes
Type 2 corrections	0.1	0.3	Yes
Detector performance			
Cross-detector stability	0.6	0.5	No
Linearity	0.5	0.3	Yes
Data acquisition			
CMS deadtime	0.5	<0.1	No
Total normalization uncertainty	1.2	1.0	—
Total integration uncertainty	1.0	0.7	—
Total uncertainty	1.6	1.2	—

1.0% σ_{vis}

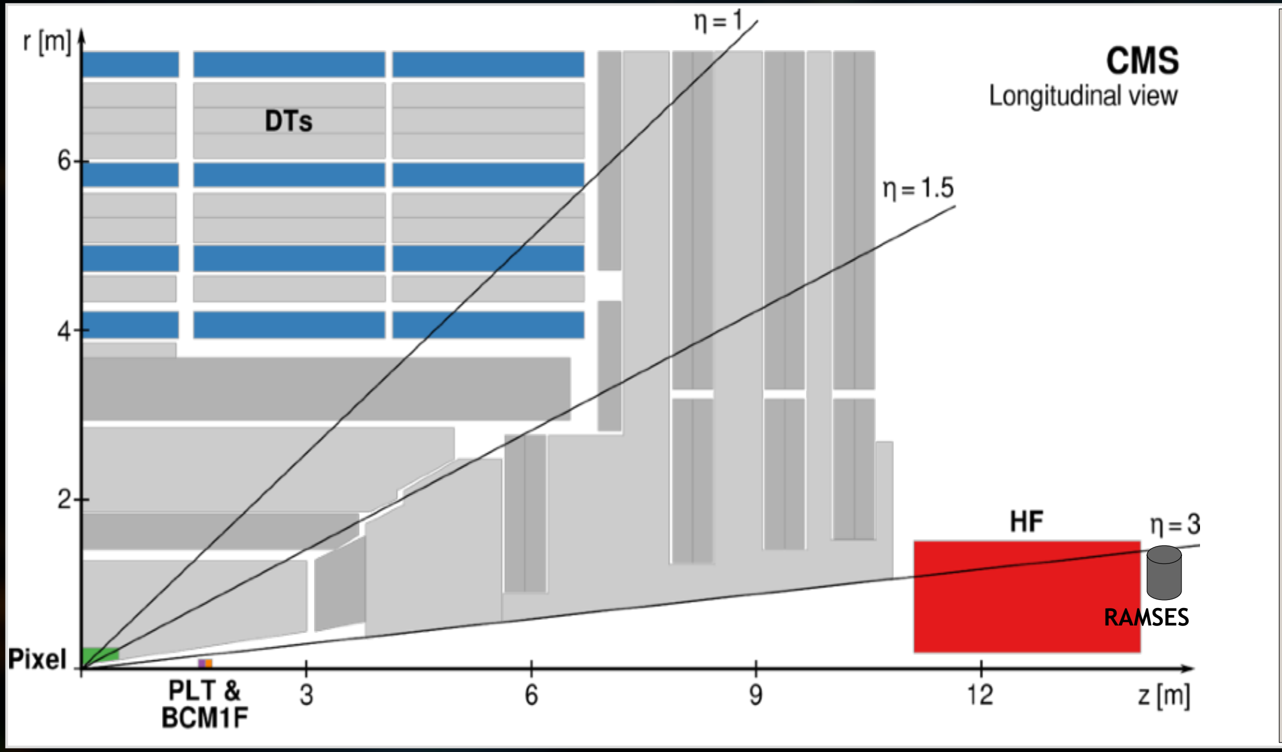
0.7% $\int R dt$

arXiv:2104.01927

LUM-17-003

How CMS measures luminosity

- Pixel detector using cluster counting (PCC)
- Hadron forward calorimeter using towers above threshold counting: occupancy method (HFOC) AND transverse energy sum (HFET)
- Pixel luminosity telescope (PLT) and Beam Condition Monitor "fast" (BCM1F) are standalone luminometers measuring triple-coincidences and hit rates, respectively.
- Muon drift tube (DT) is a counter of trigger objects.
- Radiation Monitoring System for the Environment and Safety (RAMSES) measures radiation from ionization chambers near CMS.



Rate-scaling: PCC, HFET, DT, RAMSES

Zero-counting: HFOC, PLT, BCM1F

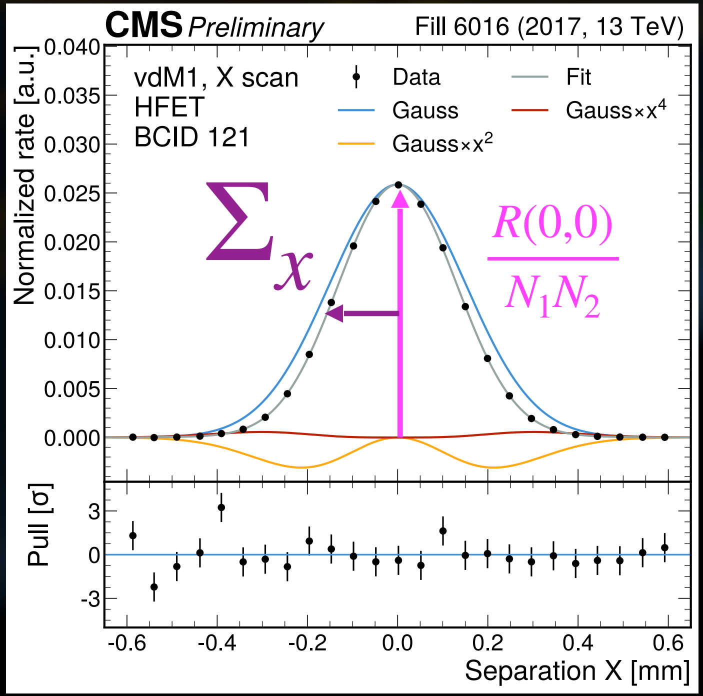
arXiv:2104.01927
LUM-17-003

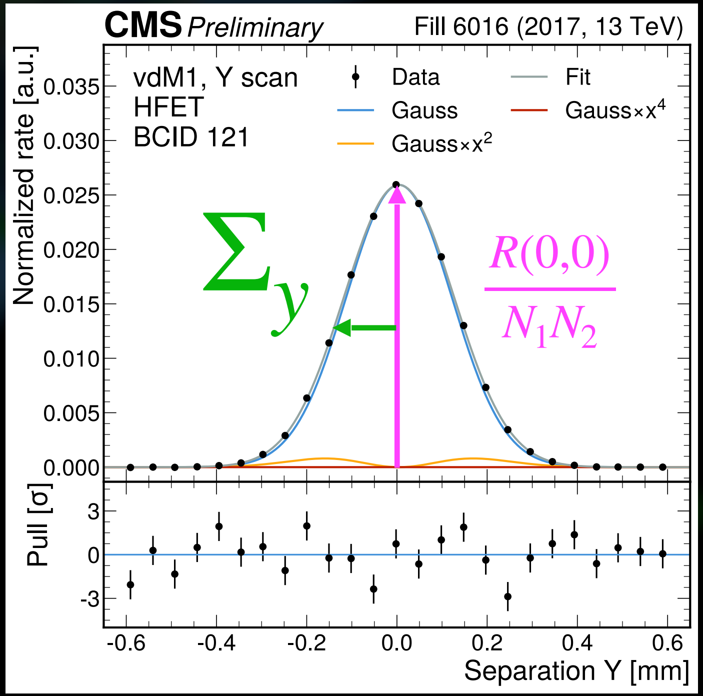
Absolute calibration at LHC: σ_{vis} from vdM method

- Rate as a function of separation provides beam overlap widths in x and y
  - Visible cross section assuming transverse factorization:

$$\sigma_{vis} = \frac{1}{\mathscr{L}_0} R_0 = \frac{2\pi \Sigma_x \Sigma_y R_0}{N_1 N_2 f_{LHC}}$$

arXiv:2104.01927
LUM-17-003
https://cds.cern.ch/record/2940794





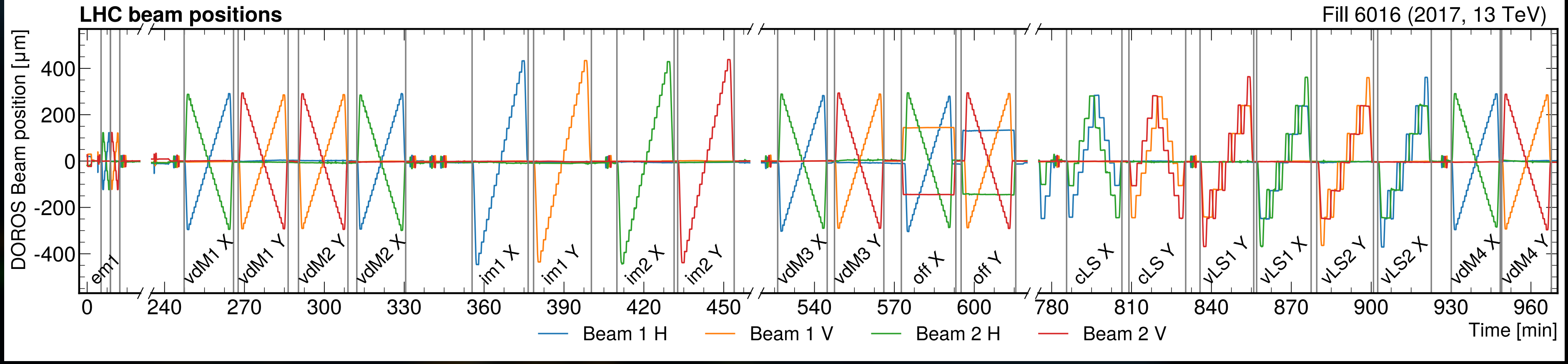
- Beam properties
  - Bunch intensity (N_1, N_2)
  - Bunch positions/shape (Σ_x, Σ_y)
    - Length-scale
    - Orbit movements affecting separation
    - Beam-beam interactions affecting position
- Background treatment affecting R_0
- Beam-beam interactions affecting expected rate

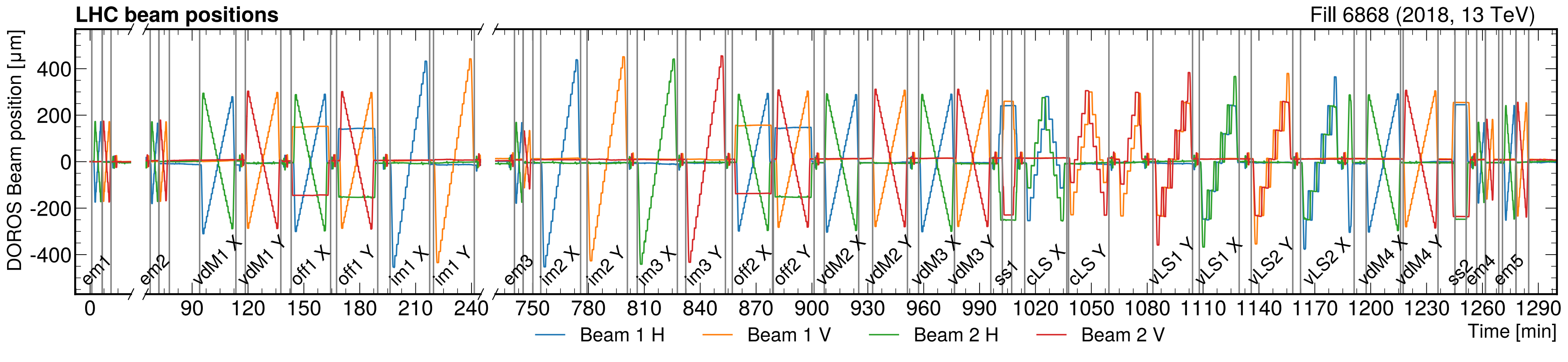
Luminometer calibrations

2017/2018 vdM Programs

- CMS's vdM program's complexity increases almost every year to nail down systematics.

- Different types of scans
  - VdM scans (vdM): 6 σ_b maximum separation in each (X and Y) direction
  - Imaging scans (im): 4.5 σ_b maximum separation with one beam stationary, the other scanning
  - Offset scans (off): similar to vdM but with constant separation (3 σ_b) in non-scanning direction
  - Two kinds of length scale (LS) scans
  - Super separation (ss) periods in 2018: Beams separated to 5 σ_b in both directions.

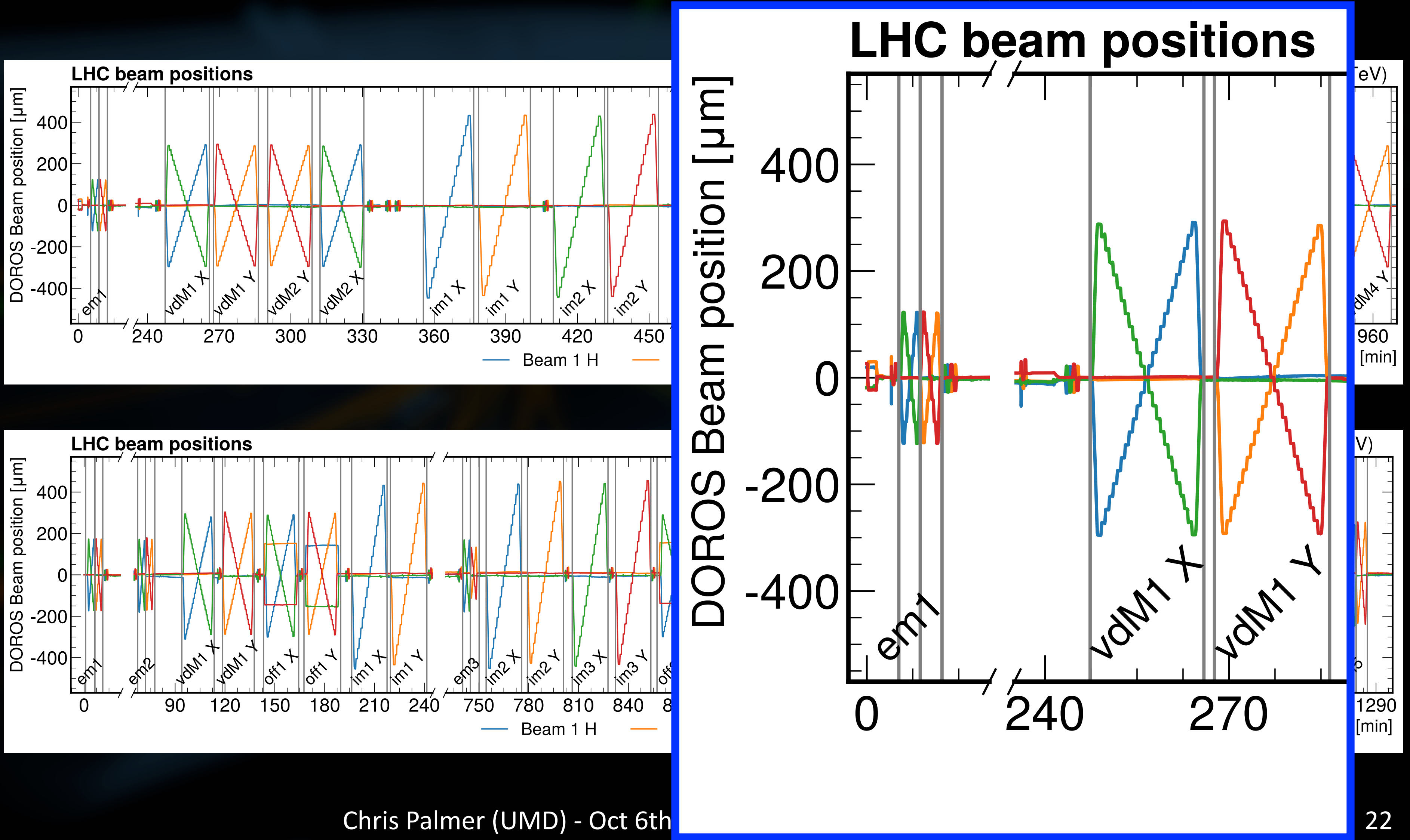




2017/2018 vdM Programs

- CMS's vdM program's complexity increases almost every year to nail down systematics.

