LHCP May 25-30, 2020

LUMINOSITY MEASUREMENTS AT THE LHC EXPERIMENTS.

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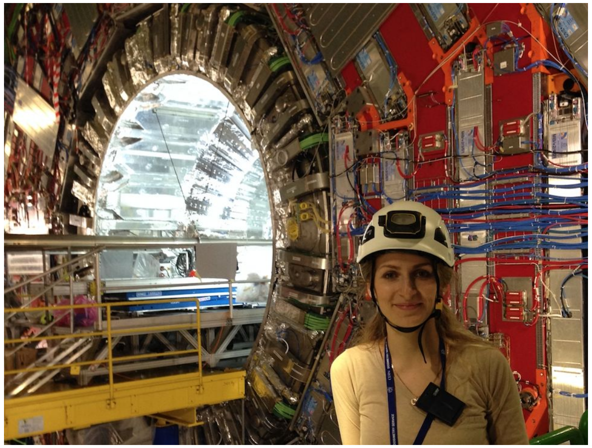

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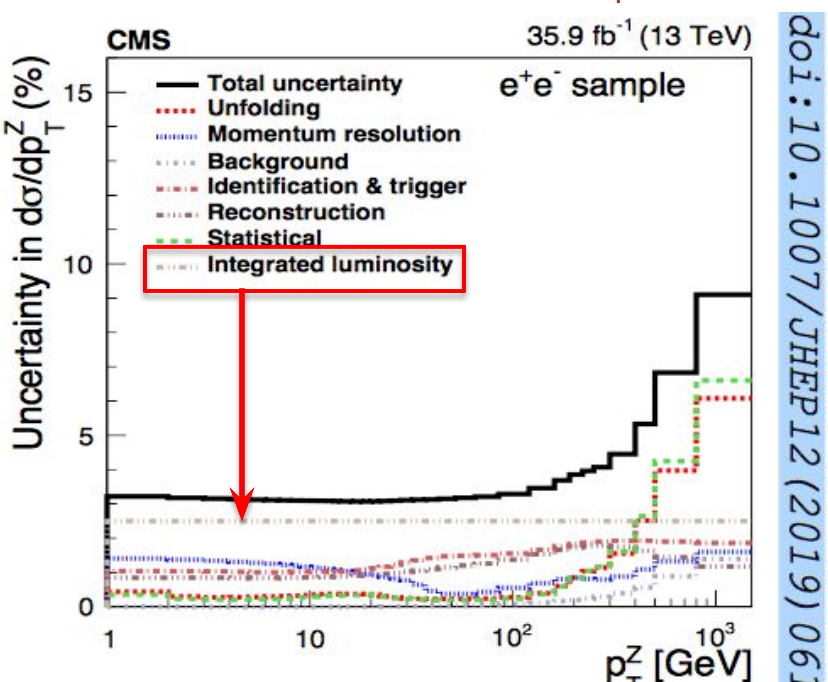
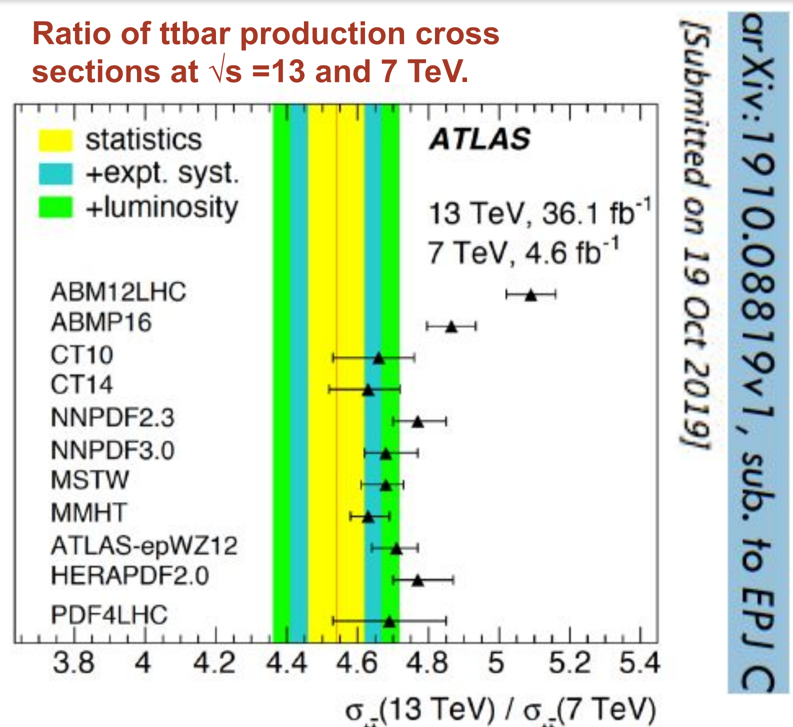
Motivation for online/offline luminosity precision

- **Online luminosity $\mathcal{L}$ with ~5% absolute accuracy is required for operating the accelerator and the experiments** (performance optimization, leveling, trigger optimization, etc.)
- **Offline $\mathcal{L}$ is required for precision cross section measurements. Current Run-2 per year preliminary $\mathcal{L}$ uncertainty is in the range of 1.6-3.4% (1.5-4.1%) for pp (HI) across experiments.**
    - **CMS/ATLAS**: for leptonic Z, W, top decays **~1%** uncertainty would make luminosity subleading among other well-controlled systematics.
    - **ALICE**: **targets 2-3%** uncertainty driven by precision measurement of diffractive, quarkonium and heavy-flavor cross-sections in pp collisions, and vector meson photo-production in Pb-Pb collisions.
    - **LHCb**: targets ≤2% uncertainty, motivated by the precise leptonic Z, W cross section measurements in the forward acceptance.

Z->ee absolute cross section in p_T bins.



Ratio of ttbar production cross sections at √s =13 and 7 TeV.



Luminosity measurement

- Luminosity ($\mathcal{L}$) is obtained from the observed rate in a detector (R) and a calibration constant, called visible cross section (σ_{vis}):

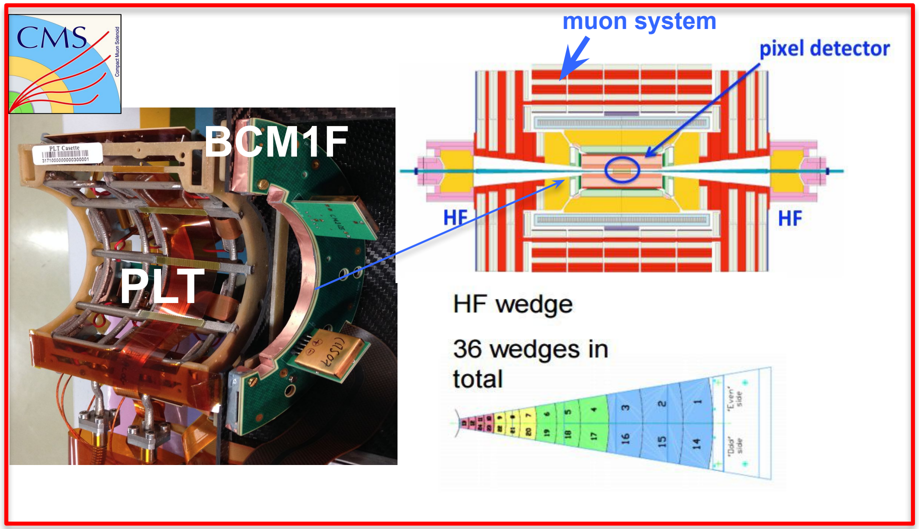
Uncertainty due to detector effects (running year)

