Luminosity Measurement at the CMS Experiment

On Behalf of the CMS Collaboration & BRIL team

Ashish Sehrawat / Universidad de Sonora
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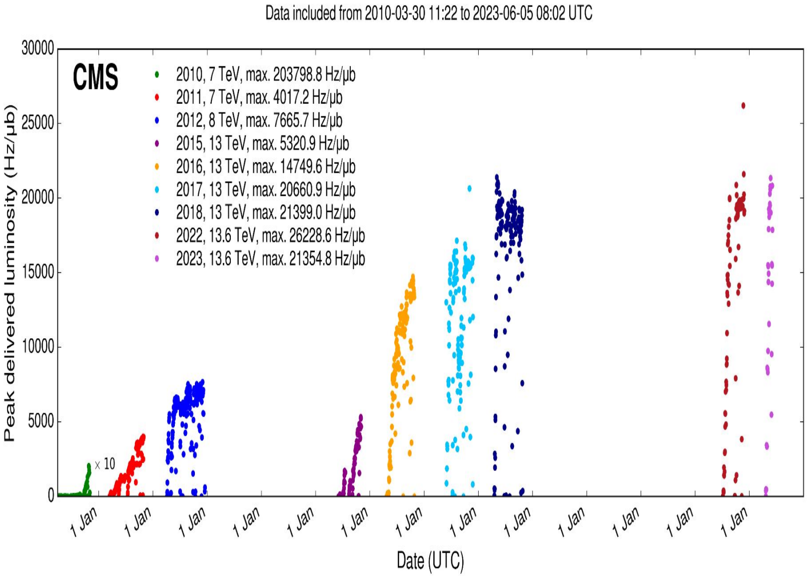
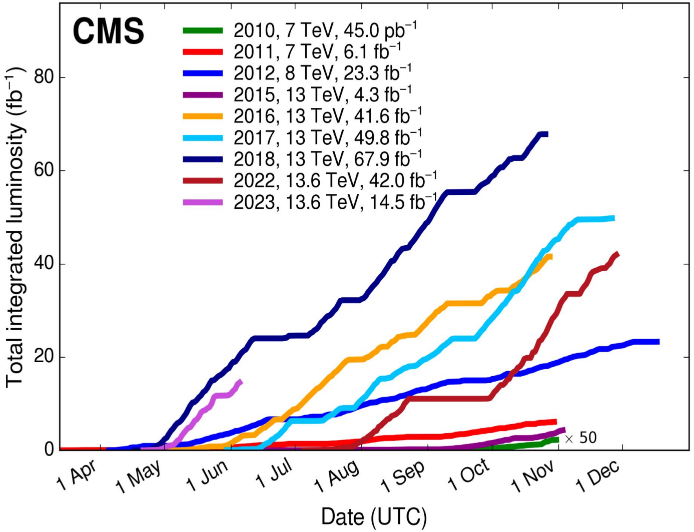
Luminosity

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

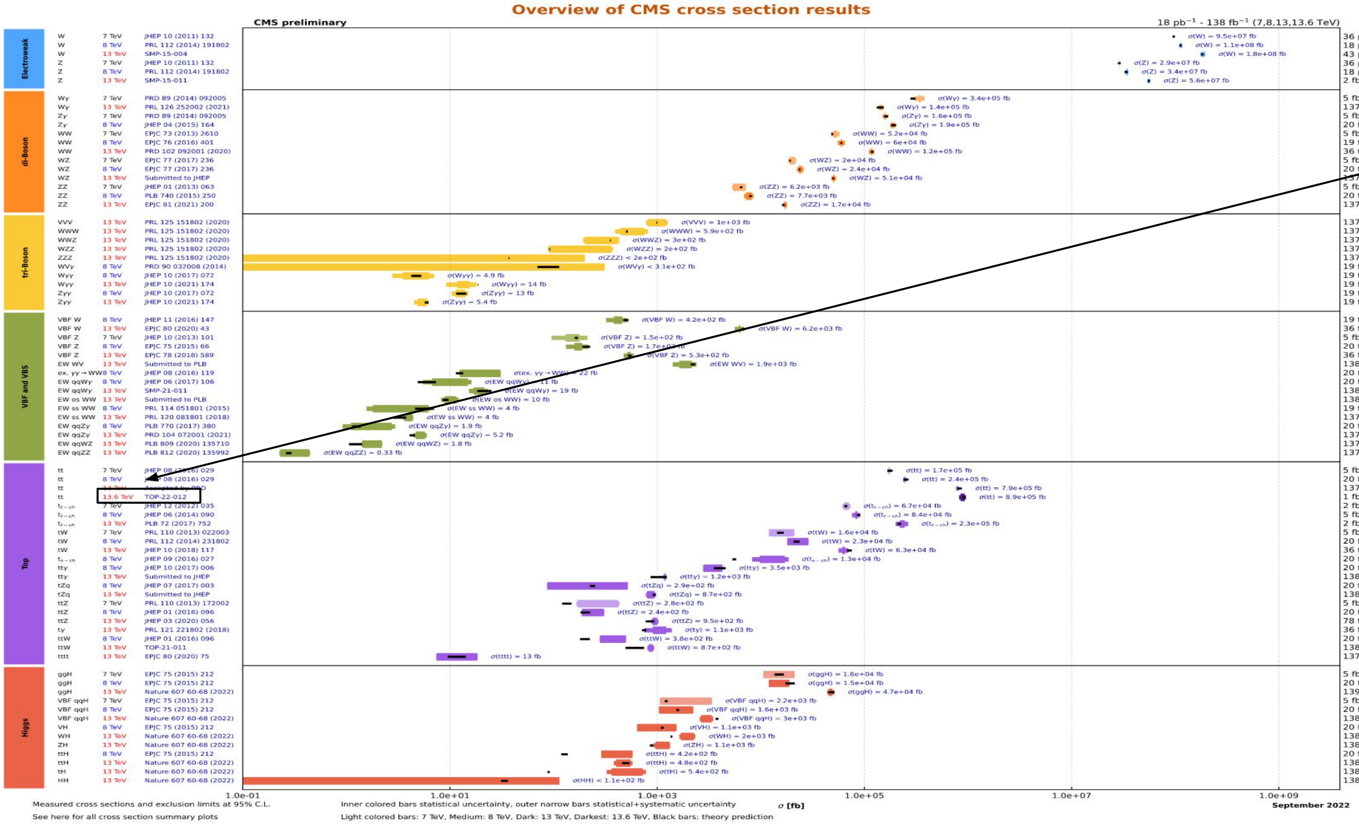
Luminosity measures collisions/unit area/unit time
Higher luminosity increases event rates, aiding rare interaction observations
Luminosity precision facilitates precise measurements for couplings, cross sections





Latest cross section results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined#CMS_Cross_Section_measurements