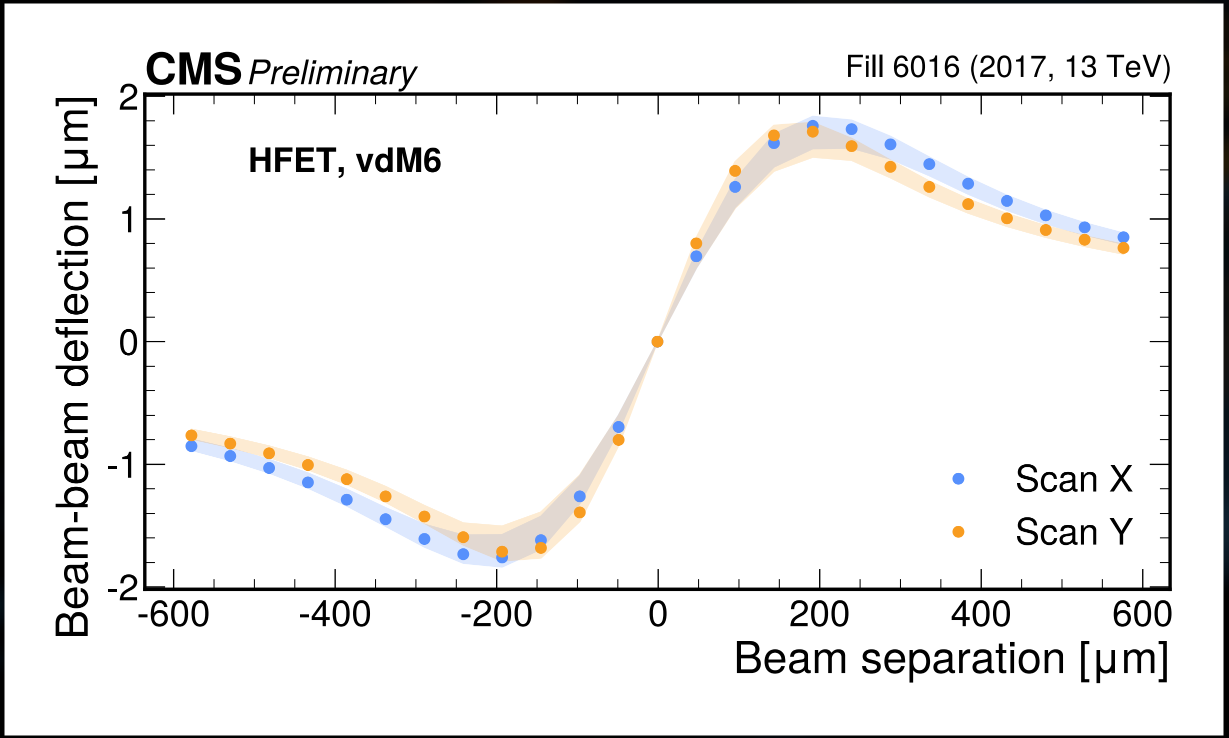
- Different types of scans
  - VdM scans (vdM): 6 σ_b maximum separation in each (X and Y) direction
  - Imaging scans (im): 4.5 σ_b maximum separation with one beam stationary, the other scanning
  - Offset scans (off): similar to vdM but with constant separation (3 σ_b) in non-scanning direction
  - Two kinds of length scale (LS) scans
  - Super separation (ss) periods in 2018: Beams separated to 5 σ_b in both directions.

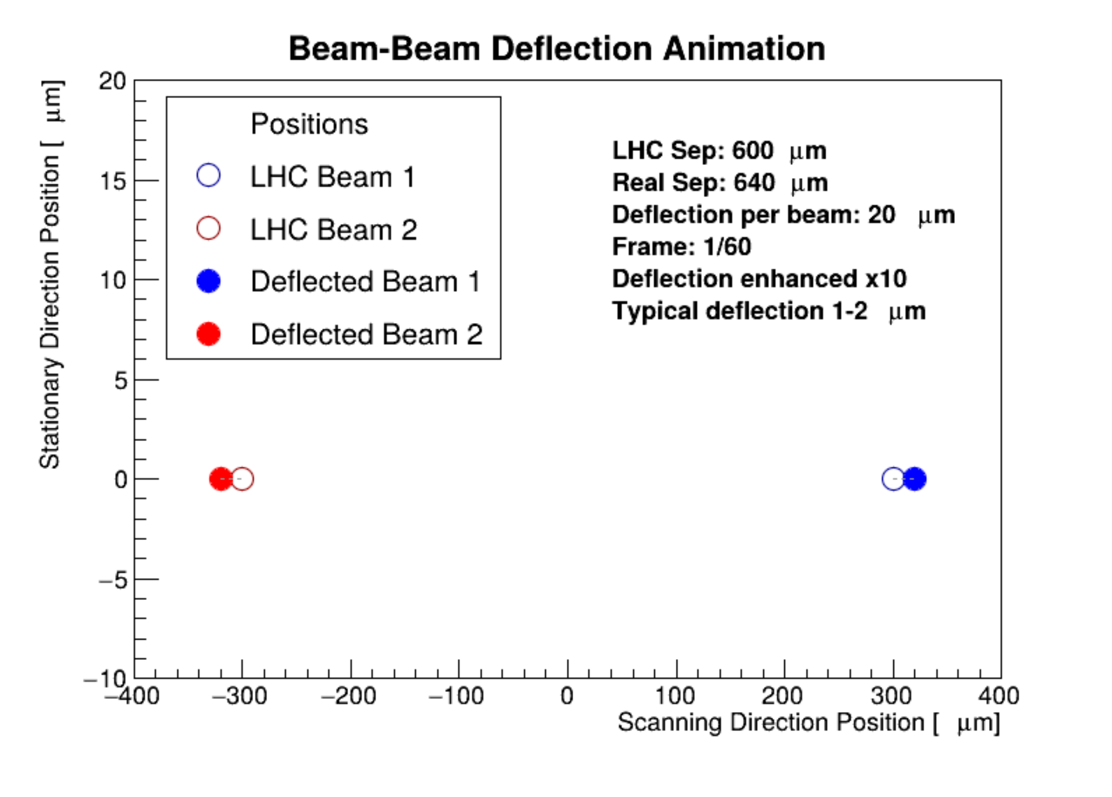


Beam-beam Deflection

- A "bunch" of protons in vdM fills is typically 10 billion protons.
- The positively charged colliding bunches push each other away.
- Classic effect; modeled well since Run 1.

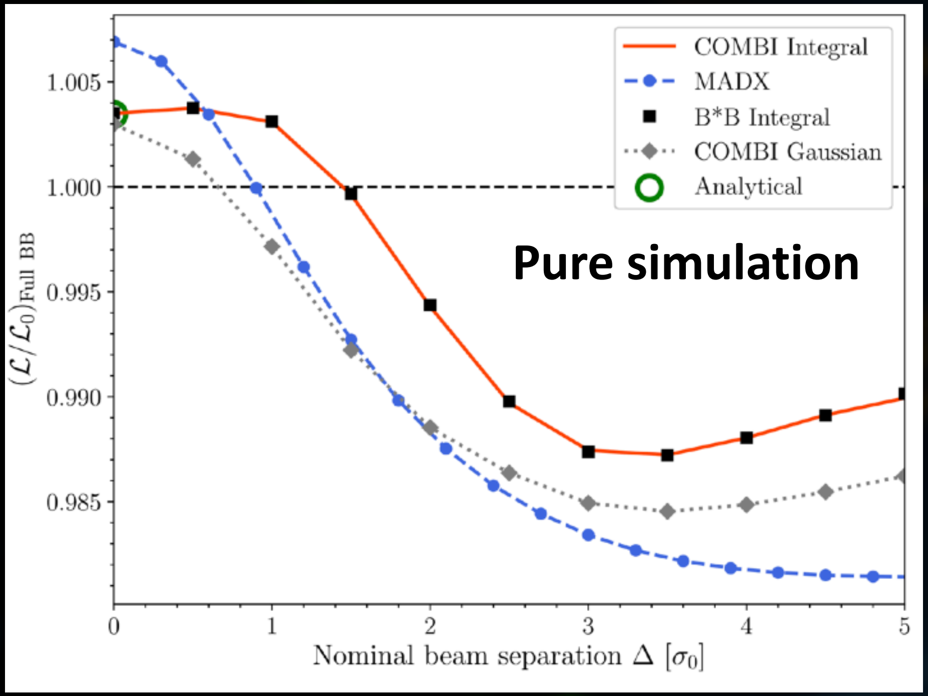
Beam-beam deflection

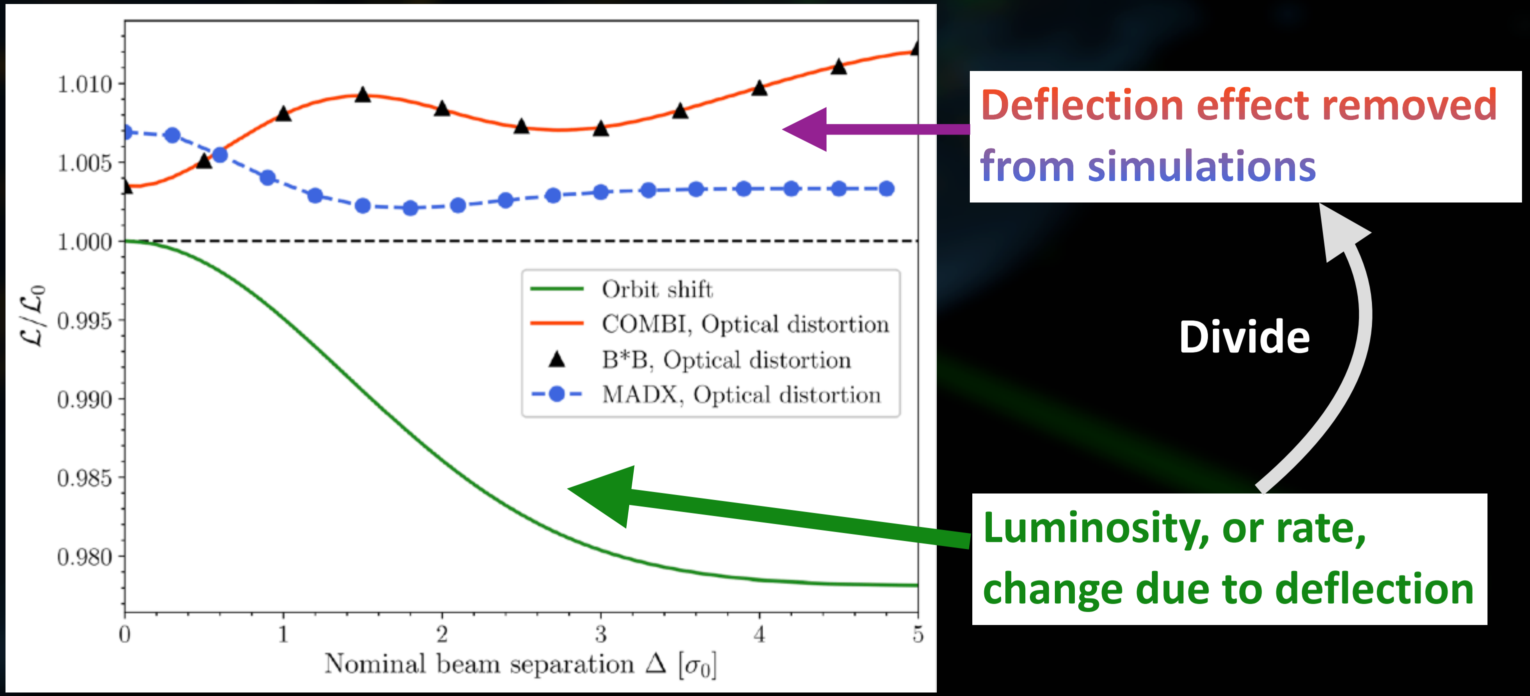




Beam-beam (de)focusing

- As the separated proton bunches pass each other they are distorted.
- Predicting the distortion analytically is too complex so beam-beam interaction simulations are used to estimate the size (first) of all beam-beam interactions and (second) the defocusing by removing the impact of just deflecting the beams.





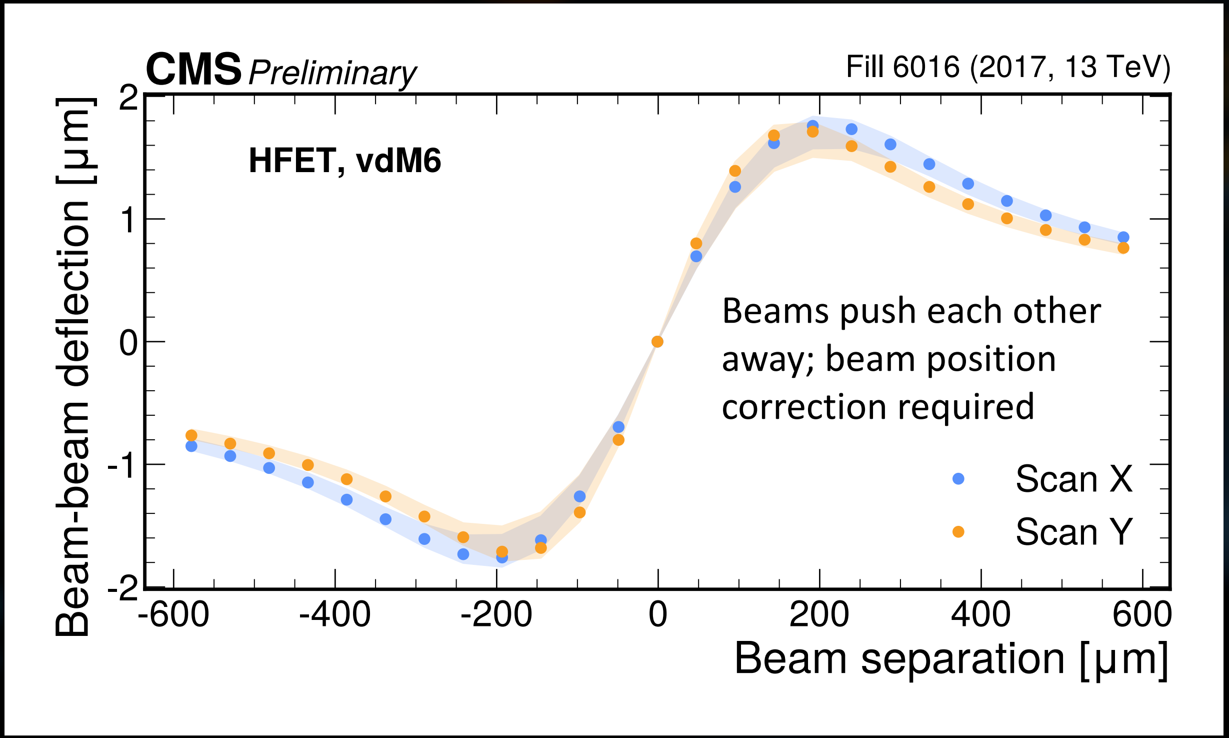
https://doi.org/10.1140/epjc/s10052-023-12192-5

Beam-beam Effects

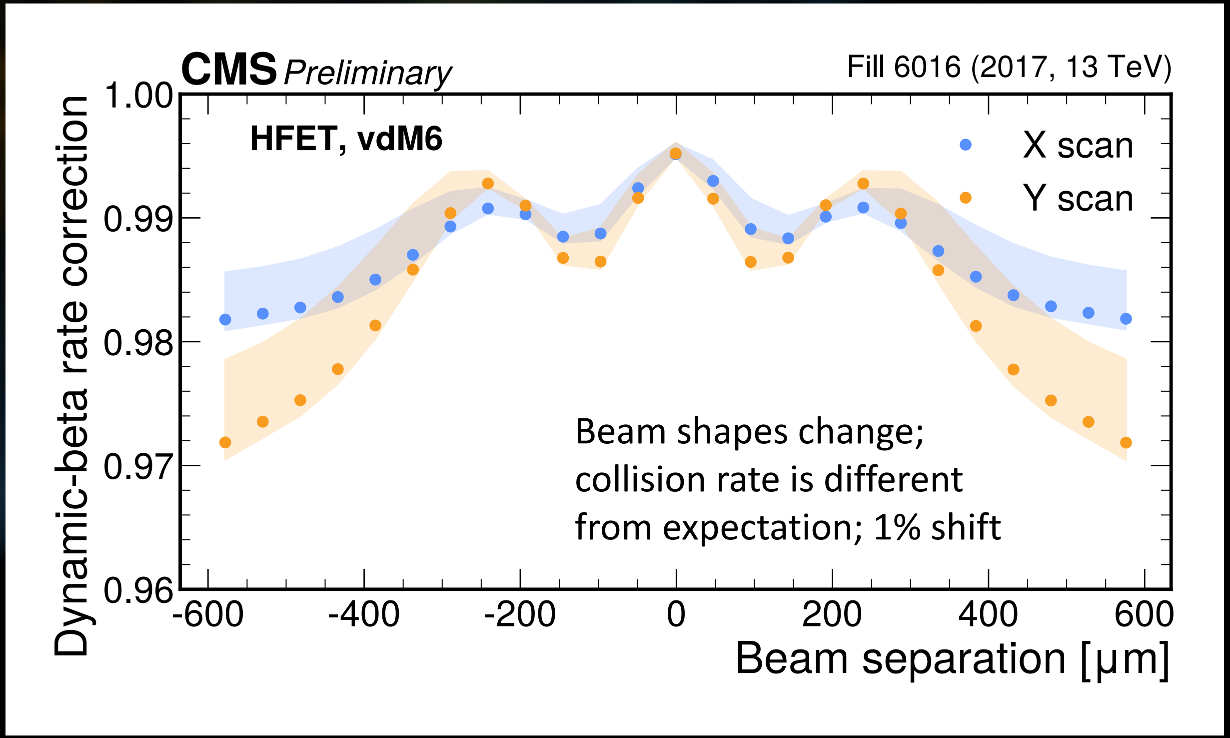
- For the first luminosity paper (2015/2016) the uncertainty was inflated because the correction was ready but not the systematic studies.
- Now these two effects are considered together and as they are inherently anti-correlated, the combined uncertainties are considerably smaller than if they are (incorrectly) considered uncorrelated.