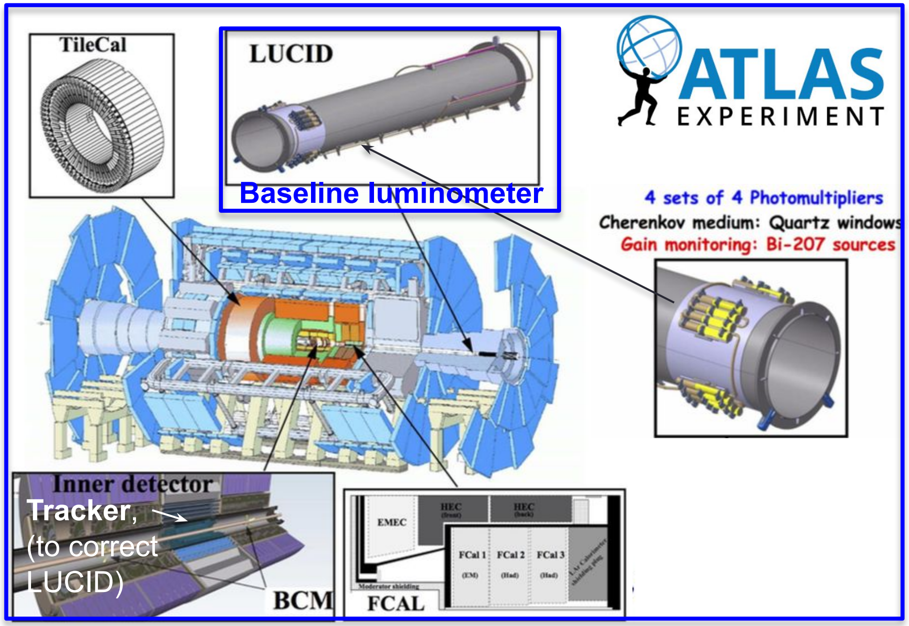
$$\mathcal{L} = R / \sigma_{vis}$$

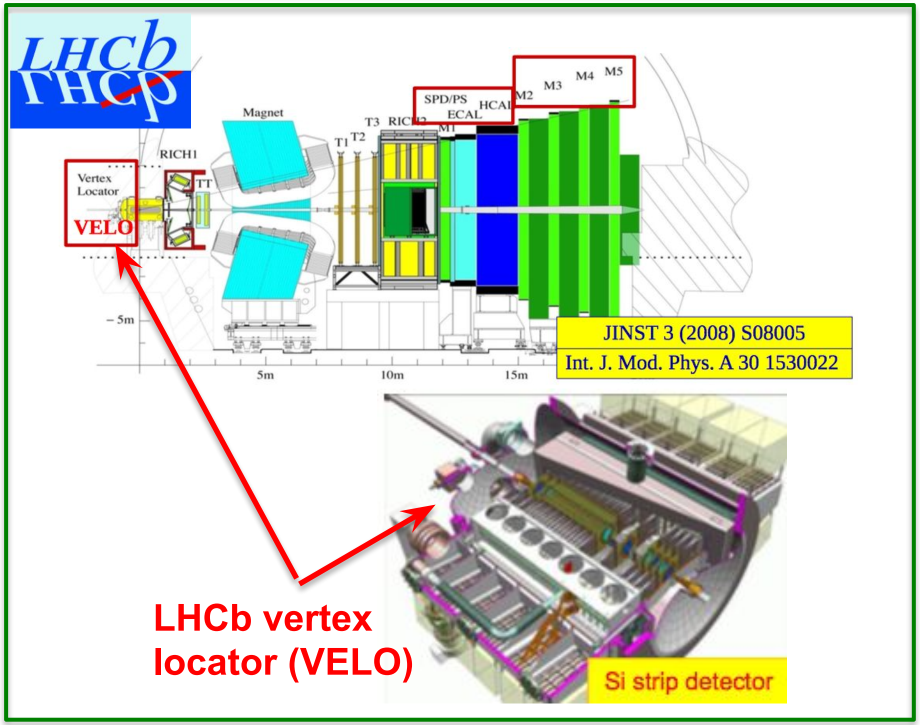
Uncertainty due to calibration and corrections (vdM scans)

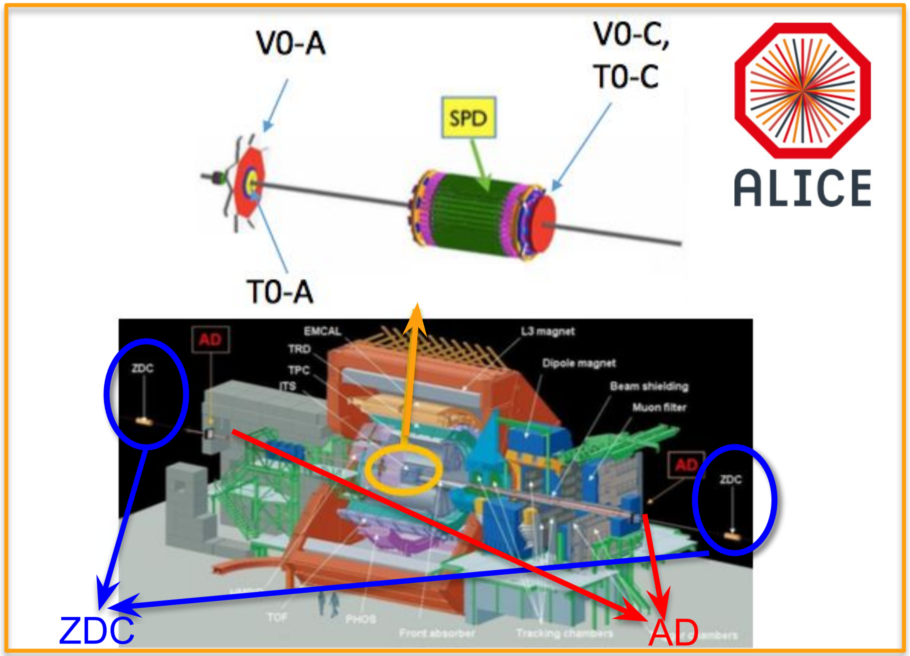
- Experiments use various counting methods to derive rate:
  - **ATLAS**:
    - hit counting (= CMS zero counting)
    - track counting
    - bunch-integrated particle flux in calorimeters
  - **LHCb**:
    - track counting
    - vertex counting
    - transverse energy sum
    - muon counting
  - **CMS:**
    - coincidence counting
    - zero counting
    - pixel cluster counting
    - transverse energy sum
    - muon counting
  - **ALICE**:
    - coincidence counting