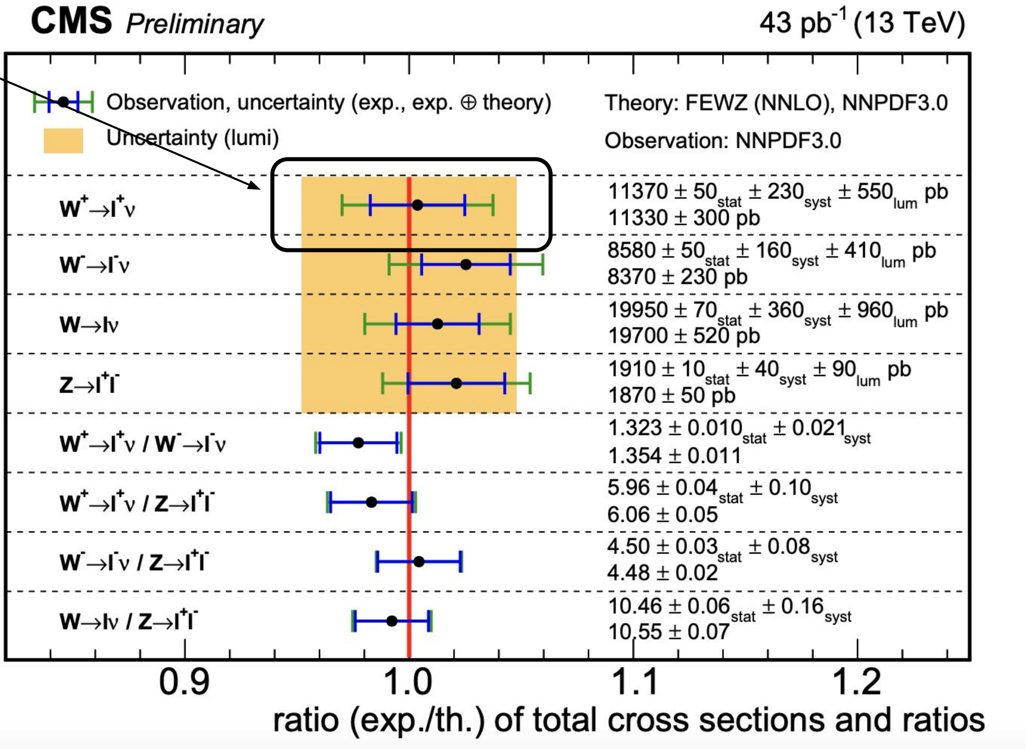
CMS-TOP-22-012
Combined uncertainty 2.6% (excluding lumi uncertainty)
luminosity uncertainty 2.3%

Precision on luminosity measurement directly propagates to precision on cross section measurement

Need for luminosity precision measurement

https://cds.cern.ch/record/2093537

Uncertainty in luminosity measurement is more than statistical and other systematics uncertainty



Luminometers

https://cerncourier.com/a/counting-collisions-precisely-at-cms/

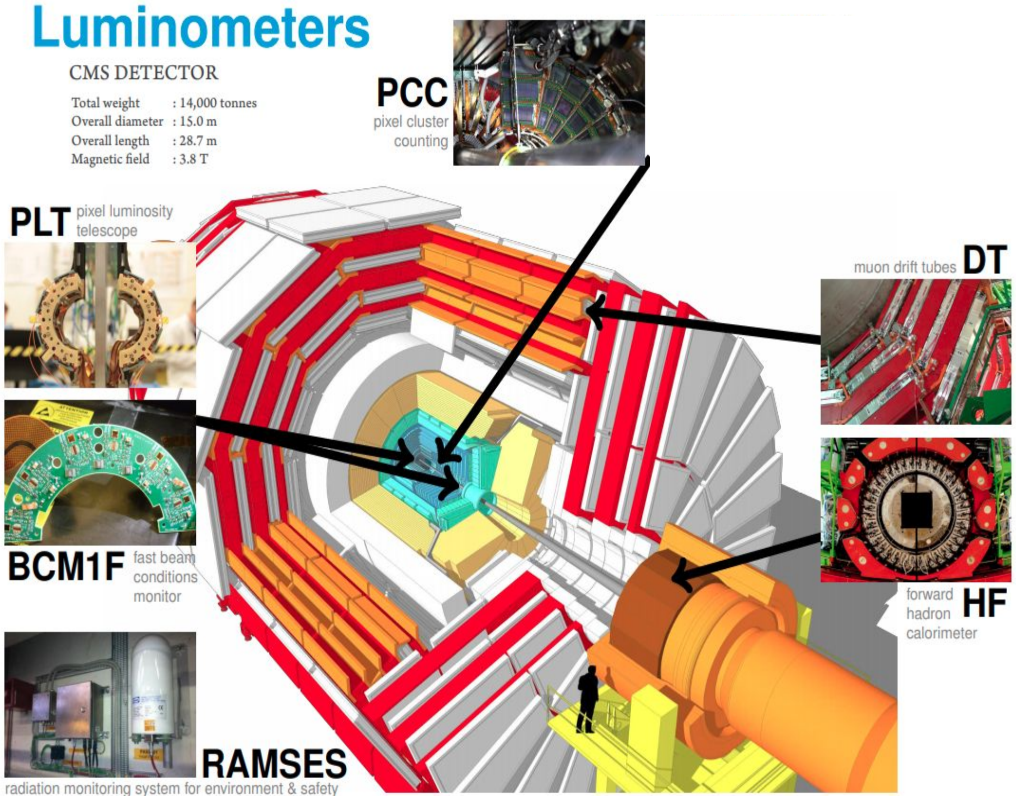
Different luminometers ensure redundancy, backup for device failures