[%]	2017	2018
Correction	0.60	0.61
Uncertainty	0.29	0.30

Beam-beam deflection



Dynamic Beta

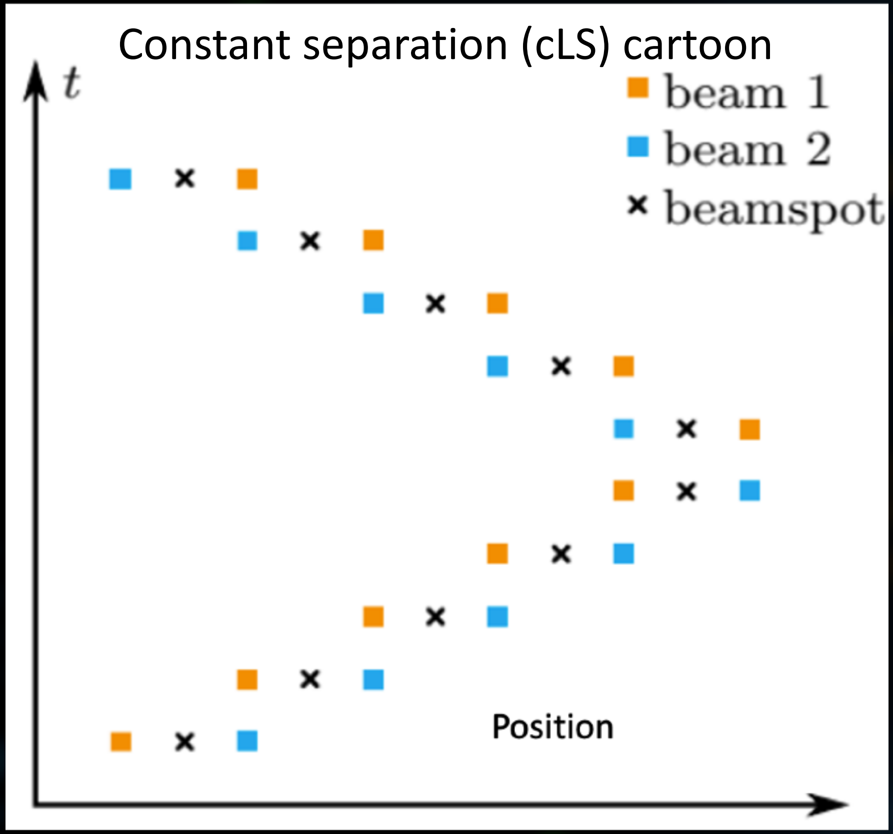


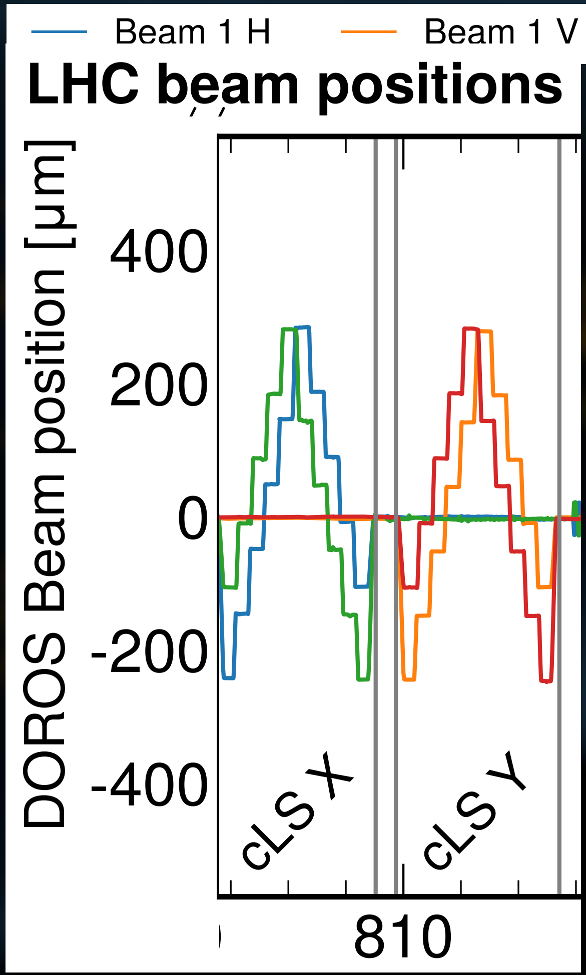
Length Scale Problem

- LHC adjusts the position of the beams by changing the current producing magnetic fields.
- The problem is that their calibration is very good, but not precise enough.
- 1% off is good enough for them, but not for precision measurements of beam positions.

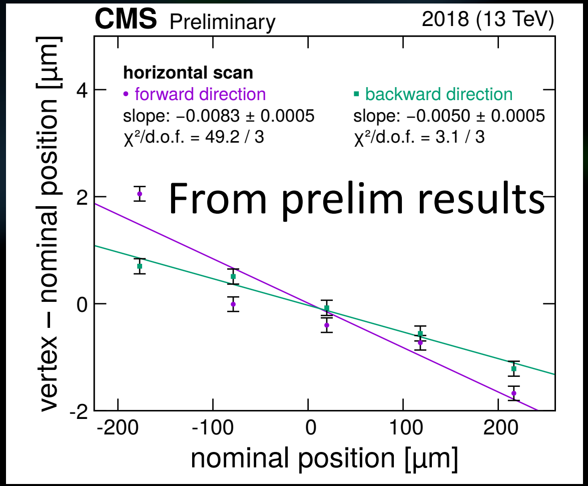
Length Scale Corrections

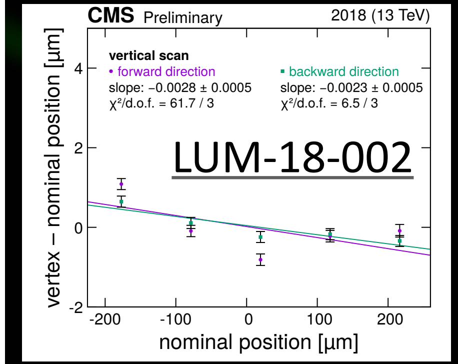
- Two methods with independent assessments of "length scale" of position changes reported by LHC.



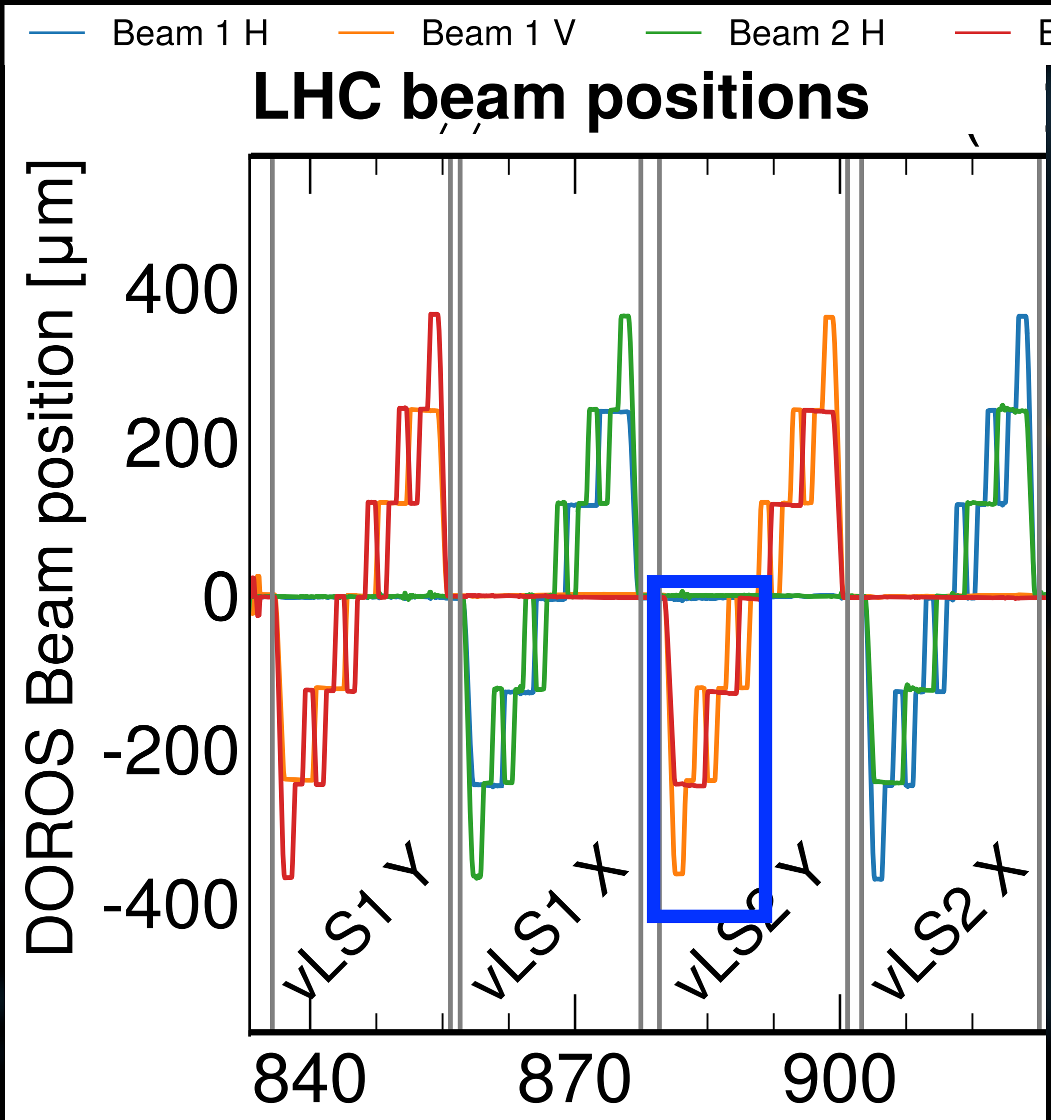


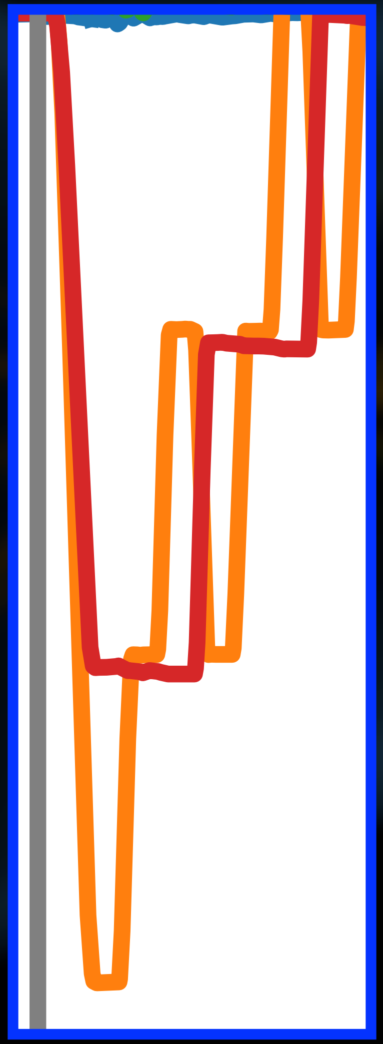
- Two beams are separated by a fixed amount by LHC.
- We check that CMS reconstructs collection position with the expected separation.
- We infer the AVERAGE additional scale calibration in EACH direction.



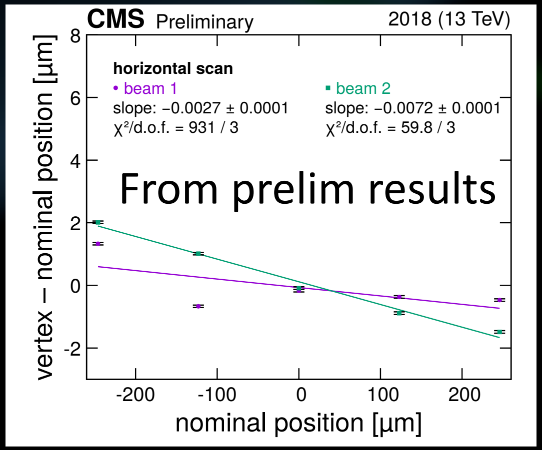


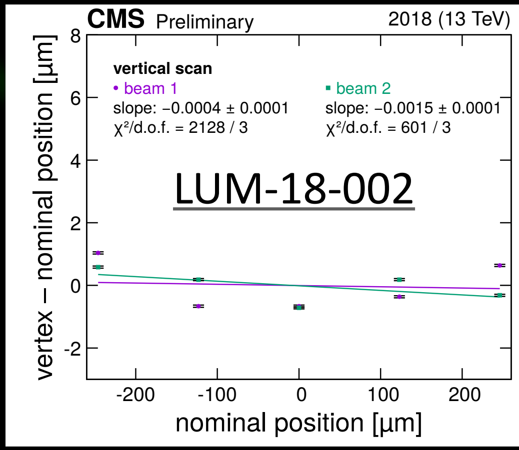
Length Scale Corrections





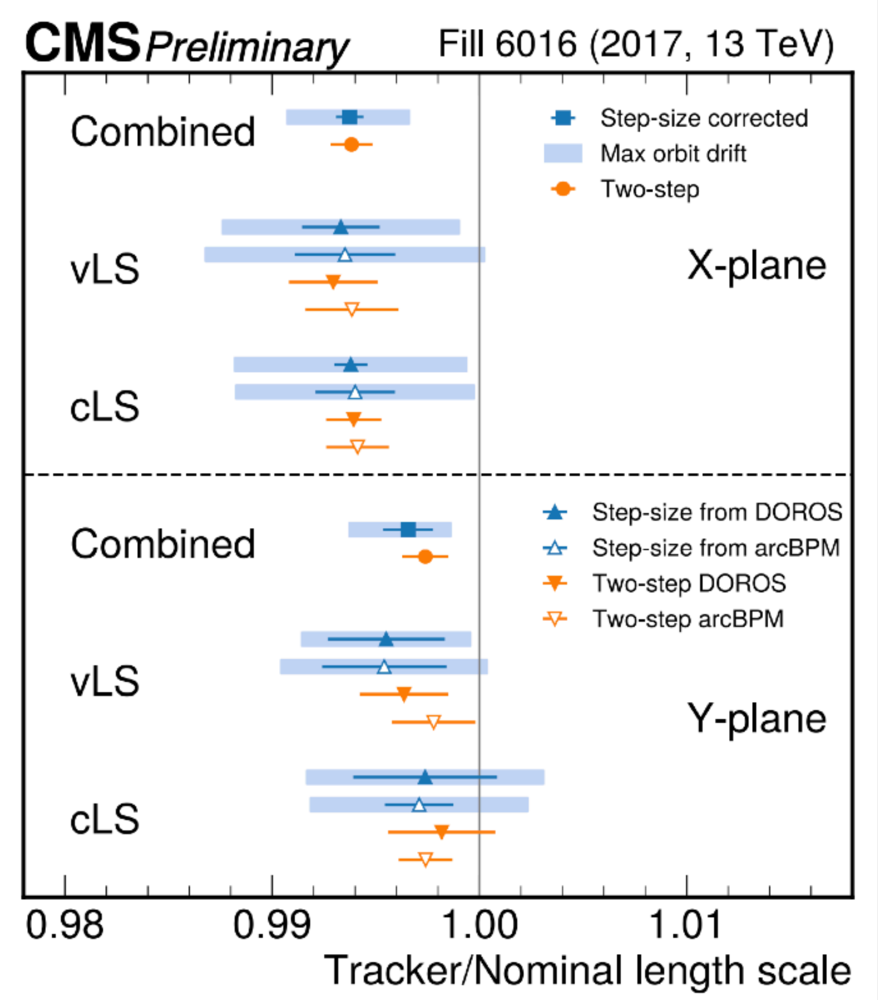
- Variable length scale (vLS) measures individual beam length scales in both directions.
- Move one beam in a single direction and scan with the other beam; then fit the rate with a parabola to determine the position of head-on collision.
- That position is calibrated against the collision location (aka luminous region).