Luminometers

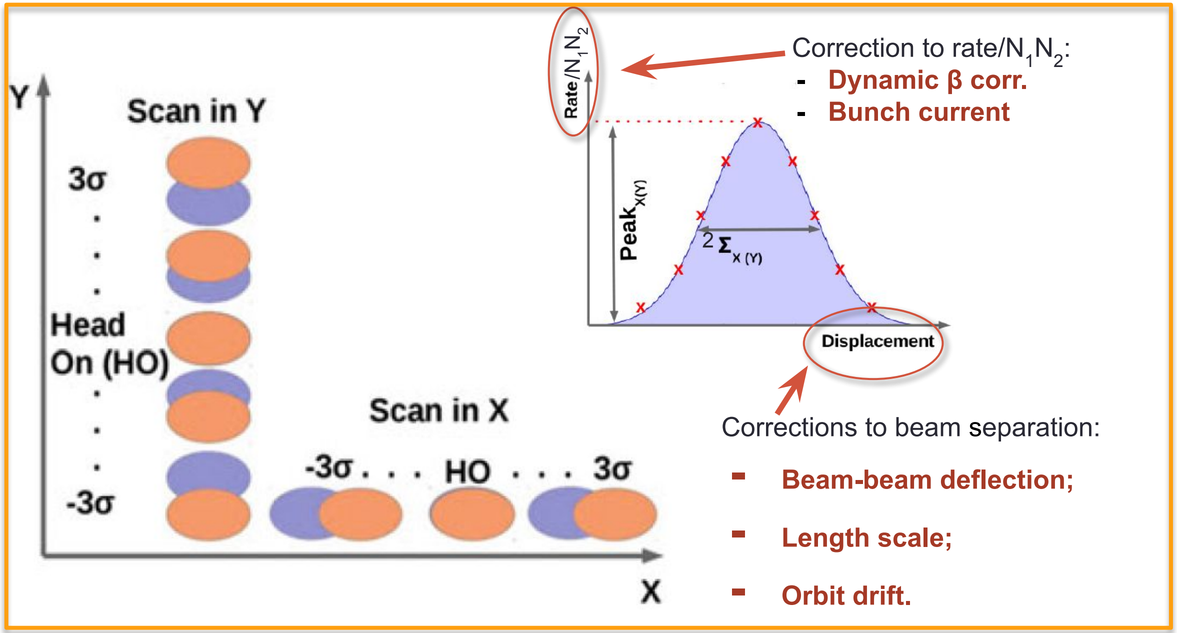


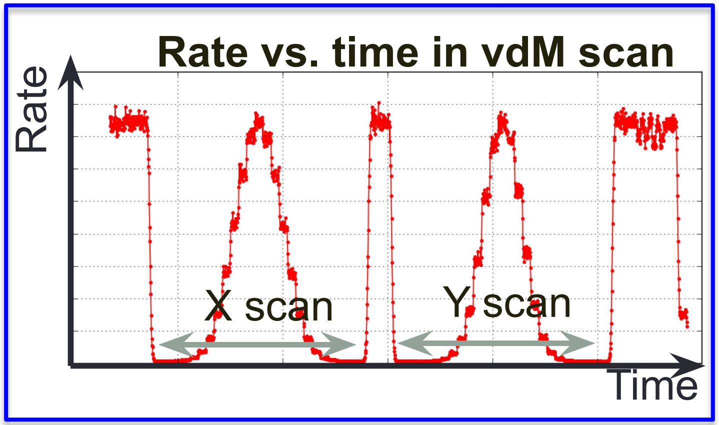






Absolute calibration in vdM scan $\mathcal{L} = R / \sigma_{vis}$





$$\sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 \cdot N_2} \cdot R_{peak}$$

van der Meer scan method is used for luminosity calibration at the LHC.

- Special beam conditions to keep systematic effects low: moderate bunch population, large emittance, large **β***, no bunch trains.
- Visible interaction rate *R* is measured vs. separation to get effective beam overlap ($\Sigma_{x,y}$). Using bunch currents ($N_{1,2}$) the visible cross section (σ_{vis}) of the luminometer is calculated.
- Multiple corrections applied to the rate and displacements.
- Some corrections, as **non-factorization correction,** applies to σ_{vis} directly.
- **Detector effects** have to be taken into account (e.g. beam-induced background correction, linearity).

See reference tables of all systematic uncertainties per experiment is the BACKUP.

As an alternative to vdM scans, LHCb is also using beam-gas imaging (BGI) method.

Beam-beam corrections

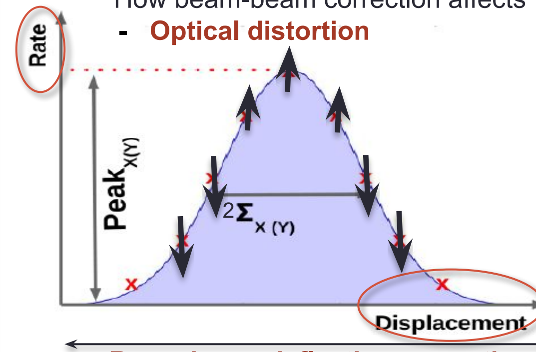
- **Beam-beam deflection (orbit shift or dipolar effect)**
- **Optical distortion (dynamic β or non-linear focusing effect)**

The luminosity correction due to beam-beam effects is under review:

- **Beam-beam** corrections based on MADX (single particle simulation) overestimate the correction;
- MADX-based **dynamic β** estimate turned out significantly biased by neglecting non-Gaussian distortions of the transverse bunch shape. **Correcting this will lead to order of 1% shift in the delivered luminosity central value of all experiments from the beam-beam correction alone.**
- Bias on the corrections due to **elliptical** shape of the beams and **fit model** selection were quantified.
- Dominant uncertainty is expected to be associated with beam-beam-induced distortions of the tune spectrum:
  - **Tune shift** due to head-on collisions at multiple IPs estimated by multiparticle simulation for groups of bunches colliding at 2,3 or 4 IPs

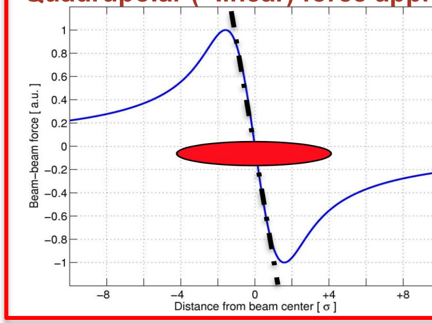
B*B and COMBI are new simulation codes for calculation of beam-beam effects with possibility to include **multiple IPs.**

How beam-beam correction affects vdM curve?
- **Optical distortion**



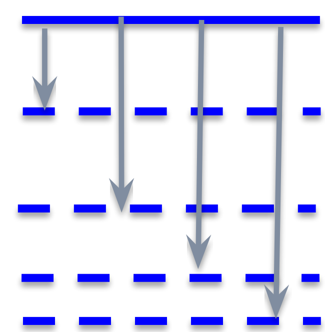
Beam-beam deflection correction

Quadrupolar (=linear) force approximation in MADX:



Lumi Days 2019
Ref[1], ref[2]

Head on tune shift:



Nominal LHC tunes (before collisions)
Qx = 0.31, Qy = 0.32

Tune shift for bunches colliding at one IP

2 IPs

3 IPs

4 IPs

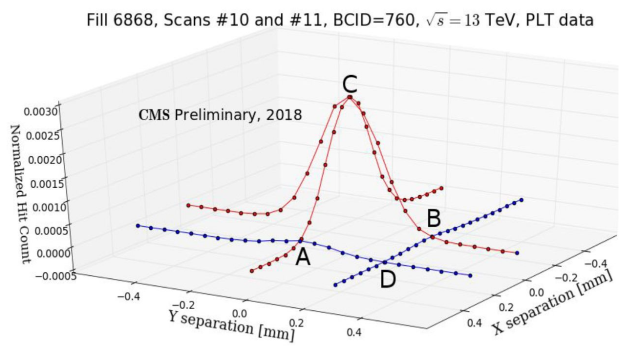
Tune shift leads to extra systematic uncertainty of up to 0.5%, which was not taken into account before.