Allow cross-checks, consistency in results

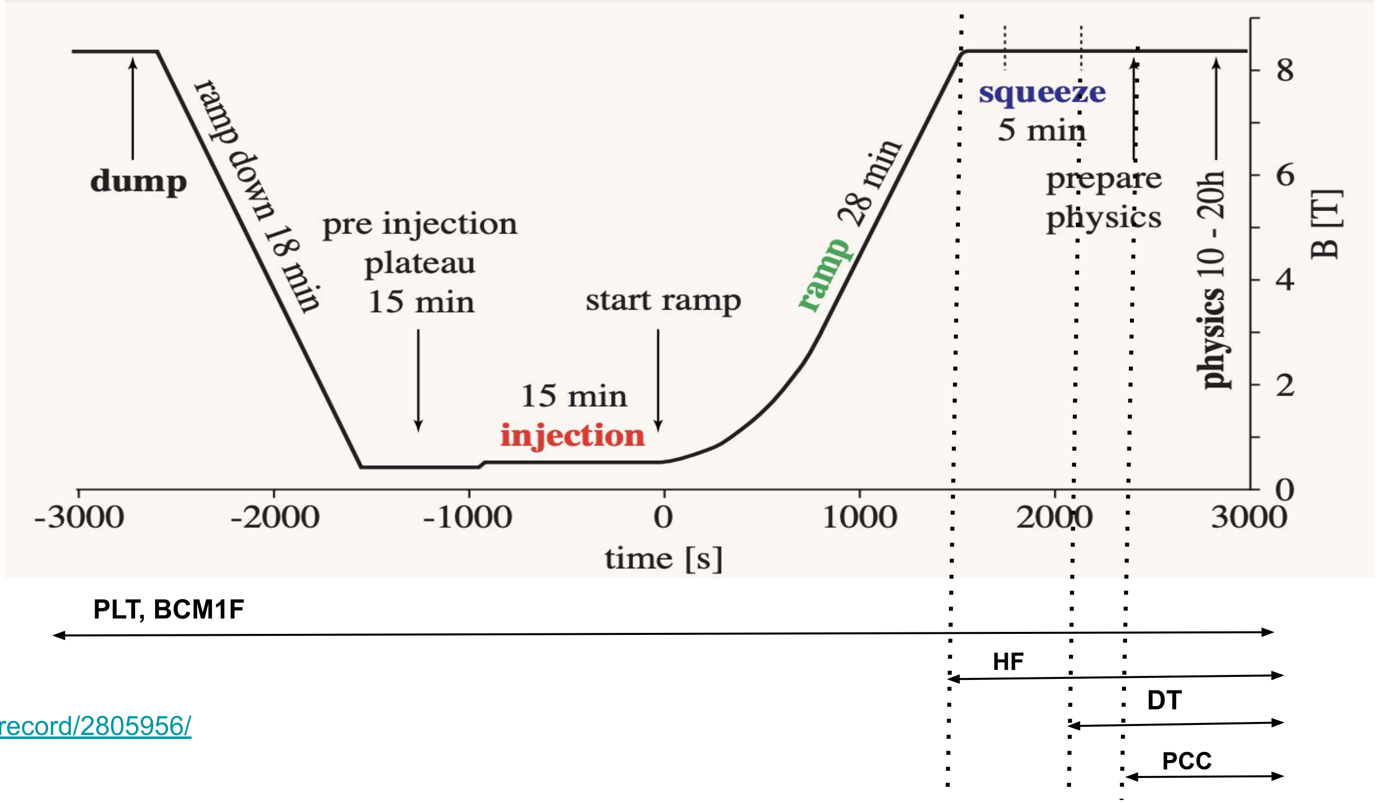
Better control on systematic uncertainties

Employ different methods, complementary information

Some with low rates can be calibrated using others



Luminometer status during LHC beam cycle



PLT, BCM1F

HF

DT

PCC

https://cds.cern.ch/record/2805956/

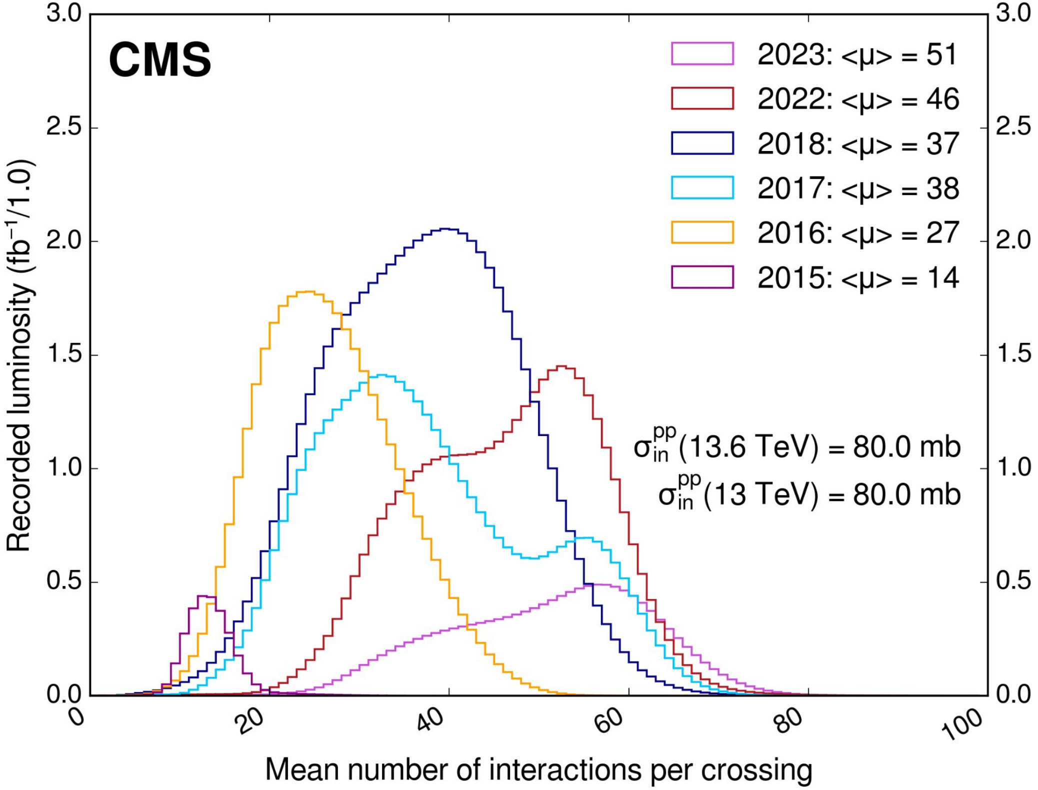
Pileup

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

Pileup is multiple collisions occurring within a single bunch crossing.

Pileup values/distributions are derived from the measured luminosity by scaling by pp cross section.