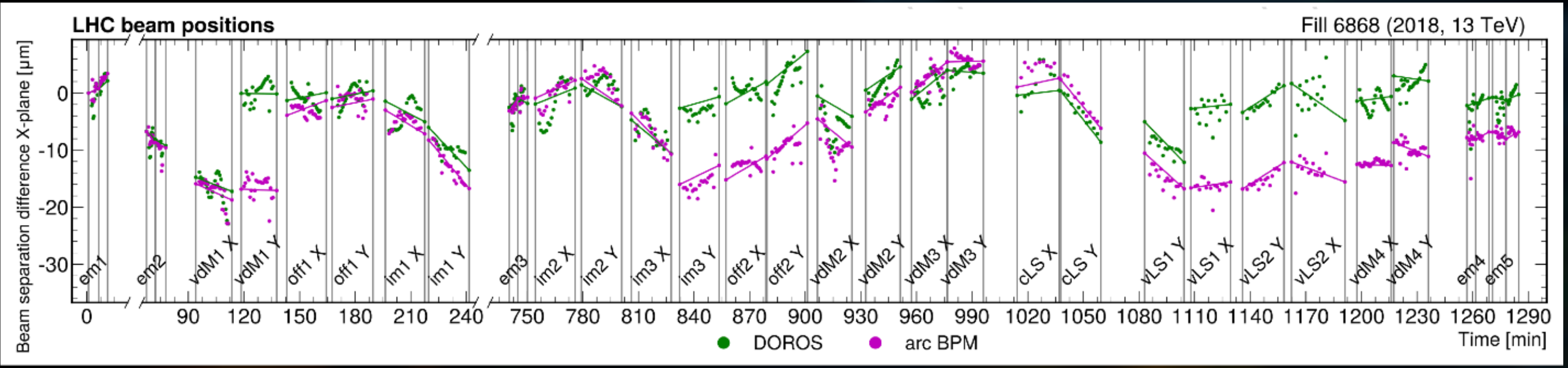
Length Scale Corrections

- Two methods with independent assessments of “length scale” of position changes reported by LHC.
  - Constant separation (cLS) and variable separation (vLS).
- Innovation is to decorrelate length scale and orbit drift with a two-step procedure.
  - Step 1: calibrate BPM positions to LHC nominal positions using data per beam throughout calibration fills.
    - MUCH less sensitive to orbit drift.
  - Step 2: further calibrate the step-1-calibrated LHC Beam Position Monitors (BPM) positions using luminous region (LR) positions during both types of scans (cLS and vLS).
    - Both LR and BPM see orbit drift during scans.



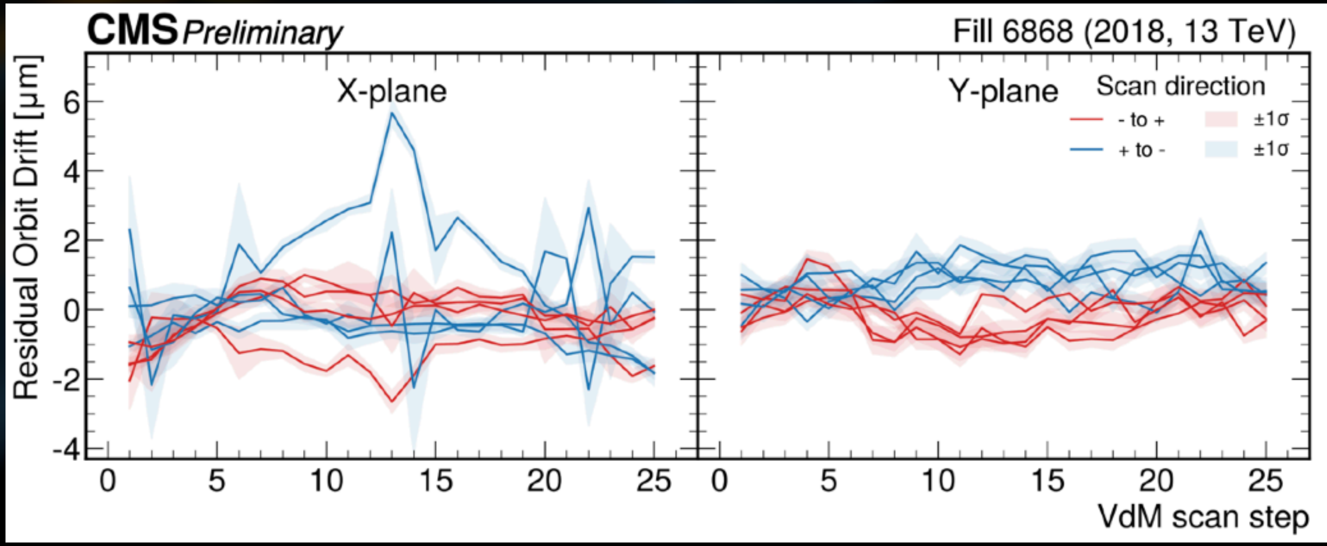
[%]	2017	2018
Uncertainty	0.09	0.19

Orbit Drift Corrections



- Two sets of beam position monitoring data used.
- First, correct head-on shift from before/after position.

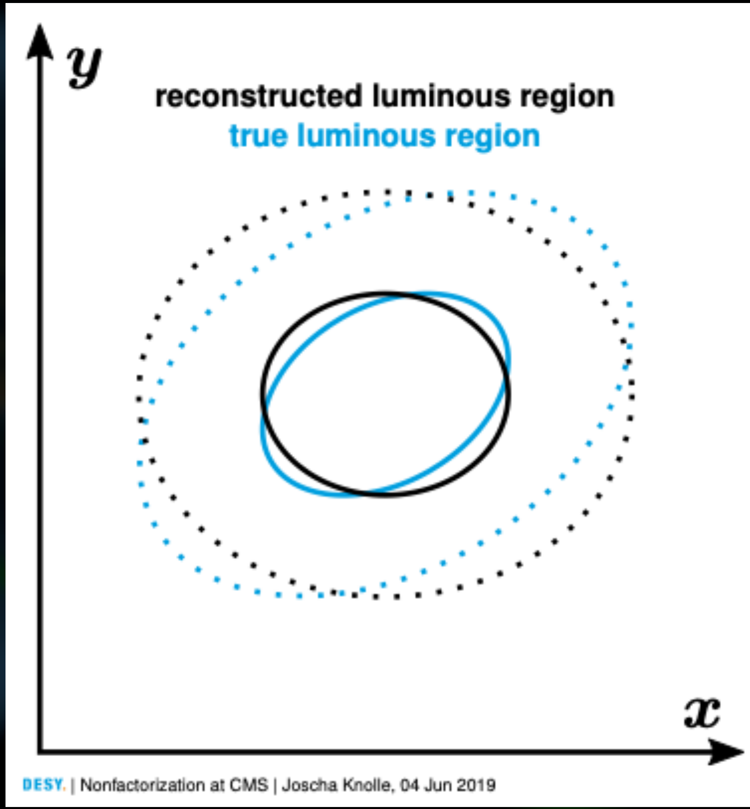
- Finally a correction per beam per step is derived after ALL other position corrections.

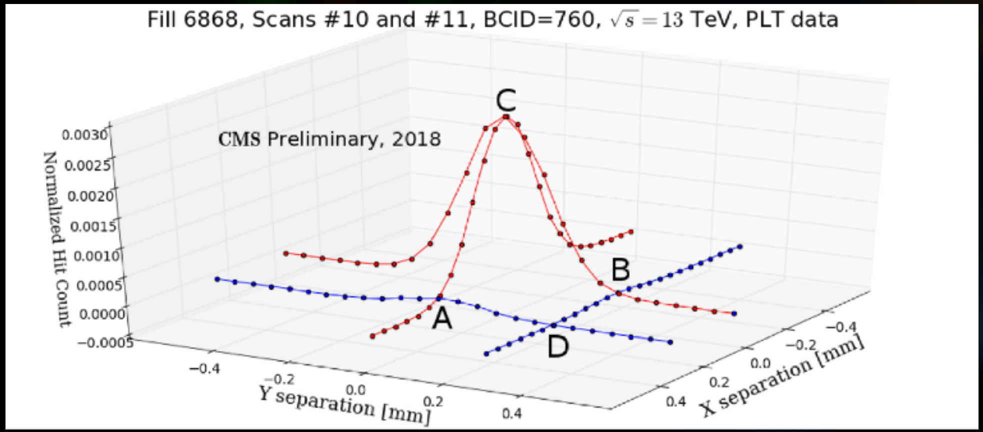


[%]	2017	2018
Uncertainty	0.09	0.19

Transverse factorization (1/2)

- Standard vdM analysis assumes the density of protons in beams are factorizable in *x* and *y*.
- LHC proton bunches in calibration fills are nearly (yet not perfectly) factorizable and Gaussian in shape.
- Luminous region (LR) analysis used to determine bunch densities throughout all vdM scans.

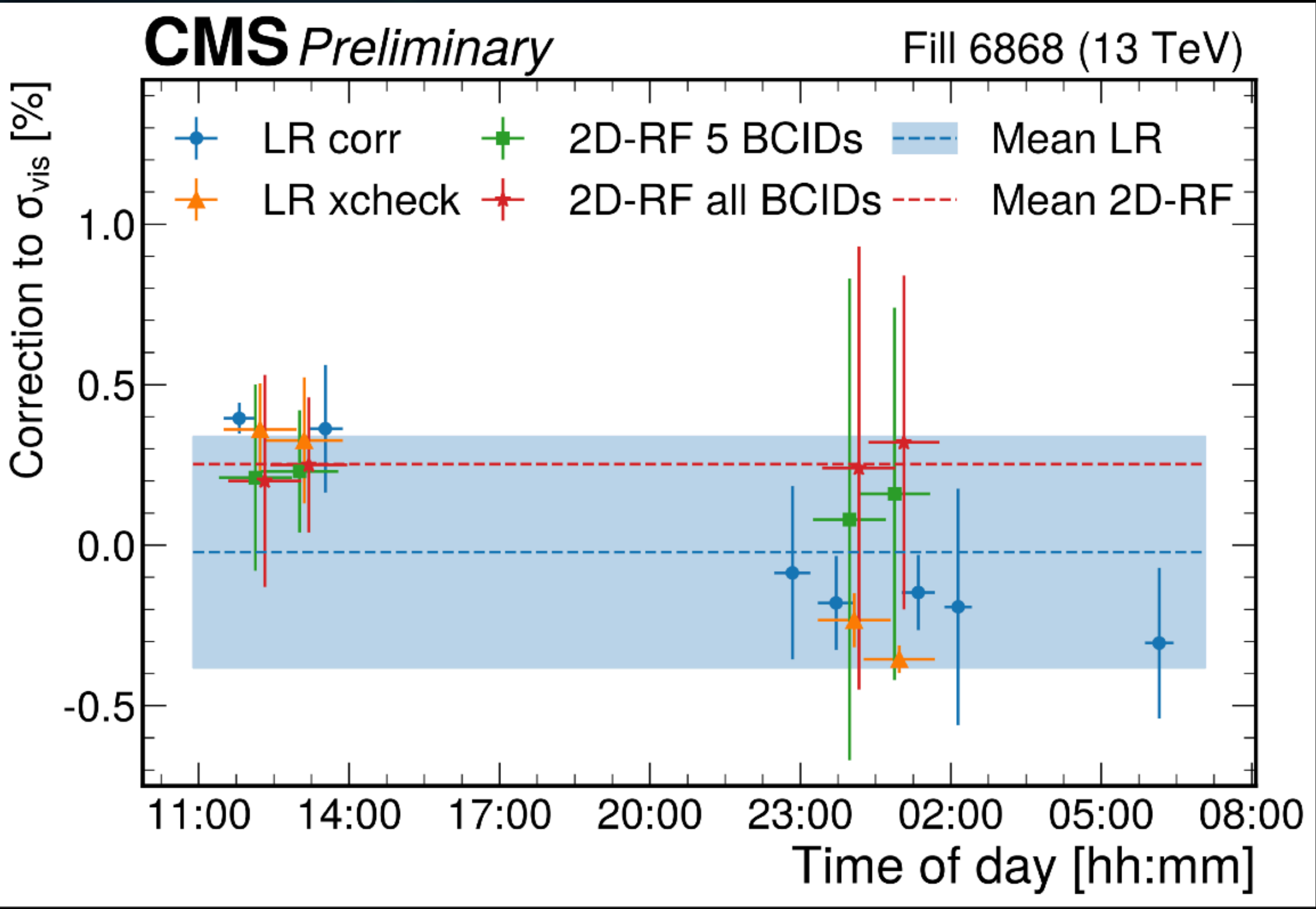




- Dedicated scans (offset) are fit with 2D models as a cross check.

Transverse factorization (2/2)

- Highly compatible results from two complementary methods.
- LR is the nominal correction.
- A total uncertainty of 0.33% is unprecedented for this particular feature.
    - Mostly (0.25%) from non-closure in toy studies.