Non-factorization: $\mathscr{L}(\delta_x, \delta_y) \neq f_x(\delta_x)\, f_y(\delta_y)$

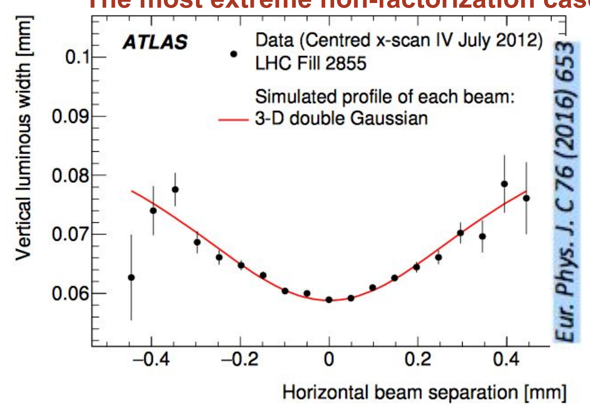
- vdM scans along only X,Y axes relies on factorization of the proton densities: ***ρ(x,y) = ρ(x)ρ(y).***
  - Presence of non-factorization introduces bias in the measured beam overlap, differs per bunch, changes in time.
  - Possibly can be minimized during preparation of the beams in the LHC injector chain (as Gaussian as possible beams).

- To quantify non-factorization of the beam (***x-y* correlations**) multiple methods are employed:
  - By ATLAS and ALICE: combined fit **offset + on-axis scan** and **luminous region** width vs. separation.
  - By CMS: **Beam imaging analyses**, where the image of each beam obtained in X and Y using vertex information from 4 special scans and **offset scans** allowing for better understanding of the "tails" of VdM scans.
  - By LHCb: **beam-gas imaging.**
- In 2017-18 LHCb pioneered 2D scans where the x-y corrections are not needed.

Standard vdM scans + offset scans in X and Y

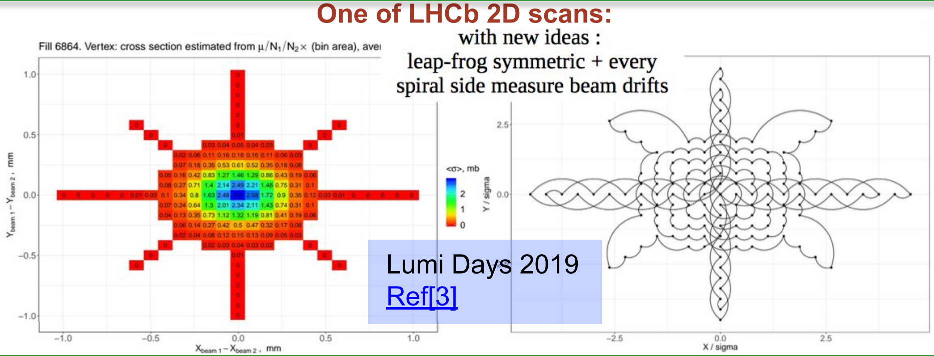


The most extreme non-factorization case in 2012 vdM scan:



Beam-separation dependence of the transverse luminous size in the non-scanning plane is a **signature of non-factorization**.

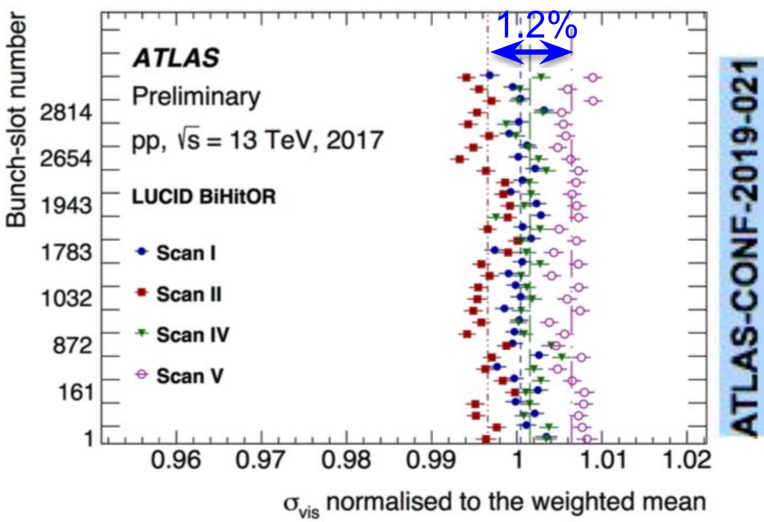
One of LHCb 2D scans:



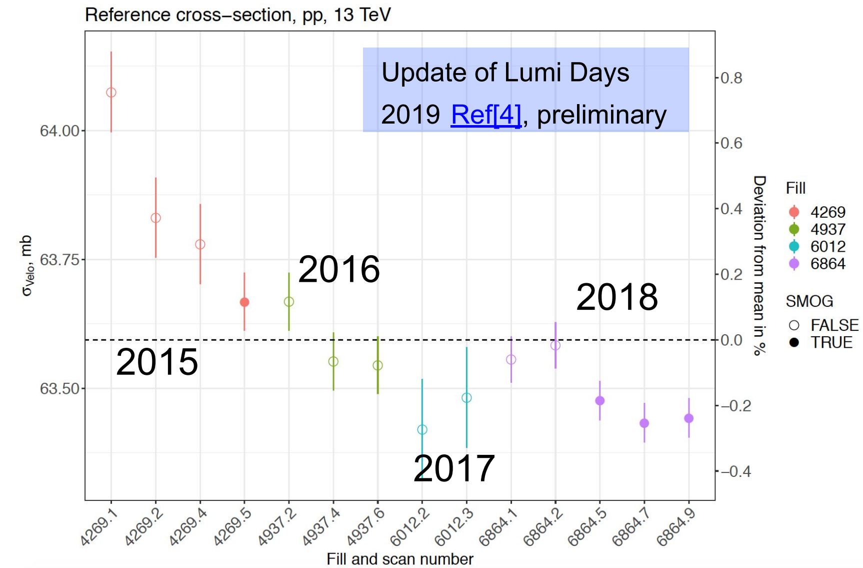
- 2D scans do not require non-factorization correction, as overlap integral is directly measured.
- ATLAS and CMS consider also performing 2D scans in Run 3.