$$R = \sigma L$$

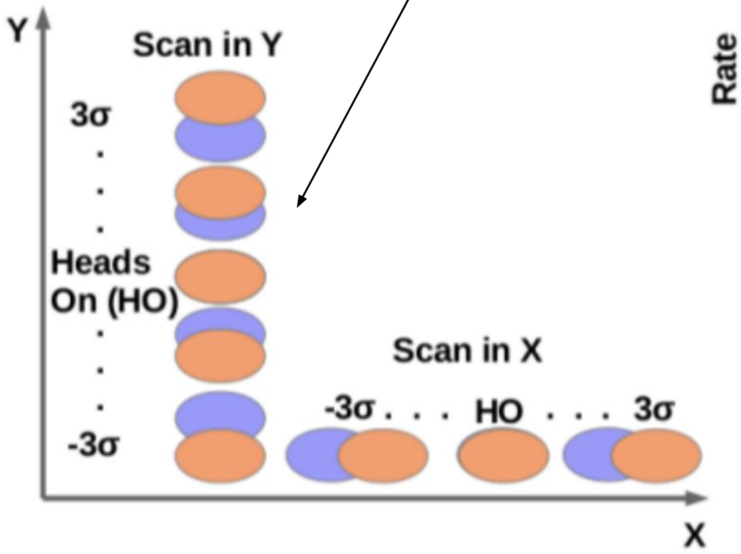


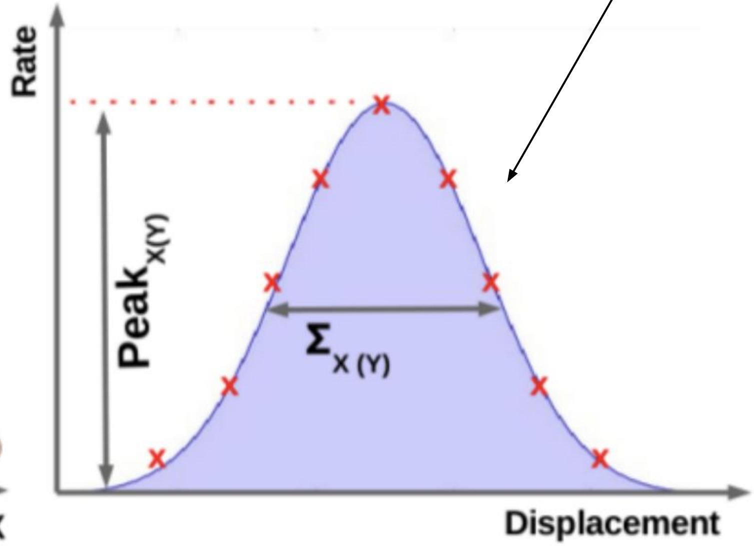
Luminometer Calibration

van der Meer scan

Scanning the beams across each other (±3σ) in the transverse plane, horizontal (x-scan) and vertical (y-scan) directions

Rate is measured as a function of beam separation

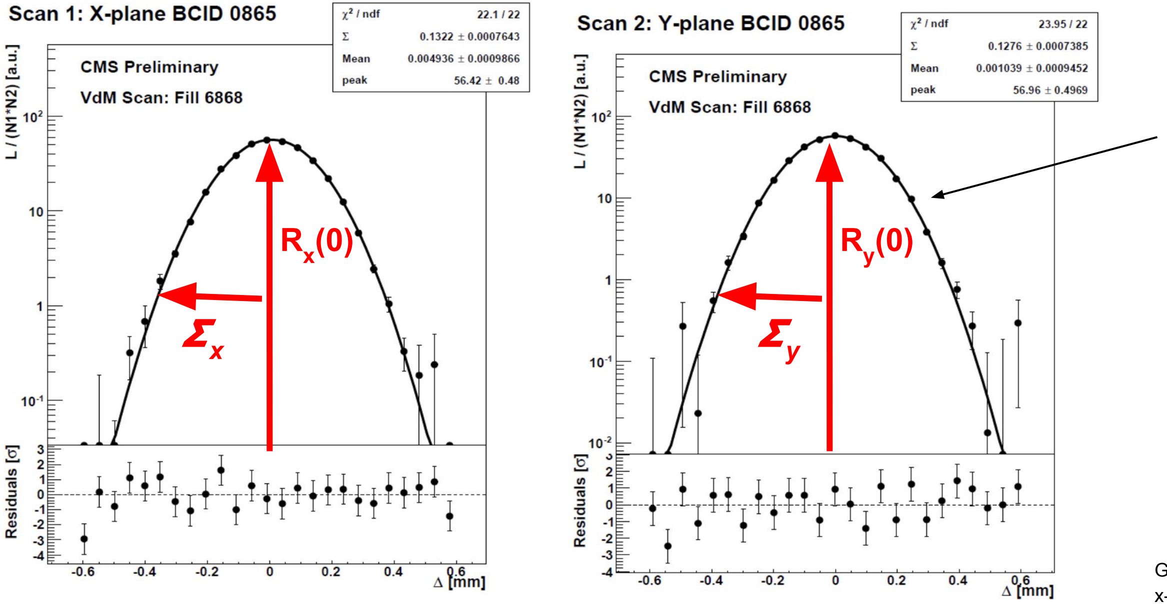




https://cds.cern.ch/record/2676164/

Rate fit

Beam overlap widths and Peak rates are obtained from the fit



Single gaussian fit

Bunch intensities (N_1, N_2) , N_b number of bunches

Beam overlap widths (Σ_x, Σ_y)

Peak rate R(0)

Beam-beam interactions

LHC orbit frequency f

Gaussian proton densities
x-y factorization
zero crossing angle

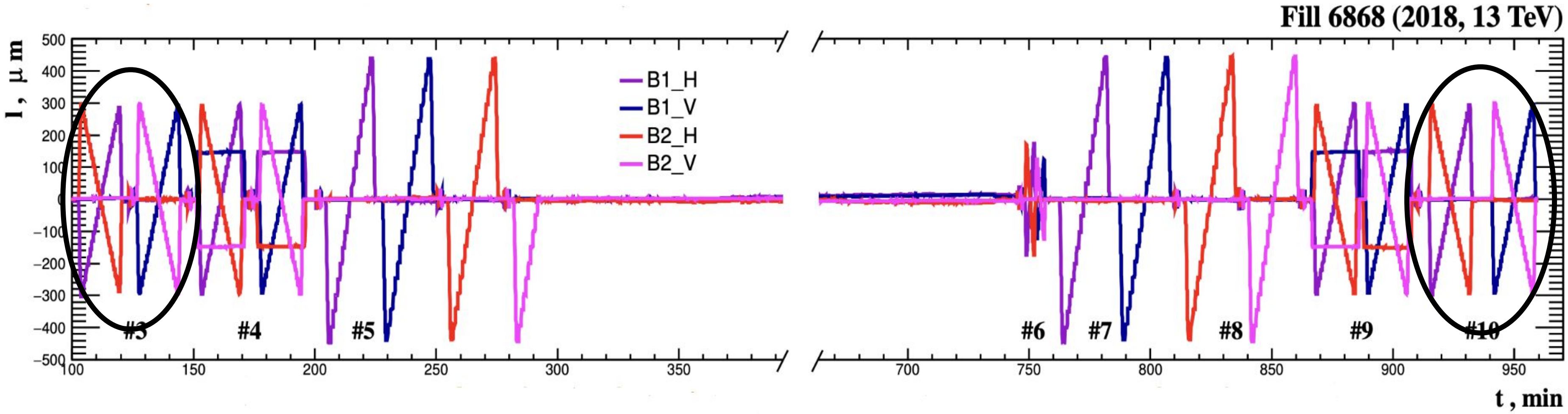
Visible cross section $$\sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y R(0)}{N_1 N_2 N_b f}$$

$$R(0) = \frac{R_x(0)+R_y(0)}{2}$$

Absolute luminosity scale $$L = \frac{N_1 N_2 f}{2\pi\Sigma_x\Sigma_y} N_b$$

https://cds.cern.ch/record/2676164/

vdM program



#3, #10 are vdM scans
#4, #9 are offset scans
#5, #7, #8 are beam imaging scans
#6 is emittance scan

vdM scans are typically conducted at least once a year to ensure the luminometer is correctly calibrated. Results of these scans are used to normalize the data collected by the experiments during physics run.