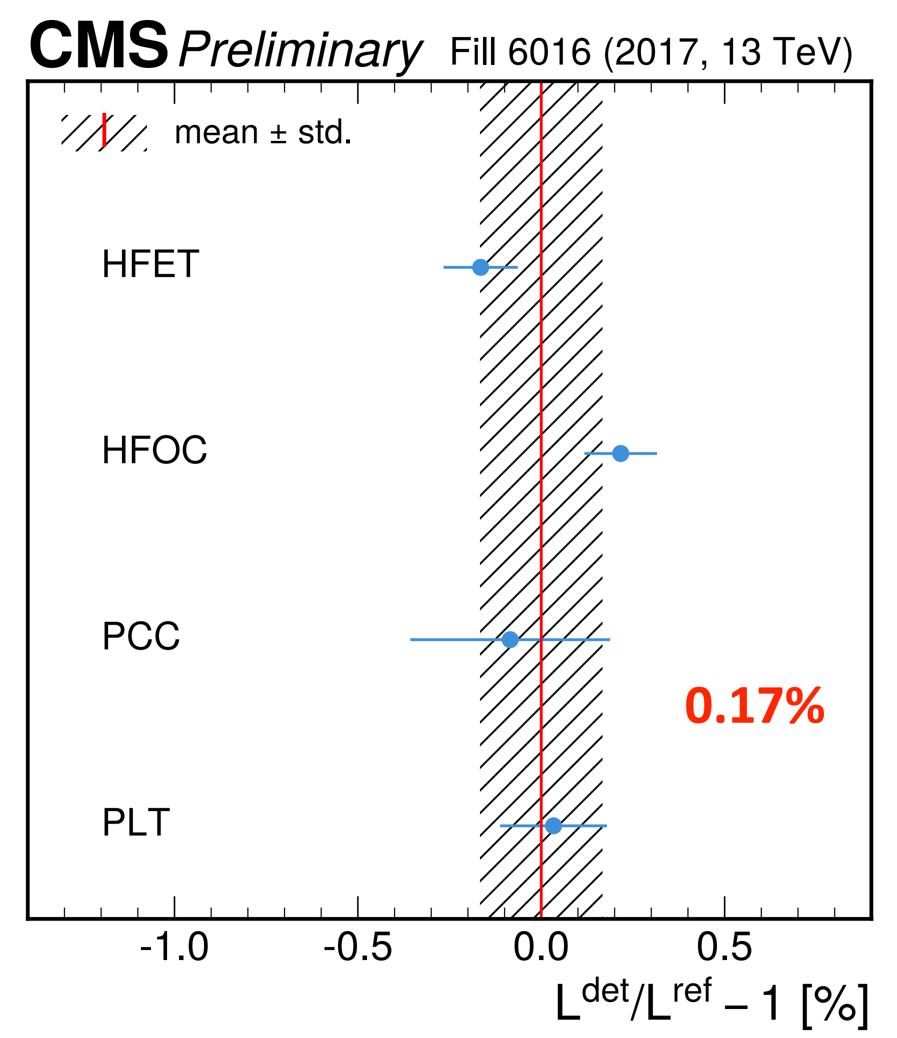
2017/2018 Corrections

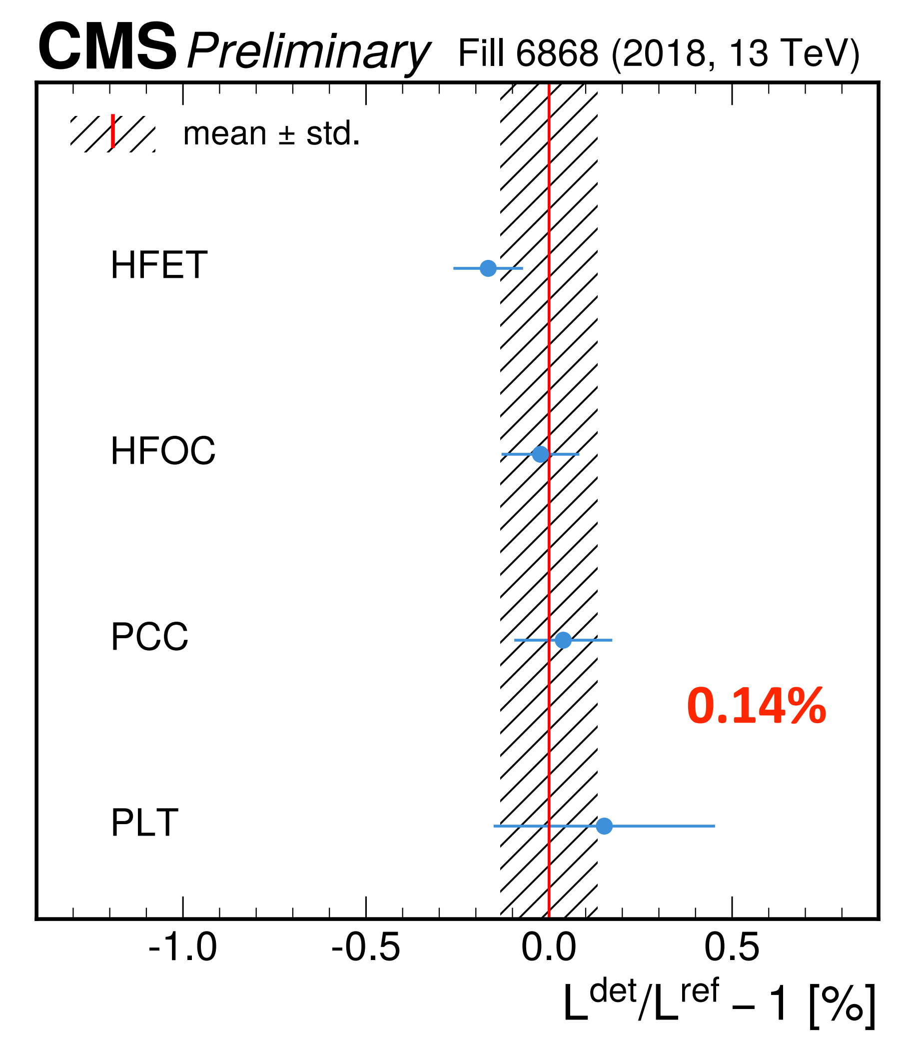
- Despite several more-than-percent-level corrections, the overall impact on calibrations (i.e., σ_{vis}) is around 0.5% for both datasets.

Correction	2017 [%]	2018 [%]
Background	-0.22	−0.17
Orbit drift – scanning direction	0.05	0.00
Orbit drift – non-scanning direction	0.08	0.05
Beam-beam deflection	1.69	1.61
Dynamic beta	−1.09	−1.00
Length scale	−0.88	−0.75
Residual orbit drift	0.20	0.13
Non-factorization	0.36	0.04
Emittance change	0.15	0.22
Total	—0.78	—0.49

Consistency in Calibrations

- All luminometers undergo the same calibration procedure.
- The calibrated luminosity in the vdM data should be consistent.
- We evaluate the variation in integrated luminosity in this small dataset to assess a non-closure uncertainty.





2017/2018 Calibrations

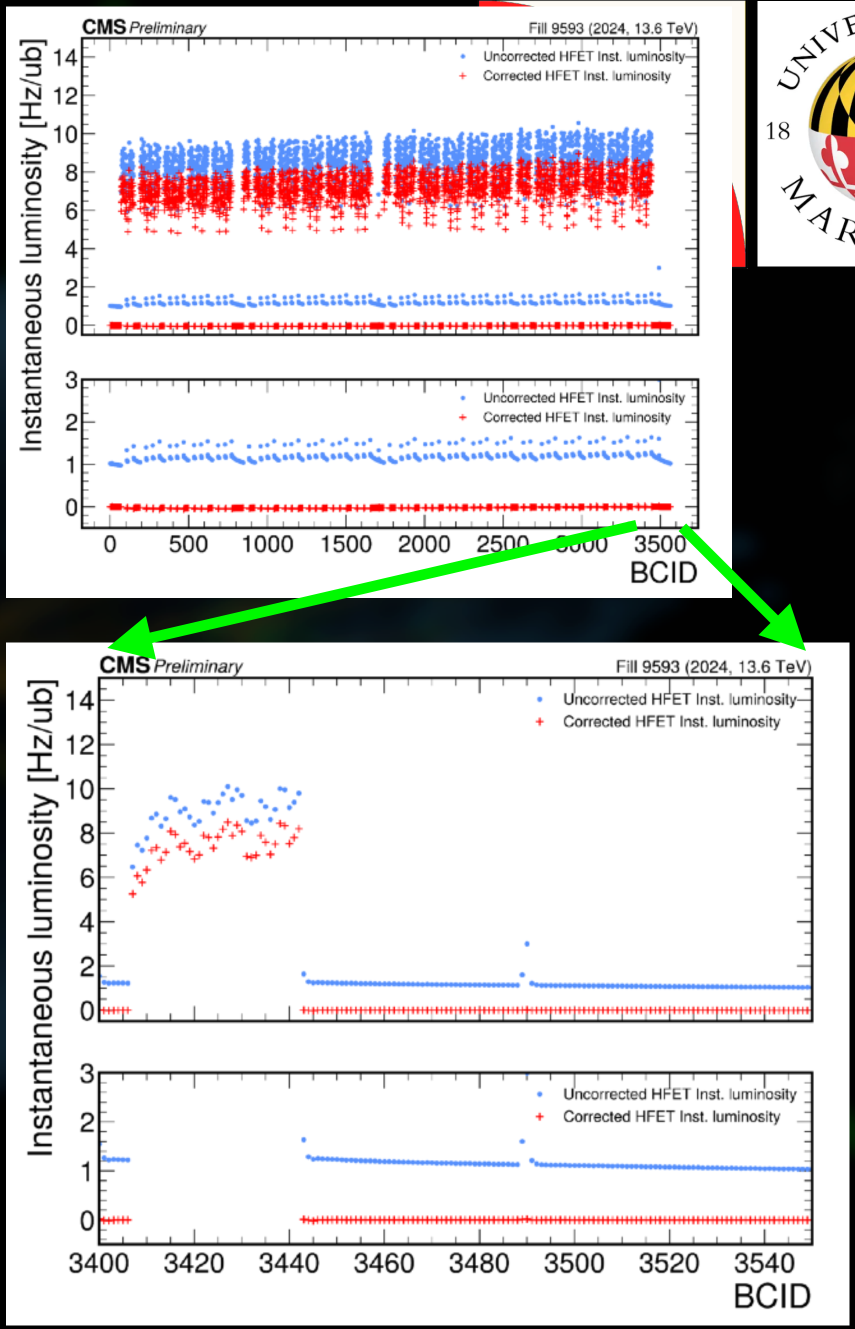
- Four of the largest uncertainties were reduced with improved methods and increasingly complex calibration scans.
- Total normalization uncertainty with vdM procedure is approaching 0.5%!

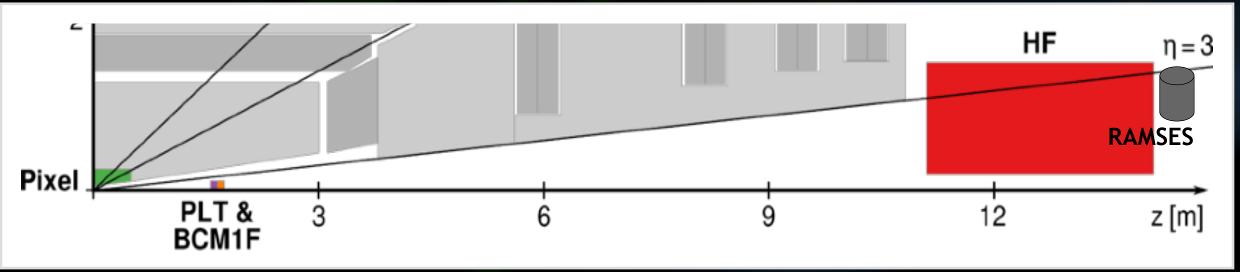
Source	2017 [%]	2018 [%]	Corr.	Corr. w. 15–16
Normalization				
Beam current normalization	0.2	0.2	Yes	Yes
Ghost and satellite charges	0.06	0.07	Yes	Yes
Beam-beam effects	0.29	0.30	Yes	Yes
Orbit drift	0.09	0.19	Yes	Yes
Length scale calibration	0.15	0.18	Yes	No
Transverse factorizability	0.33	0.36	Yes	No
Scan to scan variation	0.26	0.27	No	No
Bunch to bunch variation	0.1	0.1	No	No
Cross-detector consistency at vdM	0.17	0.14	No	No
Total normalization uncertainty	0.61	0.66	—	—

Luminometer corrections

HF Lumi

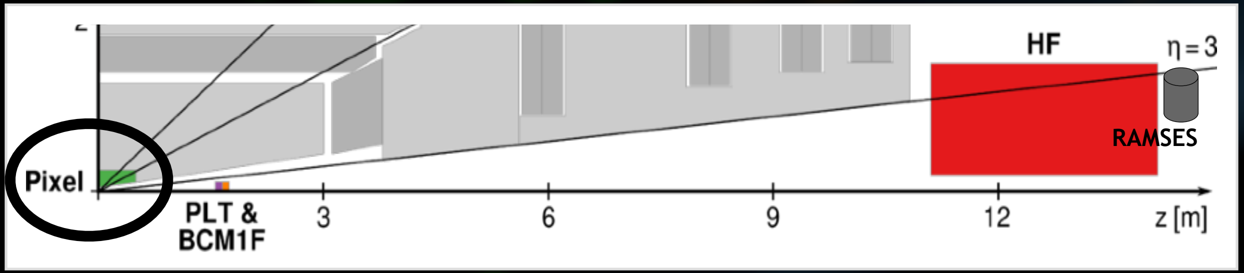
- CMS's Hadronic Forward (HF) detector is an iron absorber with quartz fibers.
- An FPGA-based backend is used to store the histograms per bunch crossing—readout every 1.45 seconds.
- Two types of out-of-time pileup
  - 1) tails of earlier, real signals are visible (electronics spillover): just the next 1-3 bunch crossing slots
  - 2) detector material is activated and radioactive decays near the detector creates new charged particles (afterglow): effect lasts on the order of the half-life of activated material.

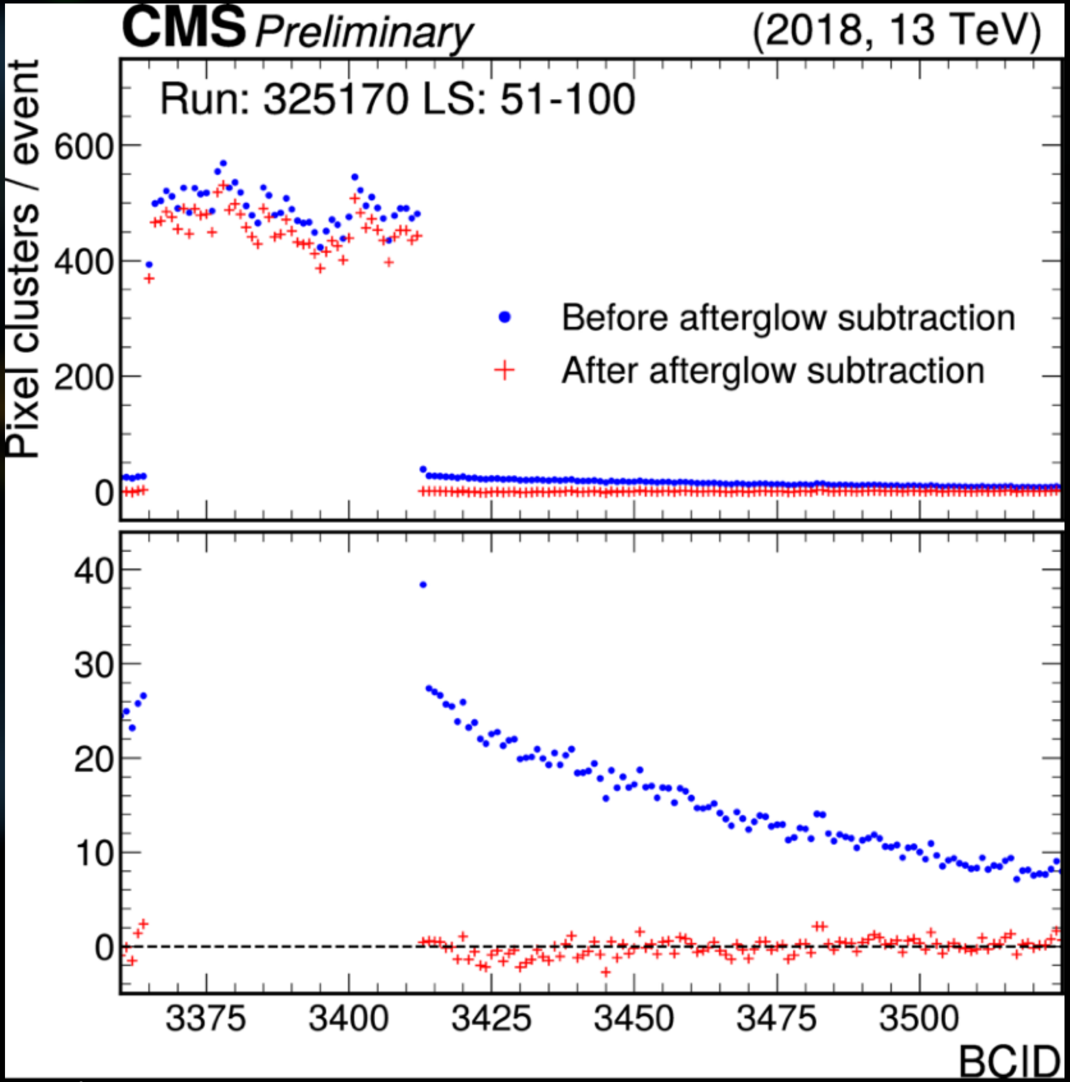




~~HF Lumi~~ PCC

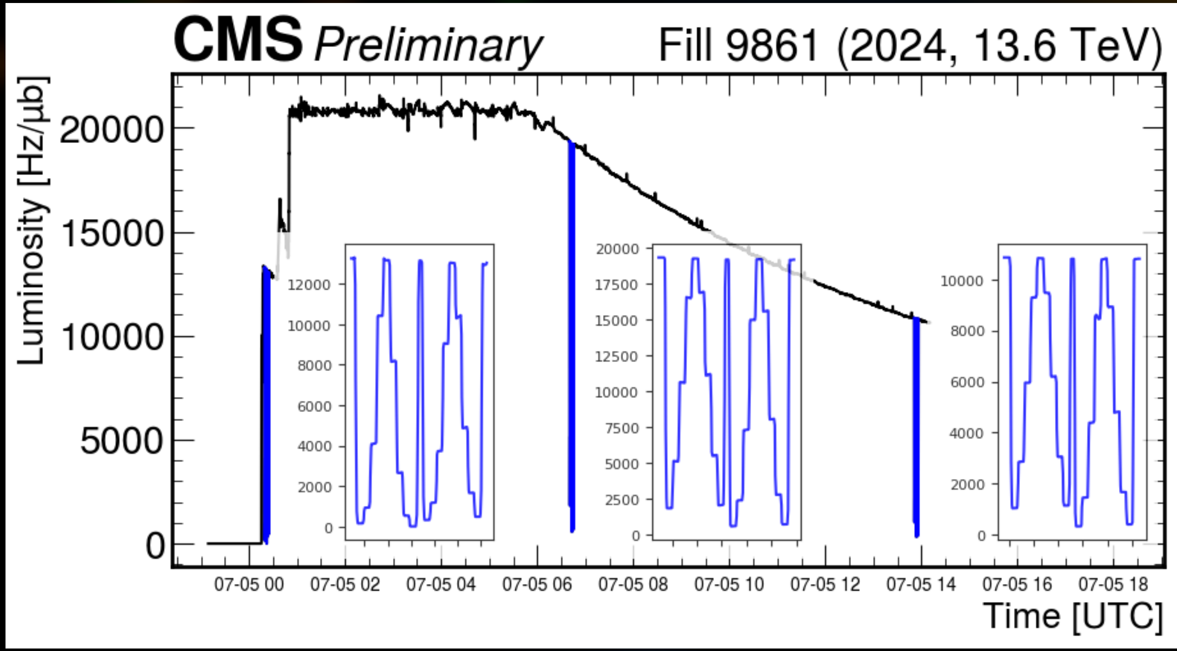
- ~~CMS's Hadronic Forward (HF) detector is an iron absorber with quartz fibers.~~
- ~~An FPGA-based backend is used to store the histograms per bunch crossing—readout every 1.45 seconds.~~
- Two types of out-of-time pileup
  - 1) tails of earlier, real signals are visible (electronics spillover): just the next 1-3 bunch crossing slots
  - 2) detector material is activated and radioactive decays near the detector creates new charged particles (afterglow): effect lasts on the order of the half-life of activated material.
- The same strategy is used for PCC afterglow corrections.