Scan-to-scan variation

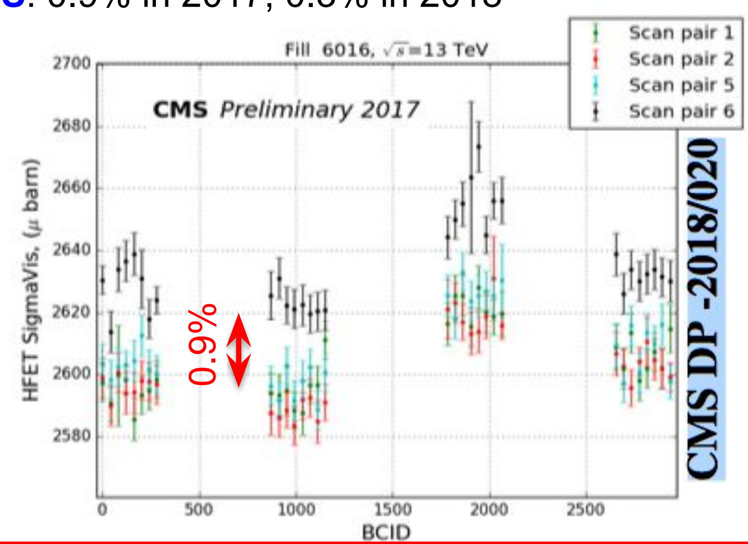
ATLAS: Gives 1.2% in 2017, 0.6% in 2018



LHCb: <1% across all years



CMS: 0.9% in 2017, 0.3% in 2018



One of the leading systematic uncertainties in 2017.

- sub-leading in other years

The reason for discrepancy between scans in particular VdM session is not clear, but confirmed by multiple experiments. Possibly due to:

- time-dependent non-factorization effects
- hysteresis effects in closed-orbit bumps
- uncorrected orbit drifts

Luminosity uncertainty components

Normalization component
Calibration precision (vdM)

+

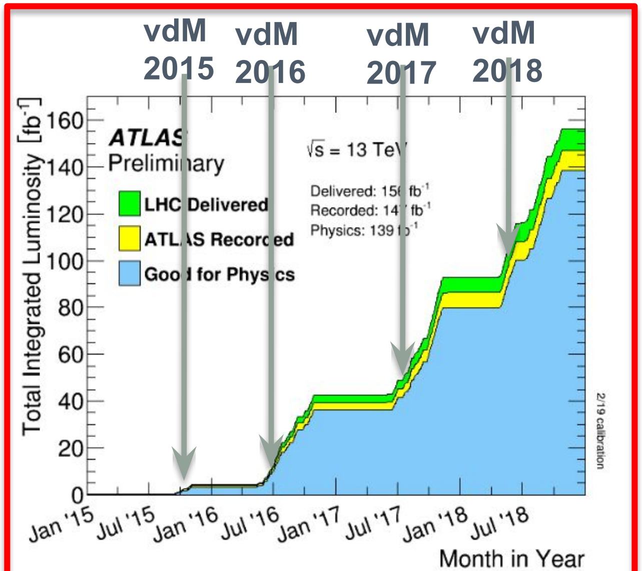
Integration component
Stability and linearity monitoring during the year

=

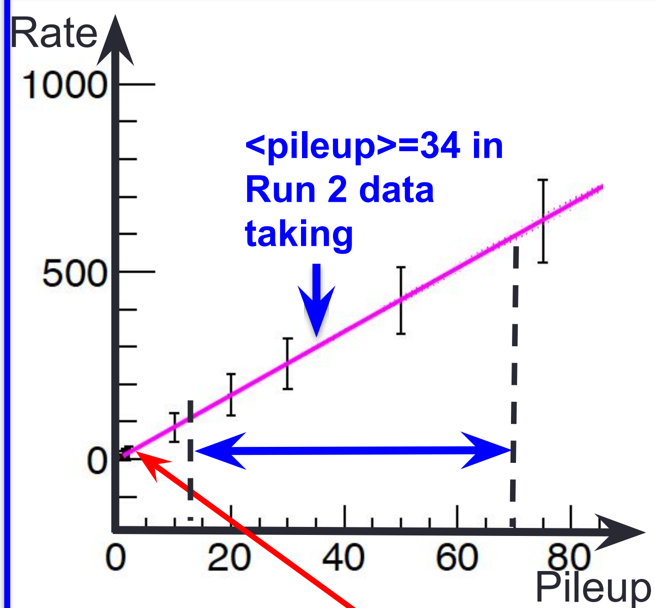
Total luminosity uncertainty

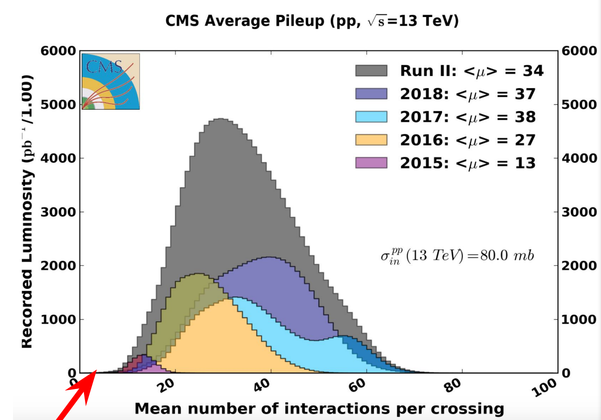
Leading uncert.:
- non-factorization uncertainty
- Scan-to-scan reproducibility
- Beam-beam corr.

Leading uncert.:
- Long-term stability and cross-detector consistency
- For CMS, ATLAS linearity/calibration transfer (LHCb operates at pileup ~1-2).



One pp VdM calibration per year extrapolated to the whole range of operation conditions!





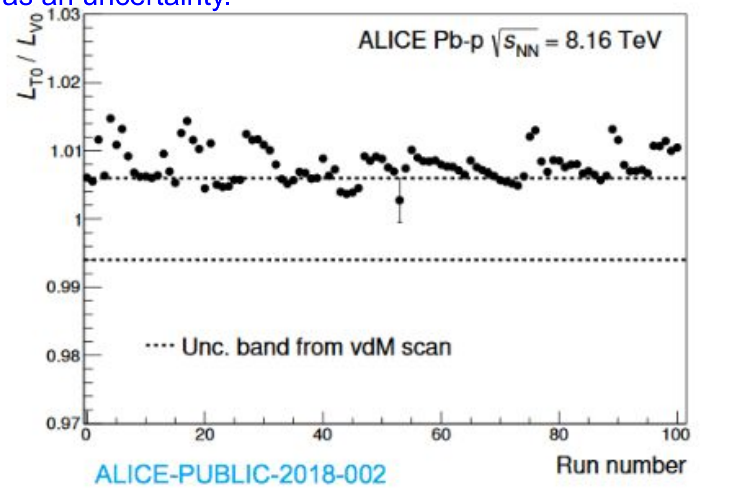
vdM calibration peak pileup ~0.5!