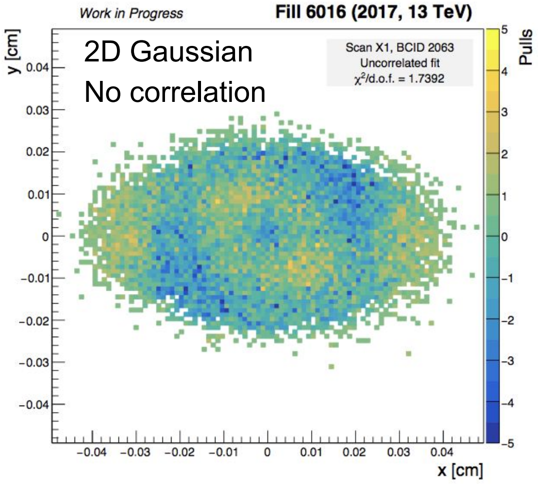
Luminosity precision

XY non-factorization

https://cds.cern.ch/record/2621960/

Beam overlap width transversal to scanning direction is not constant

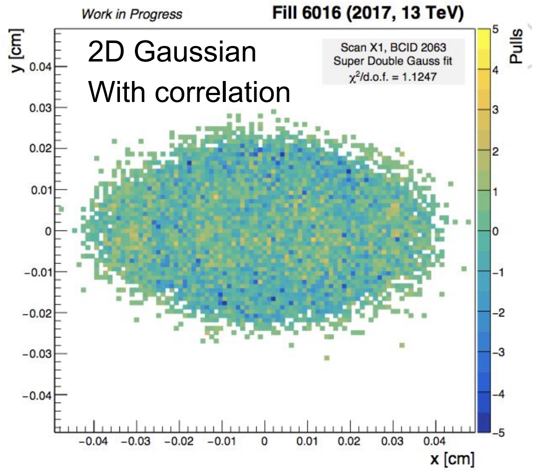
Beam Imaging scans: Beam 2 fixed and Beam 1 moved in steps, beam shape from reconstructed primary vertices
Offset scans: Beams at constant separation in non-scanning direction, luminous region profile from fit to rate vs 2D beam separation



$$g(x) \cdot g(y) = \exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)\right]$$

Pull distribution of global fit to all scan points

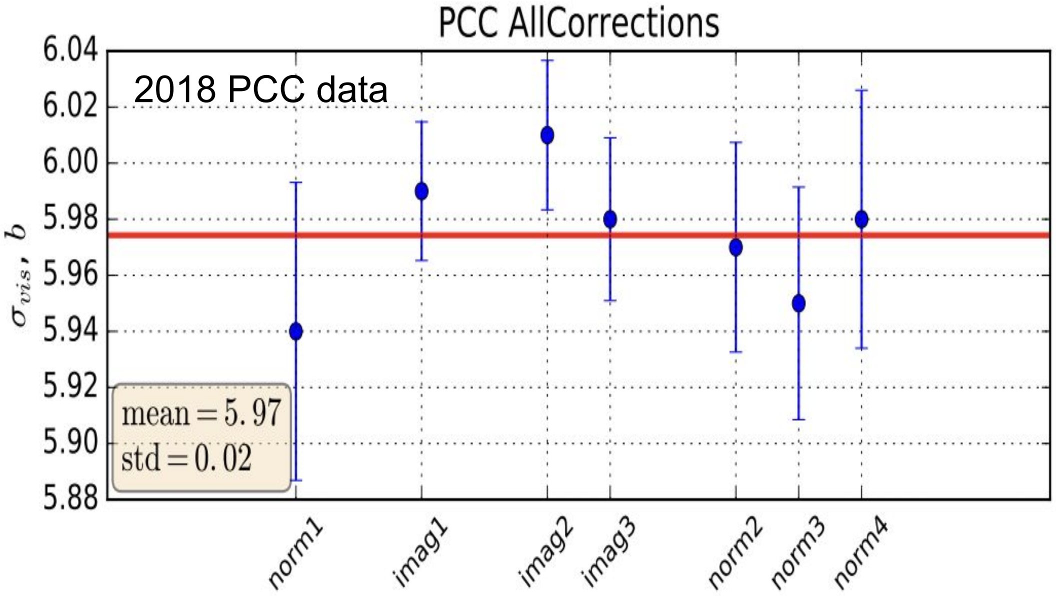
Pull is number of measured vertices and vertices from fit, divided by the statistical uncertainty



$$g(x, y) = \exp\left[-\frac{1}{2(1-\varrho^2)}\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} - \frac{2\varrho xy}{\sigma_x \sigma_y}\right)\right]$$