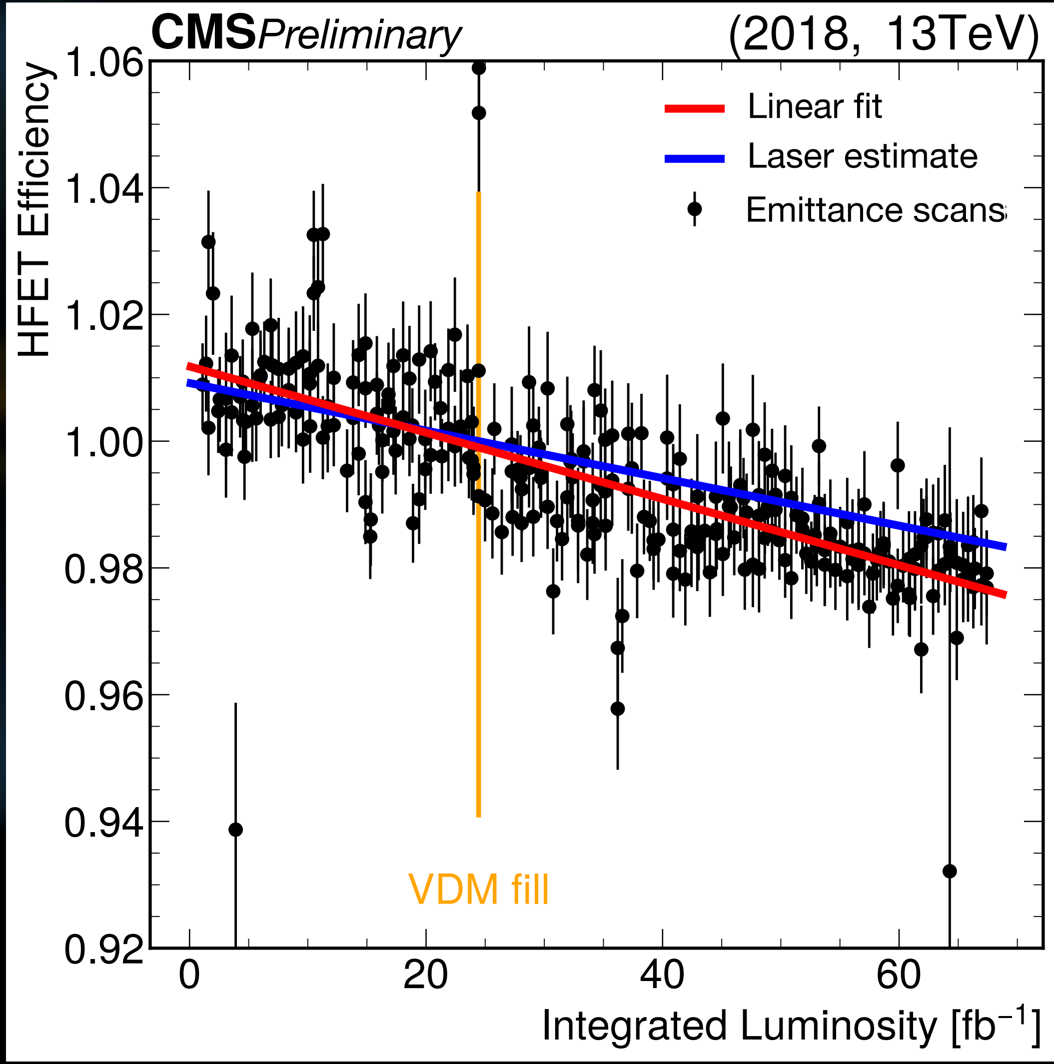




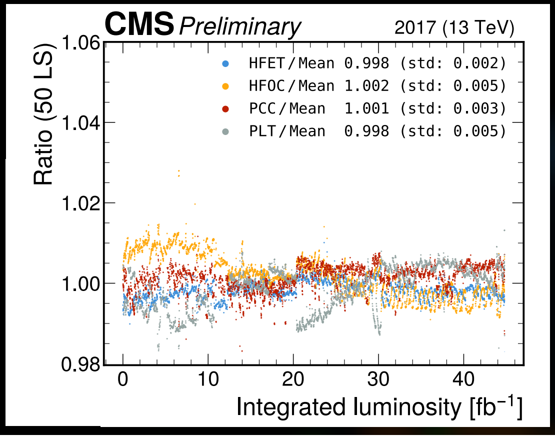
Efficiency corrections from emittance scans

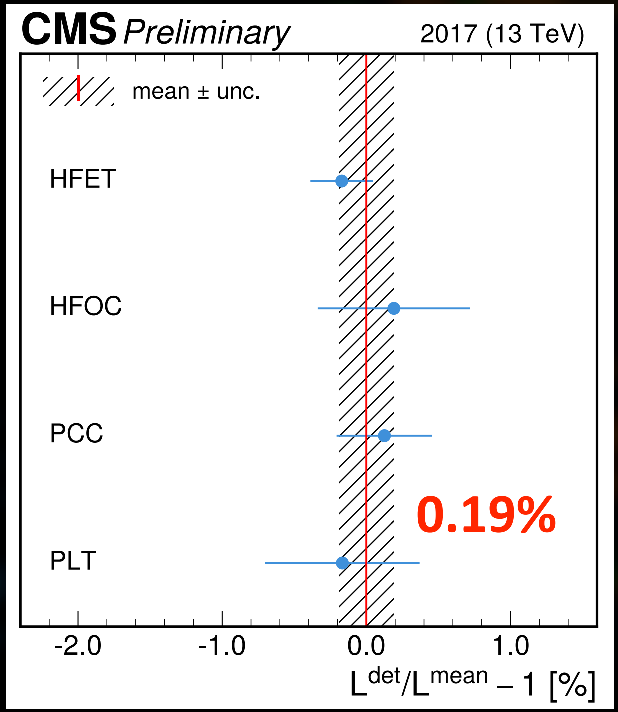
- Pairs of beam position scans can be used in a "vdM" style.
- Absolute value is not used for calibration relative value used for calibration tracking.
- Not new, but more mature with better accuracy.
- Better corrections, better comparisons, lower uncertainties!



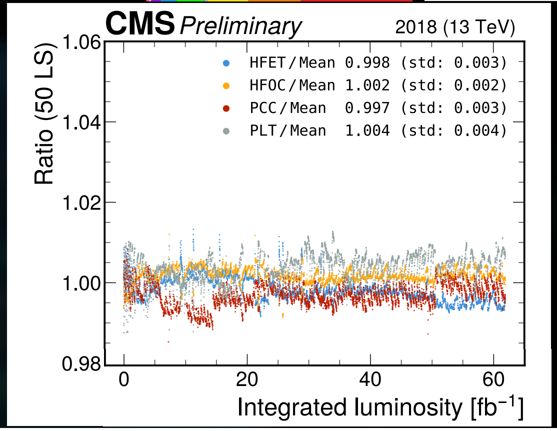


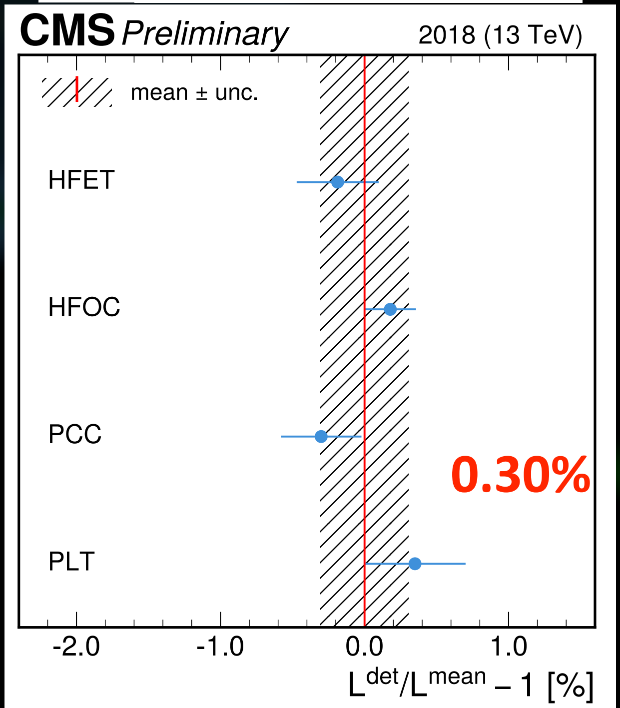
Putting it all together



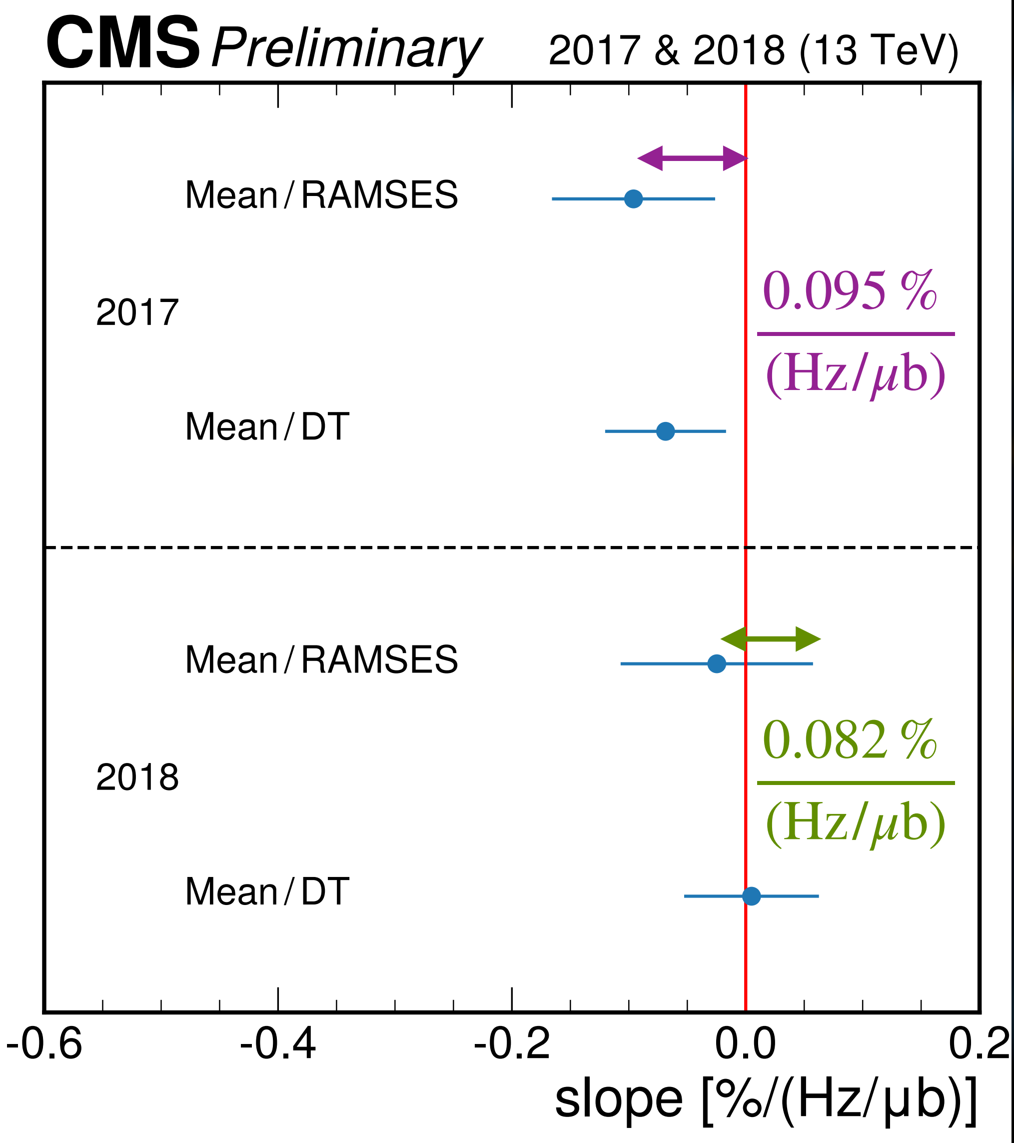


- Comparisons are tighter because luminometers' corrections are more accurate.
- NEW the central luminosity measurement is the AVERAGE of several independently calibrated measurements.
  - The RMS is now used as the stability uncertainty.





Linearity Uncertainty



- Compute the slope of the ratio of average luminosity to RAMSES and DT (assumed linear) per fill.
- Compute luminosity weighted average of those slopes—> mean and RMS are plotted to the left.
- Largest average deviation from zero or largest RMS of slopes per year is the (now dominant) uncertainty.
- It scales with the average pileup/inst. luminosity.

$$\delta_{Lin} = m_{Lin} \cdot < \mathscr{L}_{inst} >$$

	2017	2018
Linearity Uncertainty [%/(Hz/μb)]	0.095	0.082
Average Inst. Luminosity [Hz/μb]	5.34	5.14
Integrated luminosity uncertainty [%]	**0.51**	**0.42**

Full Run 2 Results!

- The initial 2017 and 2018 uncertainties were 2.3% and 2.5%.
    - Now 0.82% and 0.84%!
- Full Run 2: 0.73%!
- Largest single uncertainty is linearity.
    - Will be the most difficult to contain at HL-LHC as they grow with PU.