Long-term stability and consistency

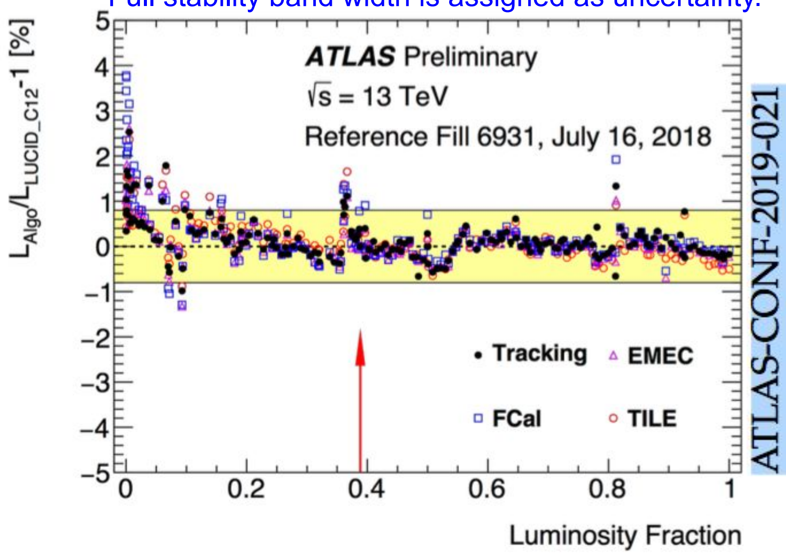
One of the leading systematic uncertainties across experiments:

- Derived from the "stability band" in the ratio of multiple luminometers

The RMS difference from unity of the ratio is assigned as an uncertainty.

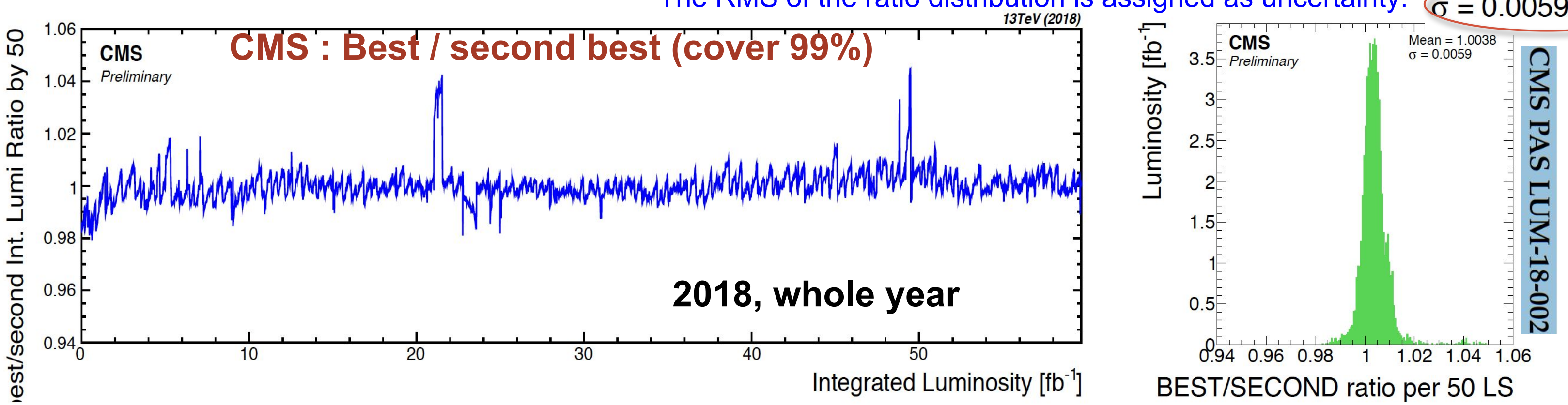


Full stability band width is assigned as uncertainty.

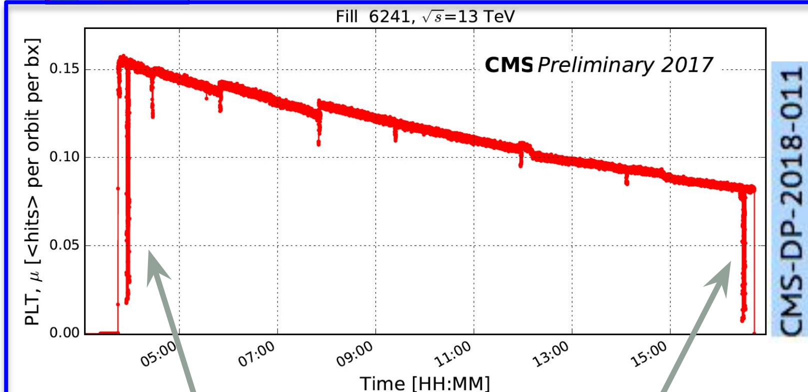


The RMS of the ratio distribution is assigned as uncertainty: Mean = 1.0038 σ = 0.0059

CMS : Best / second best (cover 99%)

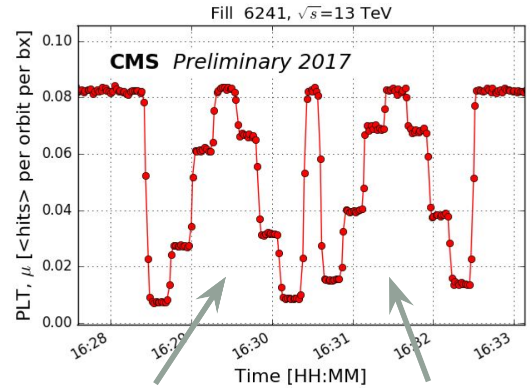


Emittance scans for stability and linearity monitoring



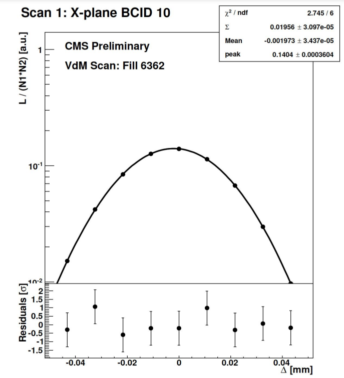
Beginning of fill "early scan",
β*=30cm, α/2=160μrad

End of fill "late scan",
β*=25cm, α/2=130μrad



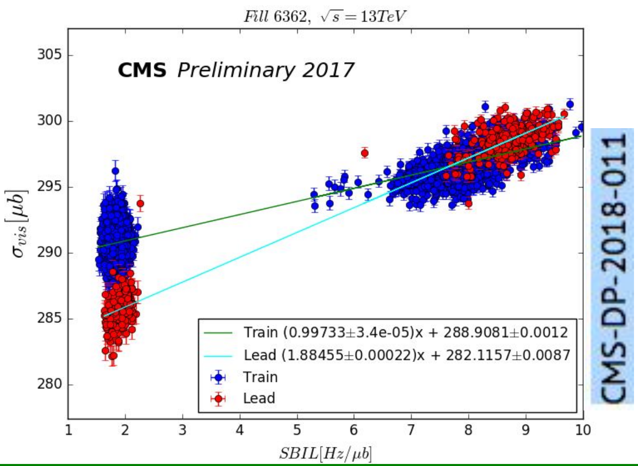
Scan in X plane **Scan in Y plane**

$$\sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 \cdot N_2} \cdot R_{peak}$$