Scan to Scan variation

CMS LUM-18-002-pas



Scan to scan variation of visible cross section averaged over all BCIDs

Statistical uncertainty is shown for each scan

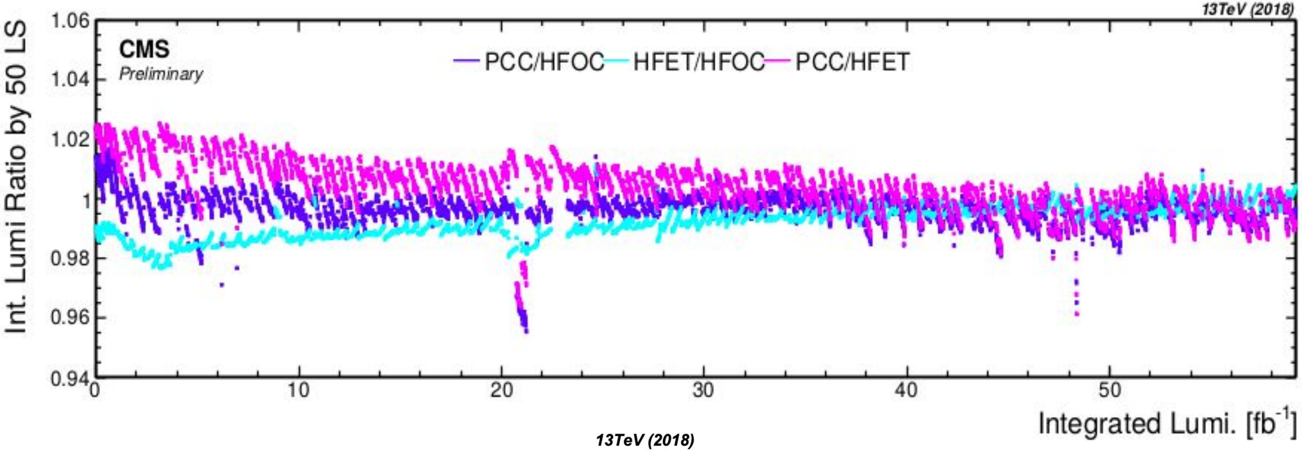
CMS-PAS-LUM-18-002

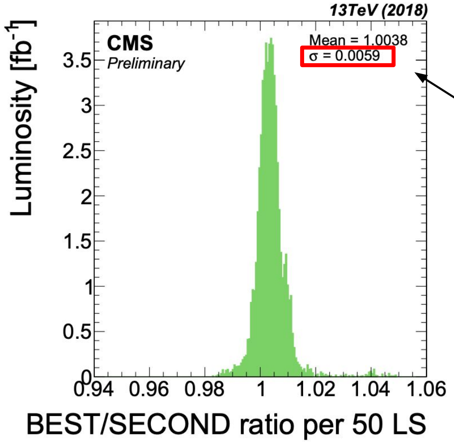
Stability

Time-dependent changes in detector performance or environmental conditions.

Detector aging, radiation damage, fluctuation in noise.

The standard deviation is used as stability systematic uncertainty.





Stability systematic uncertainty

Linearity

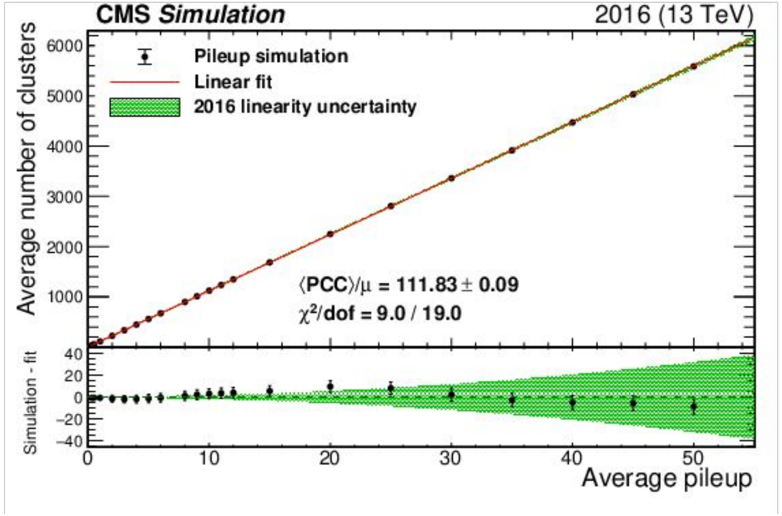
Detector response variation at different luminosity levels.

Pileup conditions affect the linearity of luminosity measurement.

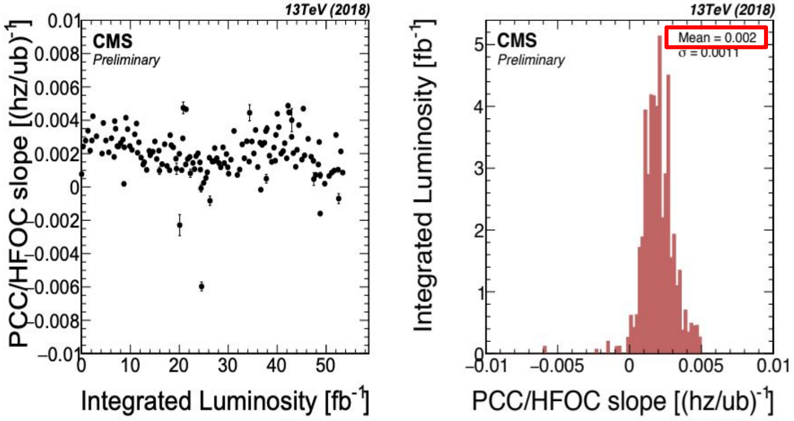
High pileup can cause over- or underestimation of luminosity.

The product of slope and luminosity range is measure of linearity systematic uncertainty.

CMS-LUM-17-003



CMS-PAS-LUM-18-002



CMS-PAS-LUM-18-002

Afterglow

Type 1 Afterglow Noise: Electronic spillover

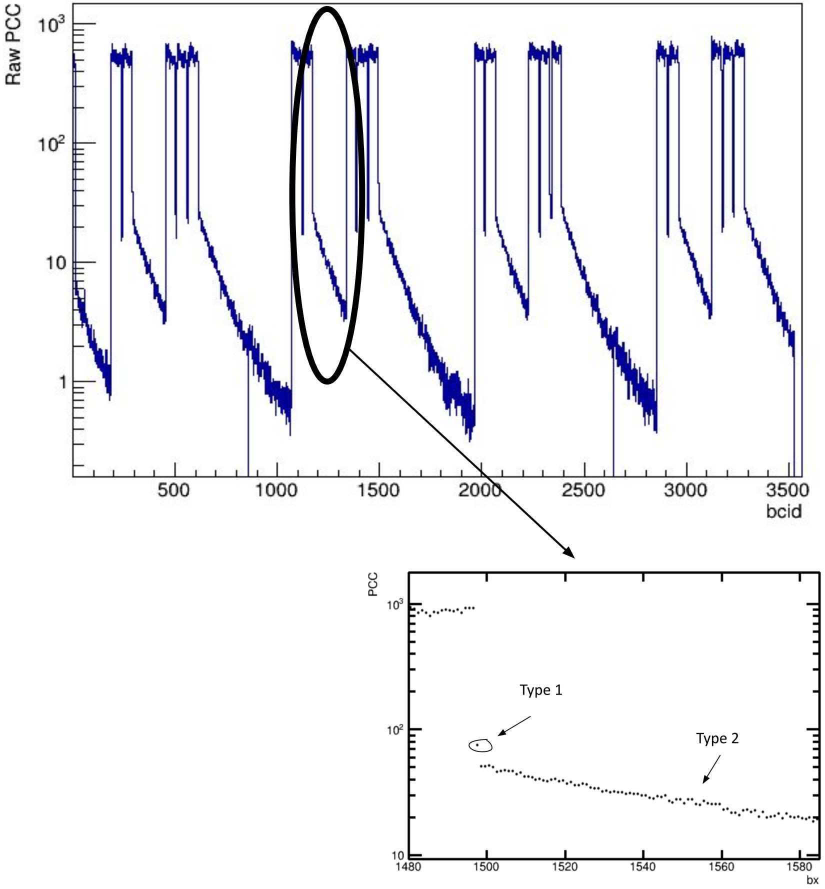
Uncertainty is mean type 1 residual

$$Type1\ residual = \frac{first\ empty\ bunch\ lumi}{colliding\ bunch\ lumi}$$

Type 2 Afterglow Noise: Exponential decay of detector activation

Uncertainty is mean type 2 residual

$$Type2\ residual = \frac{second,\ third,..\ empty\ bunches\ lumi}{colliding\ bunch\ lumi}$$