Source	2017 [%]	2018 [%]	Corr.	Corr. w. 15–16
Normalization				
Beam current normalization	0.2	0.2	Yes	Yes
Ghost and satellite charges	0.06	0.07	Yes	Yes
Beam-beam effects	0.29	0.30	Yes	Yes
Orbit drift	0.09	0.19	Yes	Yes
Length scale calibration	0.15	0.18	Yes	No
Transverse factorizability	0.33	0.36	Yes	No
Scan to scan variation	0.26	0.27	No	No
Bunch to bunch variation	0.1	0.1	No	No
Cross-detector consistency at vdM	0.17	0.14	No	No
Integration				
Cross-detector consistency per year	0.19	0.30	No	No
Linearity	0.51	0.42	Yes	No
Total normalization uncertainty	0.61	0.66	—	—
Total integration uncertainty	0.54	0.52	—	—
Total uncertainty	0.82	0.84	—	—

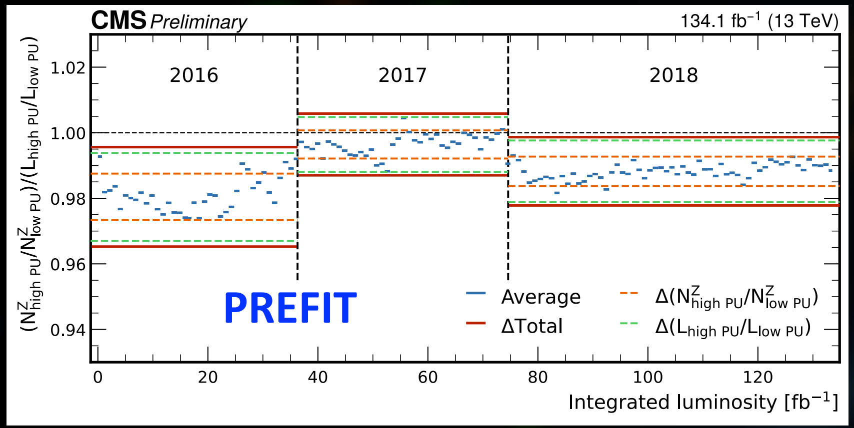
$Z \to \mu\mu$ Rate Compatibility

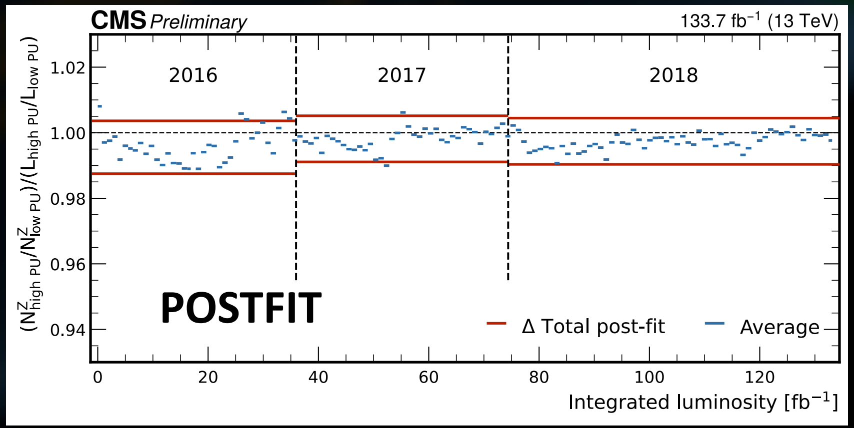
- A likelihood fit of number of Z bosons per 20 pb^{-1} is performed to assess compatibility.

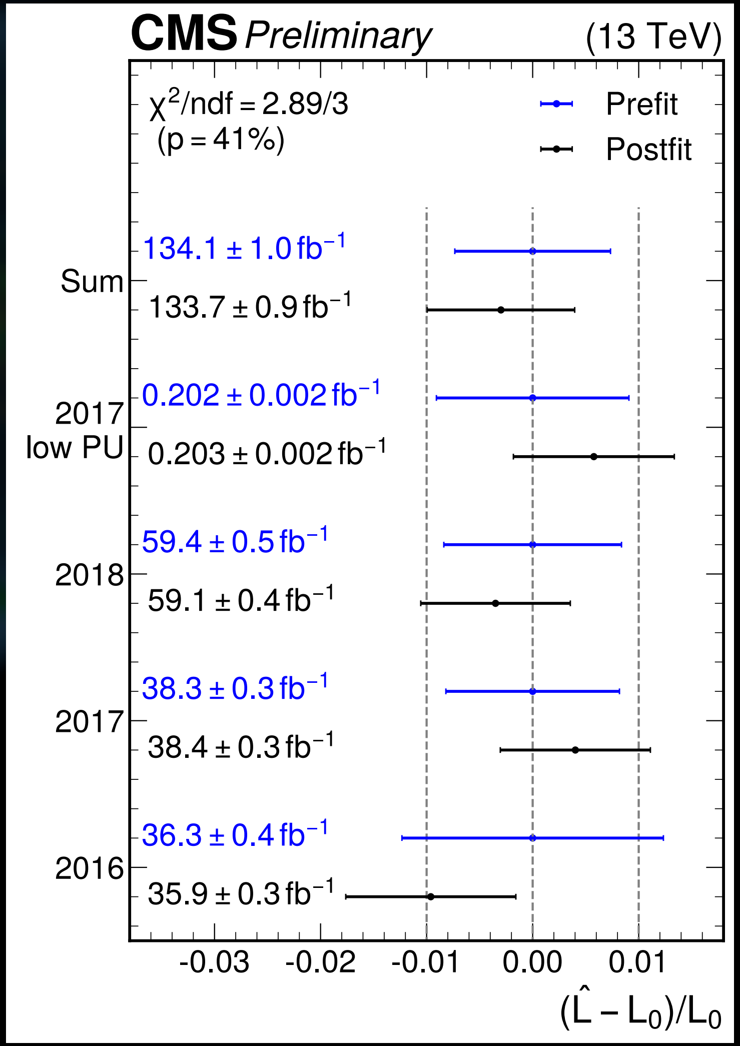
$$-2\ln(L) = \sum_i^{\text{data set}} \frac{\left(N^Z_{i,\text{pred}}(\vec{\theta}) - N^Z_i\right)^2}{\sigma_i^2} + \sum_j^{\text{syst}} \theta_j^2$$

$$N^Z_{i,\text{pred}} = \mathcal{L}_i(\vec{\theta})\,\epsilon_i^{Z\to\mu\mu}(\vec{\theta})\,\sigma_{\text{fid}}^{Z\to\mu\mu}$$

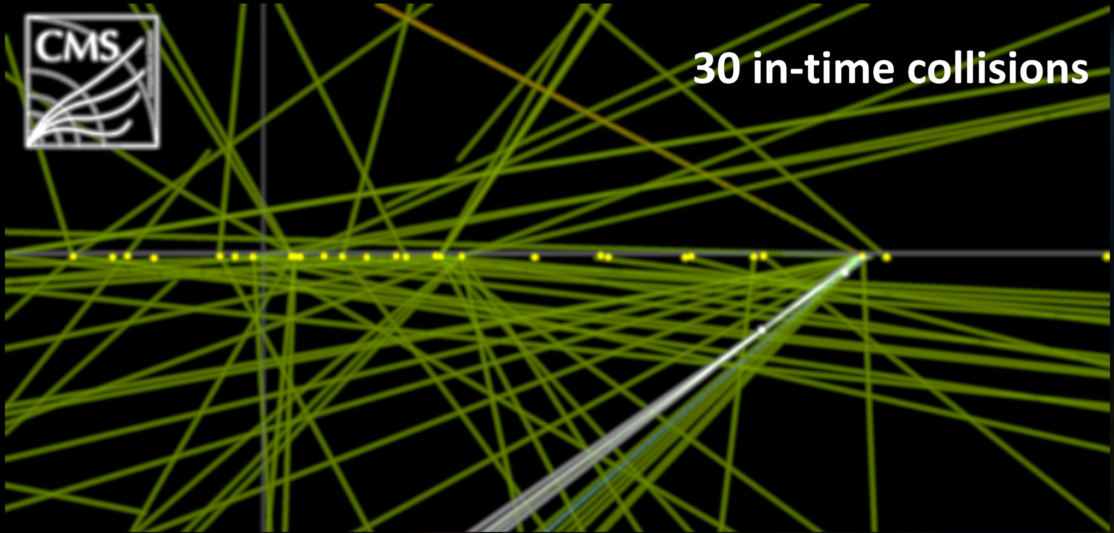
- Luminosity and Z counting efficiencies vary with correlations and prefit uncertainties shown on the previous slide.
- $\sigma_{\text{fid}}^{Z\to\mu\mu}$ floats unconstrained.
  - Fitted: 708 ± 12 pb   Theory: 734 ± 36 pb





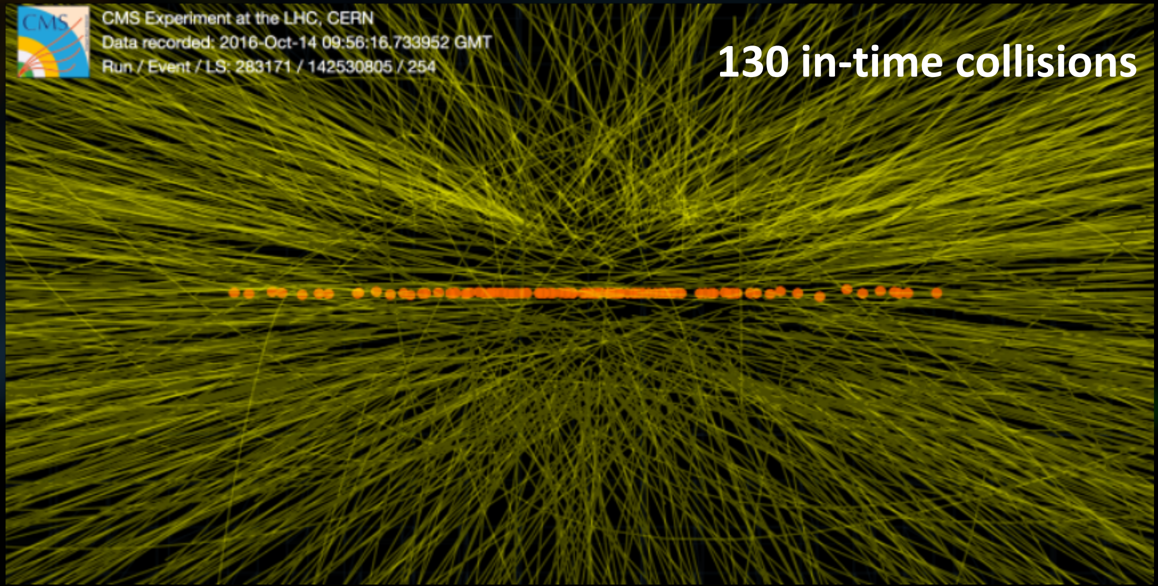


High Luminosity LHC Pileup



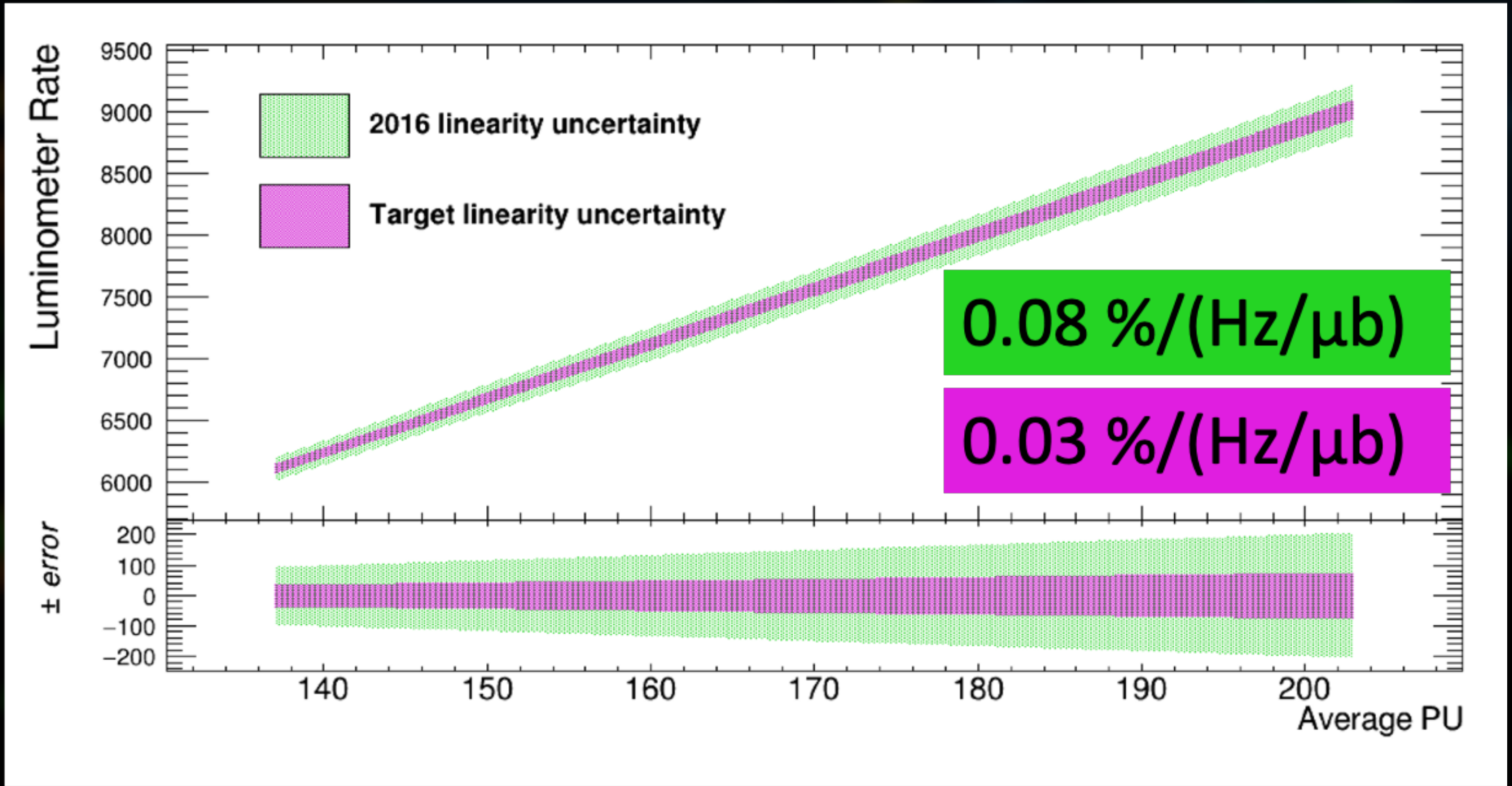
- Higher instantaneous luminosity means more collisions per crossing
- Run 2 and Run 3 have between 20-50 simultaneous pp collisions
  - Like top left

- At HL-LHC it will be more like 100-200.
- The right plot is from a special high "pile-up" fill with luminosity more like HL-LHC.



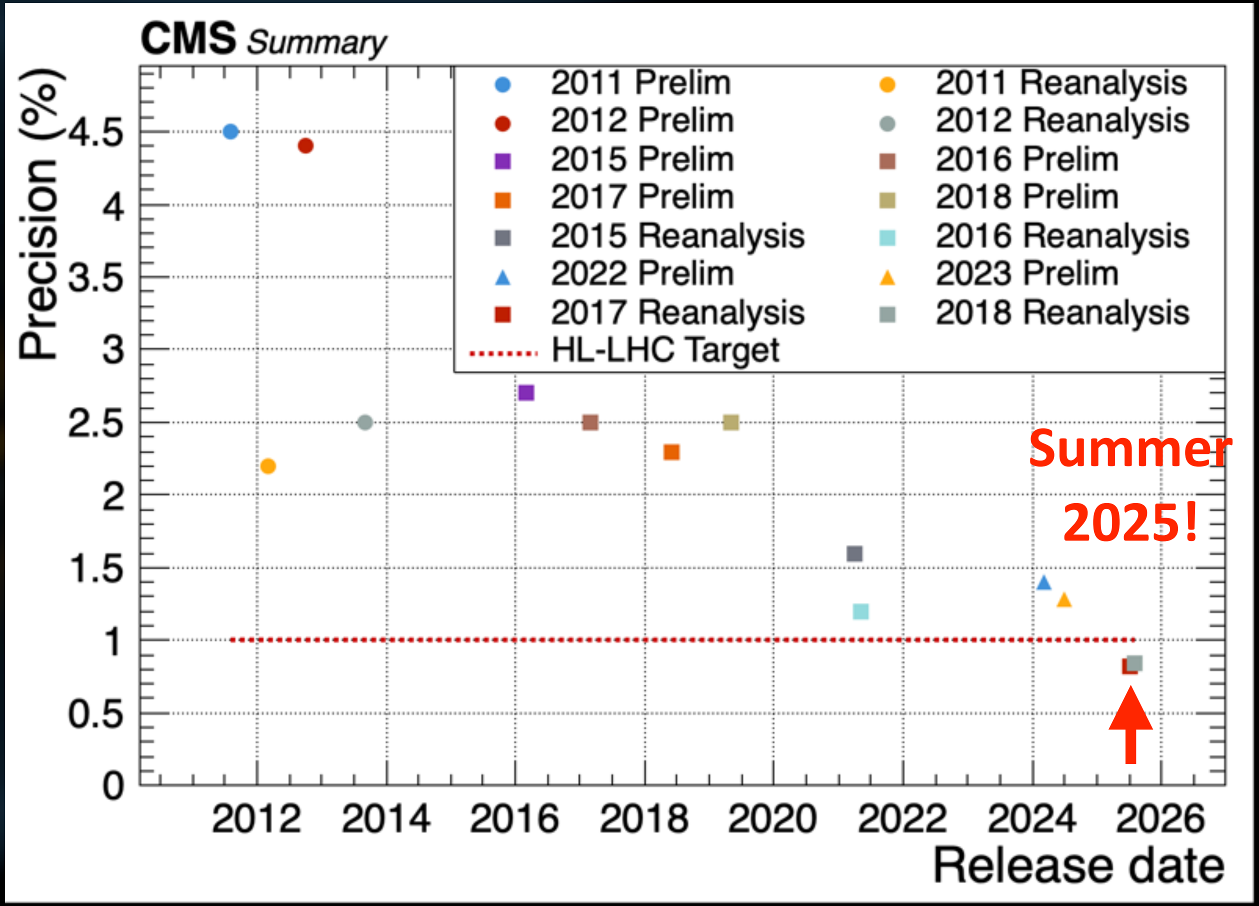
Linearity at very high PU

- The linearity uncertainty is the only one that scales with pileup.
- The same uncertainty from 2016 (or 2018) would be a 2% effect on the integrated luminosity uncertainty.