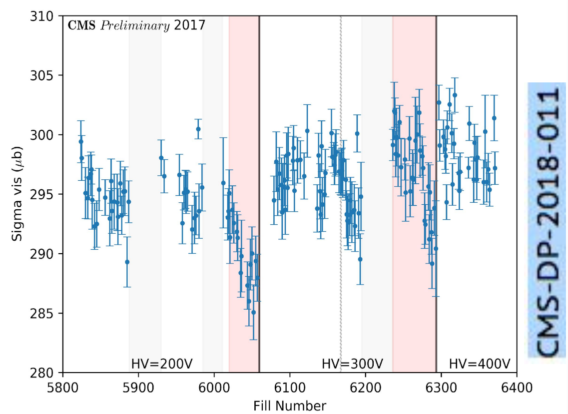


Example of the fit to measure beam overlap $\Sigma_{X(Y)}$ and peak rate

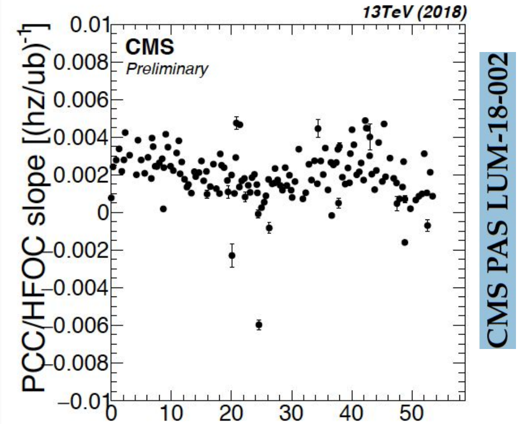
Example of non-linearity measurement with emittance scans at CMS. Only bunch-by-bunch 40 MHz readout makes it possible.



Example of stability monitoring with emittance scans at CMS.

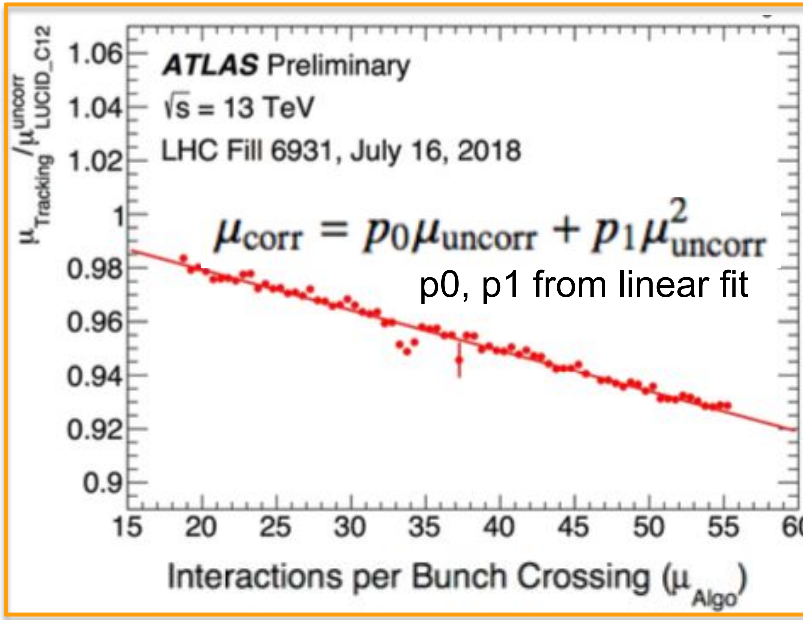


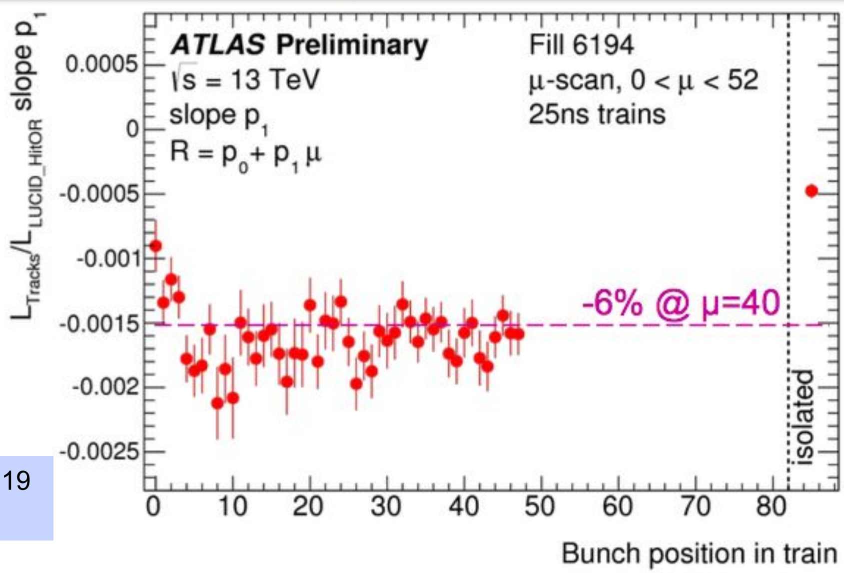
Final uncertainty due to non-linearity is defined from luminometers ratios in every fill. Leading contribution to CMS lumi uncertainty (1.1-1.5%).

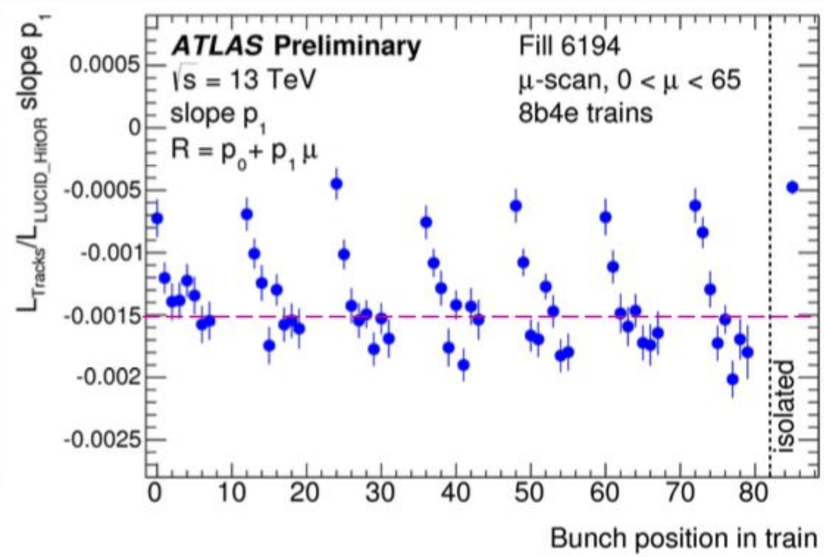


Calibration transfer & response in bunch trains

- LUCID vdM calibration needs ~10% correction at high pileup compared to tracks.
  - **Bunch-averaged p0 and p1** can be defined from any long fill – monitor stability during the year; **leading contribution to uncertainty (1.3-1.6%).**
- Special wide luminosity range scans (μ-scans) are performed with different filling schemes to measure p0 and p1 for each bunch in the bunch train:
  - **Slope is larger deeper in the train, saturates after ~5 bunches and "recovers" to lower slope after the unfilled gaps.**







Lumi Days 2019
Ref[5]

Compilation of Run 2 per year per experiment $\mathcal{L}$ uncertainty

New or updated results **in bold**

13 TeV pp

	ATLAS	CMS	ALICE	LHCb	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Year	2015				2016		2017		2018	
$\sigma_L / \mathcal{L}$ [%]	2.1	2.3	3.4[T0]	3.9	2.2	2.5	2.4	2.3	**2.0**	**2.5**

Run 2 combined uncertainty at 13 TeV:
- **ATLAS 1.7%**
- **CMS 1.8%**

Most of the results are preliminary and will be updated within a year or two.