Mathematical model:

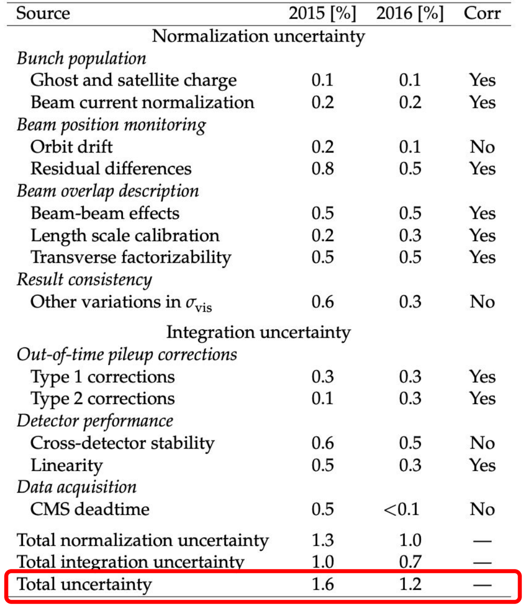
$$F(x) = \sum_{k=0}^{Nbcid} N_k[(x-k==0) + A(x-k==1) + Bexp\big(-C(x-k-1)\big)(x-k>=1)]$$

LUM-17-004-pas

Uncertainty in Run 2 luminosity

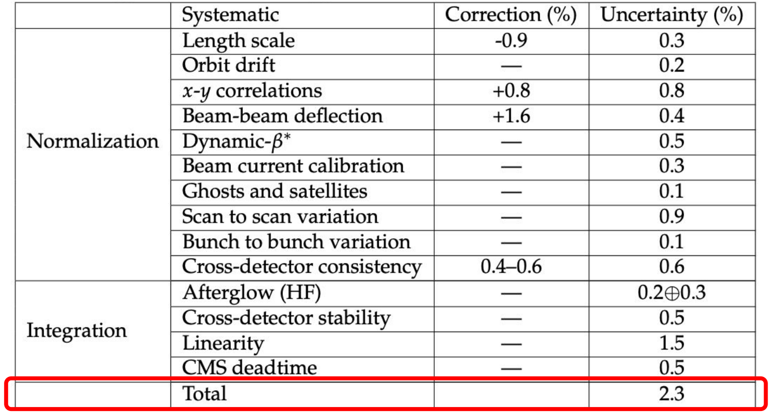
https://doi.org/10.1140/epjc/s10052-021-09538-2

2015-2016



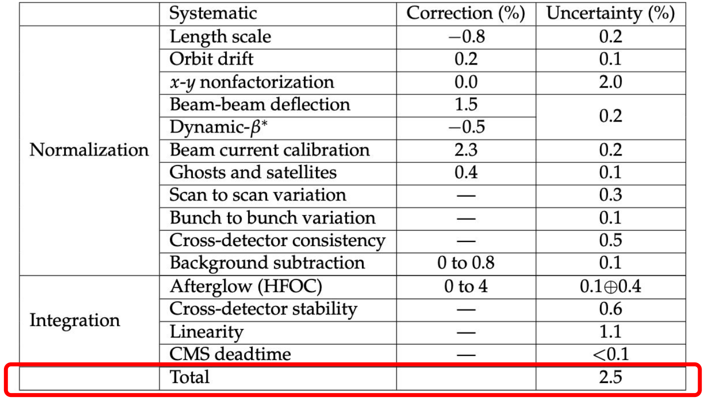
Source	2015 [%]	2016 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.6	0.3	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	1.3	1.0	—
Total integration uncertainty	1.0	0.7	—
Total uncertainty	1.6	1.2	—

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

2018

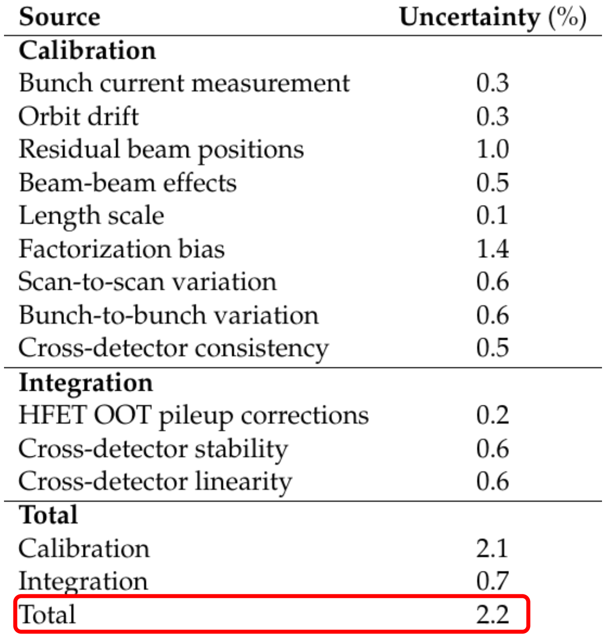


	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—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

Systematic uncertainty expected to improve due to ongoing work

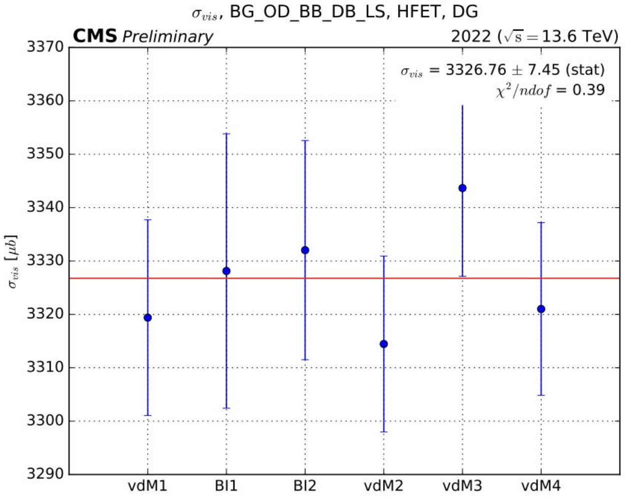
LUM-18-002-pas

Run 3 preliminary results

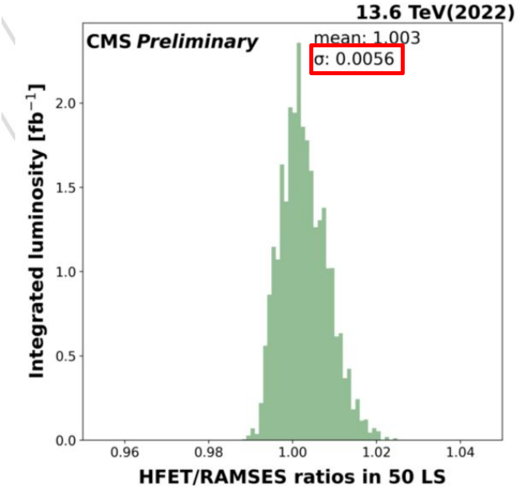


Source	Uncertainty (%)
Calibration	
Bunch current measurement	0.3
Orbit drift	0.3
Residual beam positions	1.0
Beam-beam effects	0.5
Length scale	0.1
Factorization bias	1.4
Scan-to-scan variation	0.6
Bunch-to-bunch variation	0.6
Cross-detector consistency	0.5
Integration	
HFET OOT pileup corrections	0.2
Cross-detector stability	0.6
Cross-detector linearity	0.6
Total	
Calibration	2.1
Integration	0.7
Total	2.2