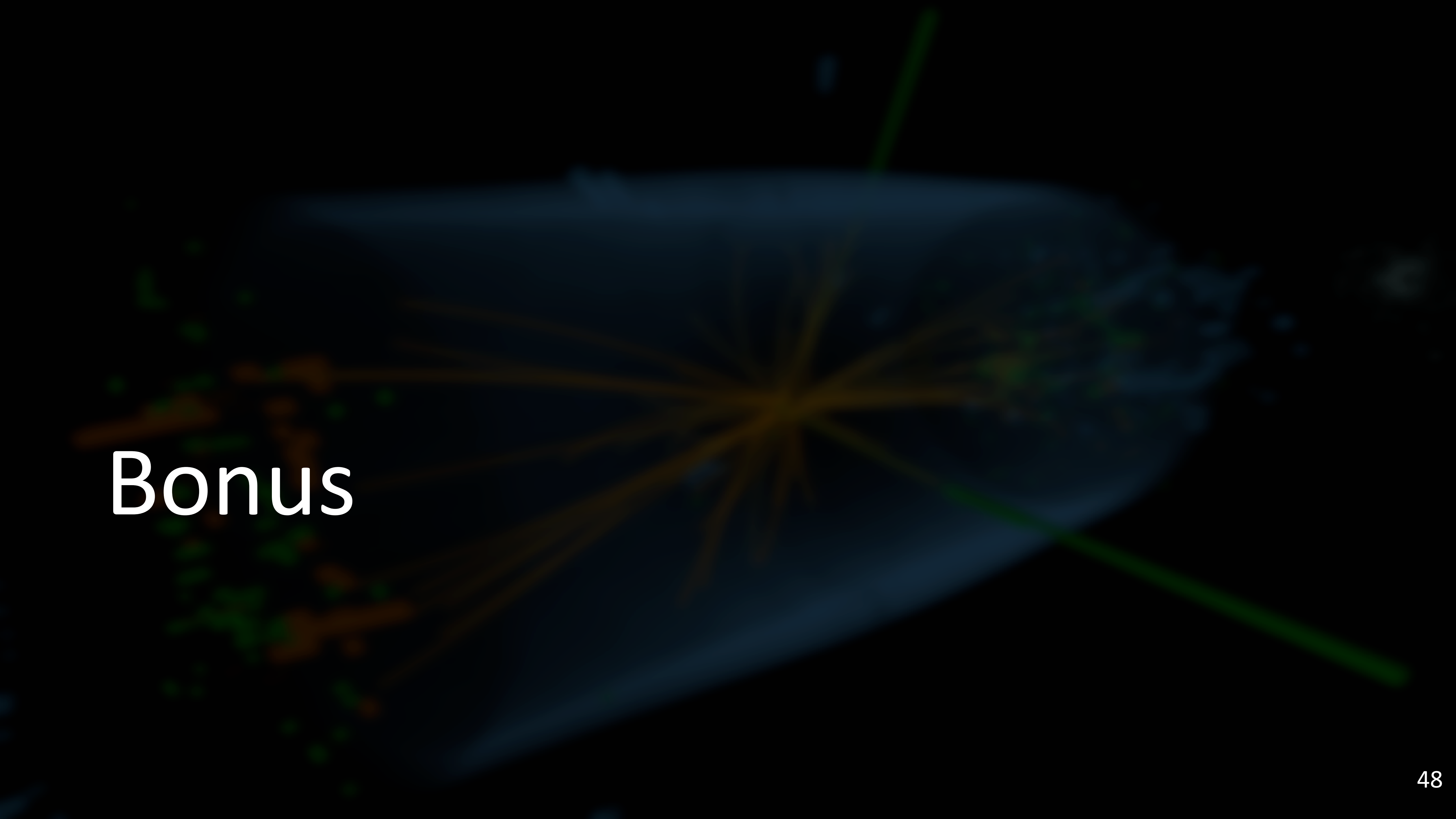
Outlook

- The latest results from CMS show that today's objectives of HL-LHC are achievable.
  - Linearity uncertainties will require further innovation to meet HL-LHC goals.
- Percent-level uncertainty is now obtainable with multiple stable, linear, independent luminosity measurements AND with sub-percent calibration uncertainty.
- Cross check from Z counting is reassuringly consistent.
- The best is yet to come.



Thank you!

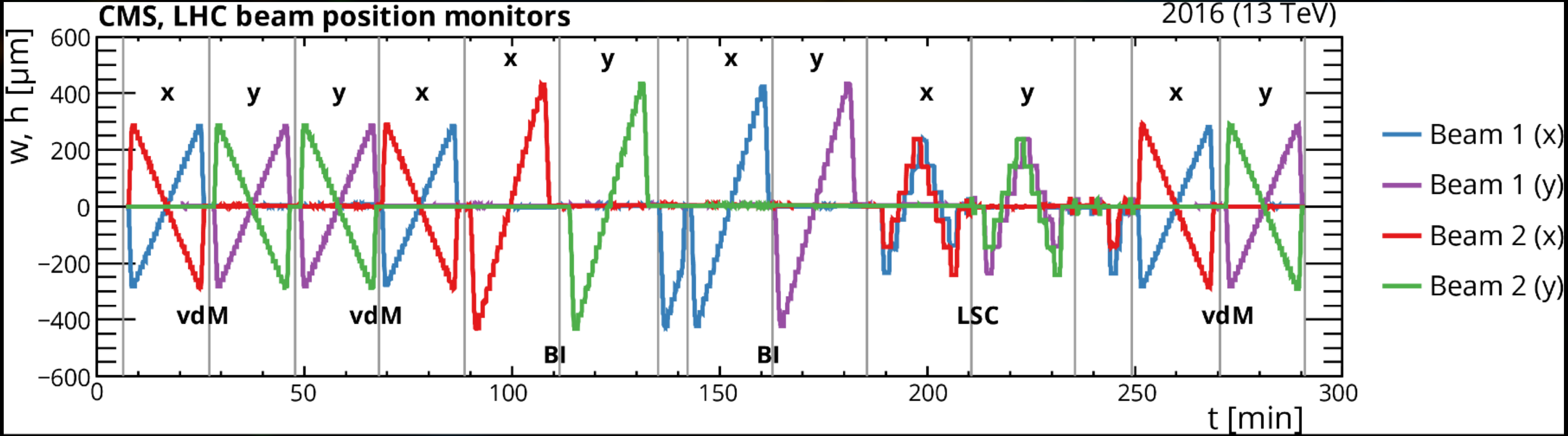
Questions?



Bonus

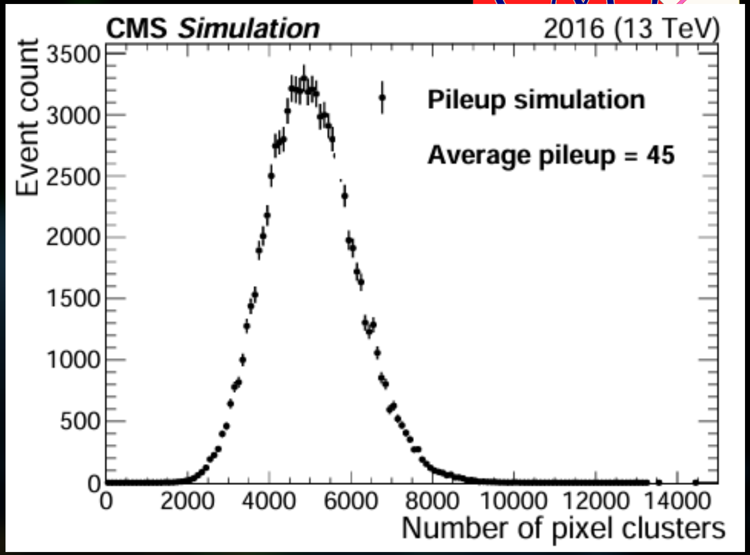
CMS 2016 vdM scan program

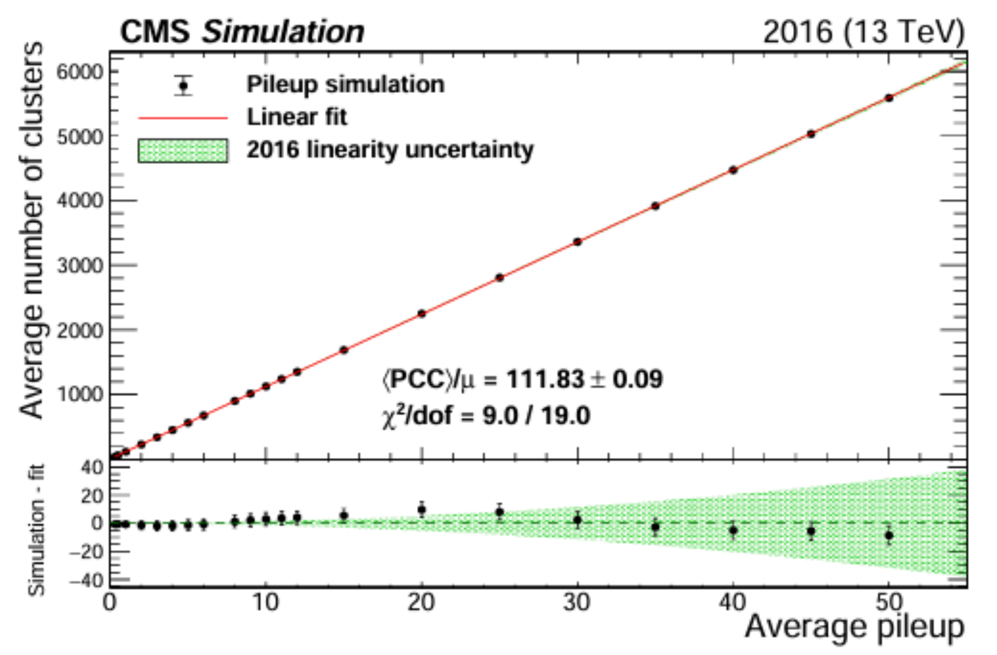
- Traditional **vdM scan**: beams move in 25 steps of 30 s each to scan separation range of $\pm 6\sigma_{beam}$
- **Beam-imaging scan** (BI): one beam fixed, other moves in 19 steps of 40 s each over $\pm 4.5\sigma_{beam}$
- Constant-separation **length-scale scan** (LSC): 2 beams separated by $1\sigma_{beam}$ move together in $1\sigma_{beam}$ steps from $-2\sigma_{beam}$ to $+2\sigma_{beam}$ average position and then with $-1\sigma_{beam}$ separation back in total of 5+5 steps of 60 s each



Pixel Cluster Counting

- The average number of charged particles is proportional to the number of proton-proton collisions.
- Since reconstruction is complex, the strategy in CMS is to count the clusters in silicon layers rather than number of reconstructed tracks.
- This method is very effective at low pileup as well, so if the number of tracks/clusters per collision is large enough, then it could work for online luminosity.
- For the moment this is an offline analysis in CMS, but there are HL-LHC luminometers (e.g., outer tracker and TPEX) with dedicated FPGA-based backends that will histogram counters per bunch crossing.

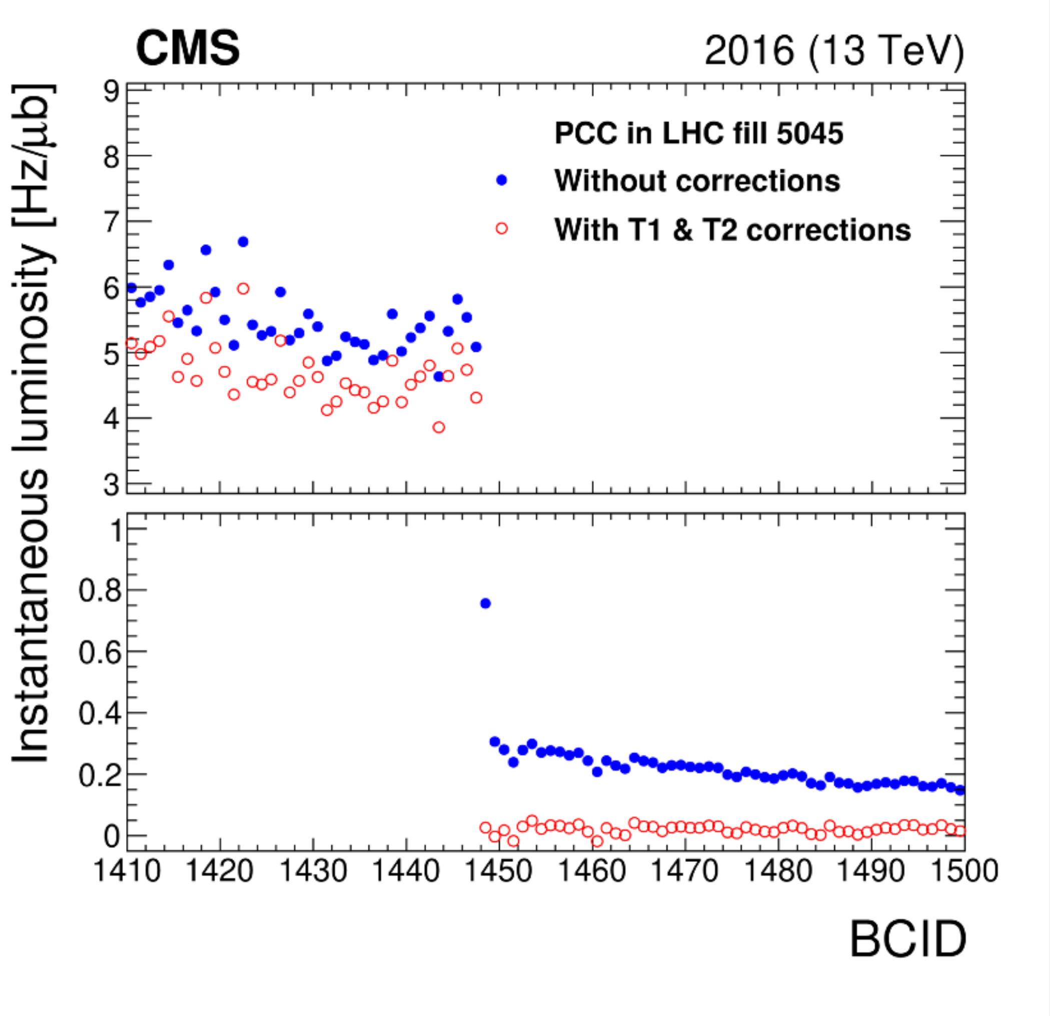




arXiv:2104.01927
LUM-17-003

Pixel Cluster Counting

- There are a couple of ways to get clusters that aren't from collisions:
    - 1) tails of earlier, real clusters are visible (electronics spillover): just the next 1-3 bunch crossing slots
    - 2) detector material is activated and radioactive decays near the pixel detector creates new charged particles (afterglow): effect lasts on the order of the half-life of activated material.



arXiv:2104.01927
LUM-17-003

Preliminary 2017 Results

- https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LUM-17-004/index.html

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

Preliminary 2018 Results

- https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LUM-18-002/index.html

	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