Calibration



Stability



Luminosity measurement from Z boson

Z counting method

LUM-21-001-pas

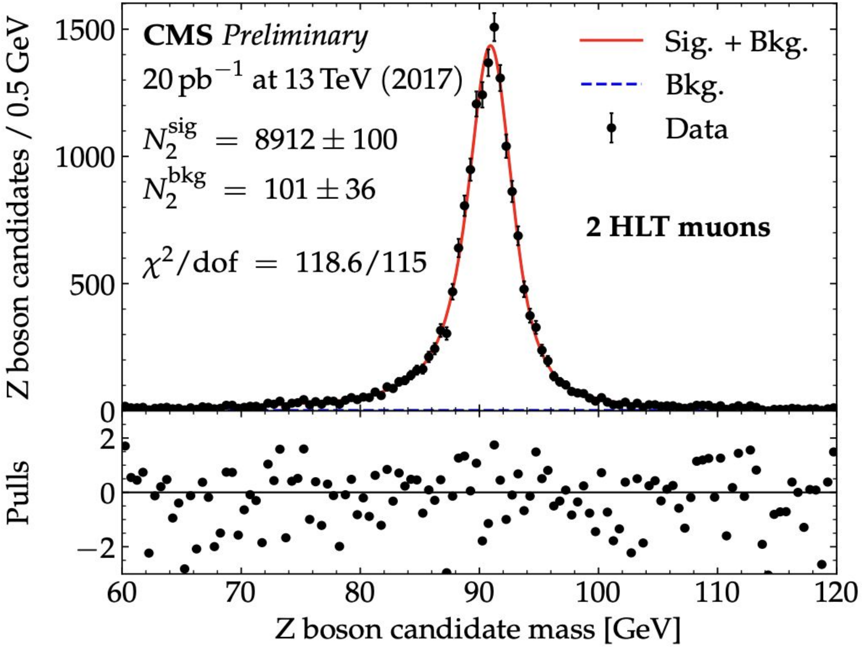
Muons penetration ensures accurate identification, low background.

Large sample Z events allow in situ efficiency calibration.

Comparison of Z counts under varied pileup conditions cancels systematic uncertainties, enhancing precision.

Two datasets considered: low and high pileup samples.

High pileup luminosity is calculated using low pileup sample.

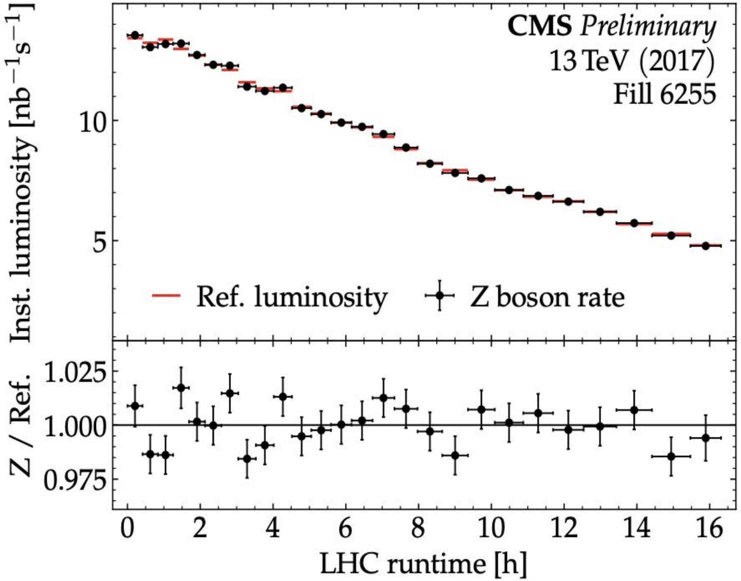


Fit used to get number of Z boson events (N^Z) and muon trigger efficiency. Muon trigger correlation coefficient from Z boson and trigger efficiency.

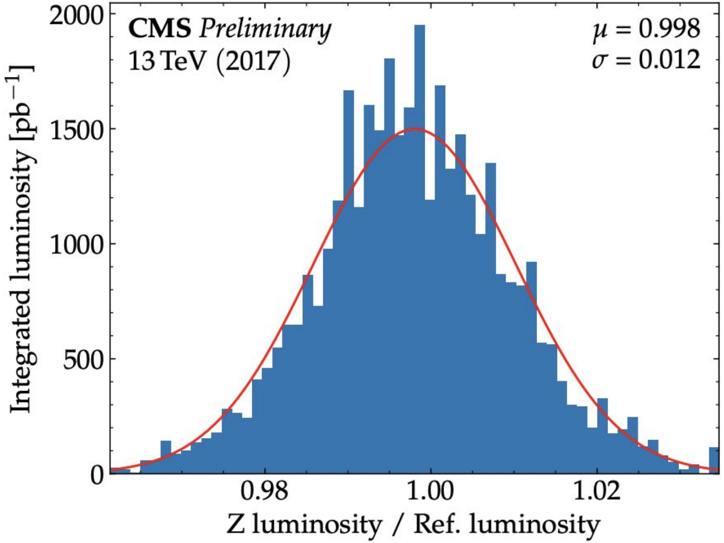
$$L_{highPU} = \frac{N^Z_{highPU}}{N^Z_{lowPU}} L_{lowPU}$$

Z luminosity

LUM-21-001-pas



Efficiency corrected Z boson rate compared with HF



Consistency between two methods within 0.2%

Summary

- Precision on luminosity measurement directly propagates to precision in coupling, cross section measurement of various physics processes.
- Several luminometers are used to have backup for luminometer failure, better estimation of systematic uncertainty, carry out luminosity measurement using different techniques.
- Dominant uncertainty comes from xy non-factorization during 2018, scan to scan variation during 2017 and residual differences between the measured beam positions and the ones provided by the operational settings of the LHC magnets in 2015.
- Best precision on luminosity measurement during Run 2 is 1.2 % for 2016 data taking.
- Due to several improvements in reanalysis, the expected precision for 2017-2018 is 1%.
- Phase II HL-LHC will increase luminosity by 10 times its current value. CMS detector will have extended tracker, upgraded data acquisition system, improved muon system, upgraded trigger system, robustness to radiation and new readout electronics.