5 TeV pp

	ALICE	LHCb	ATLAS	CMS	ALICE	ATLAS
Year	2015				2017	
$\sigma_L / \mathcal{L}$ [%]	2.1[T0], **2.3[V0]**	3.8	1.9	2.3	1.8 [T0], **2.1[V0]**	**1.6**

Heavy ions

	ATLAS	ALICE	ATLAS	CMS	ATLAS
Running period	2015 PbPb	2016 p-Pb (Pb-p)			2018 PbPb
$\sqrt{s_{NN}}$ [TeV]	5 TeV	8 TeV			5TeV
s_L / L [%]	**1.5**	1.8[T0], 2.0[V0]	2.4	3.7(3.2)	4.1

Work is ongoing to propagate our best knowledge from the last year analysis to the previous years.

In lieu of summary: how can we reduce the uncertainty?

To reach 1% uncertainty we need to reduce not only leading, but also subleading contributions. Only possible with collaborative work of experiments and LHC experts.

- 2D scans to be pursued in all experiments to reduce **non-factorization** systematics. Also: beam-gas imaging at LHCb, combination of 1D measurements from all IPs.
  - **Non-factorization** can be much better understood combining measurements from all IPs.
- Reduce **beam-beam correction uncertainty,** per bunch LHC tune measurement in vdM scan.
- **Improve long-term stability and cross-detector consistency** introducing more techniques for fast (online) detector performance monitoring.
- CMS/ATLAS: improve on **linearity/calibration transfer** via regular fast emittance scans and dedicated slow μ-scans, length scale scan with operations optics (β* = 25-30 cm).

Reducible subleading contributions to uncertainty. Required/goal LHC measurements precision:

- Bunch current product: 0.1-0.2%, ghost/satellites fraction meas. precision: at the level <0.05%
- Improved stability and ~1 um precision of beam position measurements at the IPs

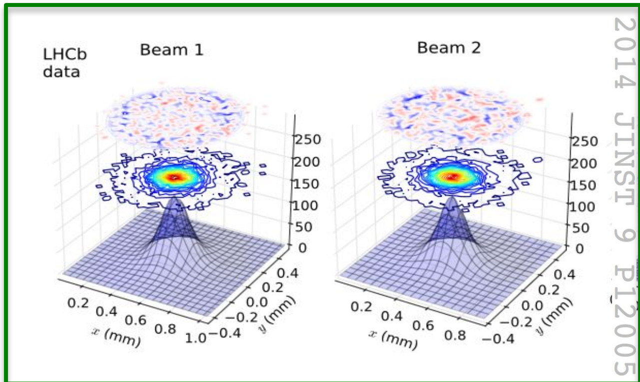
Machine developments (MD) are required/supported by experiments:

- MD to measure vdM optics (CMS request: to reduce 15% uncertainty on β*).
- MD to measure β* and crossing angle early in the year during commissioning (for emittance scans)
- MD to measure hysteresis-induced non-linearity of the closed-orbit bumps
- MDs to validate beam-beam simulations

Run 3 is transition between LHC & HL-LHC. What is new and challenging for Run 3?

- **pileup leveling at ~60** (60% higher bunch charge)
- **changing β* and crossing angle α/2** during the fill (β* 1 m -> β* 25 cm, α/2 110 μrad -> 160 μrad)

Hardware upgrades: new luminometers (ALICE, CMS); new proposals in LHCb; re-build/upgrade of Run 2 luminometers (ATLAS, CMS, LHCb).



- **Join your experiment lumi team!**
- Contribute to the challenging task of reaching 1% lumi uncertainty!

Come to the **luminous side!**

We also have cookies ☺

Contact me in vidyo: https://vidyoportal.cern.ch/join/tRgQeQsRHC
or e-mail olena.karacheban@cern.ch

References & Backup slides

The most recent luminosity publications of the experiments

- **ALICE** Collaboration:
  - ALICE luminosity determination for pp collisions at $\sqrt{s}$ = 8 TeV (ALICE-PUBLIC-**2017**-002)
  - ALICE luminosity determination for p-Pb collisions at $\sqrt{s_{NN}}$=8.16 TeV (ALICE-PUBLIC-**2018**-002)
  - ALICE 2017 luminosity determination for pp collisions at $\sqrt{s}$ =5 TeV (ALICE-PUBLIC-**2018**-014)
- **ATLAS** Collaboration:
  - Luminosity determination in pp collisions at $\sqrt{s}$ = 13TeV using the ATLAS detector at the LHC (ATLAS-CONF-**2019**-021)
  - Luminosity determination in pp collisions at $\sqrt{s}$ =8 TeV using the ATLAS detector at the LHC (Eur. Phys. J. C76 (**2016**) 653)
  - Production of ϒ(nS) mesons in Pb+Pb and pp collisions at 5.02 TeV with ATLAS (ATLAS-CONF-2019-054, p.8, 5 TeV 2017 ATLAS reference).
- **LHCb** Collaboration:
  - Precision luminosity measurements at LHCb (JINST 9 (**2014**) P12005)
- **CMS** Collaboration:
  - CMS luminosity measurement for the 2018 data-taking period at s√=13 TeV (CMS-PAS-LUM-**18**-002)
  - CMS Luminosity Measurements for the 2017 data-taking period at s√=13 TeV (CMS-PAS-LUM-**17**-004)

Reference talks/links to approved results

- **LHC Lumi Days, 4-5 June 2019** (https://indico.cern.ch/event/813285/)
  - [1] V.Balagura, "Simulation of beam-beam effects in vdM scans: impact on precision"
  - [2] T. Pieloni "Beam-beam simulations with COMBI & TRAIN in vdM fills"
  - [3] V.Balagura, "Non factorization at LHCb : Two-dimensional vdM scans"
  - [4] V.Balagura, "Overview of LHCb luminosity determination methodology in Run 2"
  - [5] R. Hawkings, "Overview of ATLAS Run-2 luminosity determination"
  - [6] M.Gagliardi, "Overview of ALICE luminosity-determination methodology in Run 2"

- W.Kozanecki "Manchester Particle Physics Seminar" Manchester Particle Physics Seminars, Dec. 2019 http://indico.hep.manchester.ac.uk/conferenceDisplay.py?confId=5556

- ATLAS all lumi results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2
- CMS all lumi results: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/LUM/index.html

LHCb

Cross-sections and known systematics (preliminary) *pp*

	pp, 13 TeV	pp, 5 TeV
σ(Velo>1), mb	**63.6 ± 1.6 %**	**56.2 ± 1.3 %**
Early 2015 BGI measurement	63.4 ± 3.9 % (- 0.3% off)	56.4 ± 3.8 % (+ 0.4% off)
preliminary BGI, fill 4937	65.8 ± 2.1 % (+3.5 % off)	
	Error, %	**Error, %**
DCCT	0.2	0.2
Ghost charge, BGI+LDM	0.0	0.3 (in fill 4634)
FBCT A/B/BPTX	0.0	0.0
LSC	0.3	0.3
Fit model	**1.1**	0.3
statistics	0.0	0.0
Scan-to-scan variations	**0.9**	**1.0**
RZ Velo – Velo diff.	0.1	0.1
Velo z-efficiency	0.0	0.0
X-Y non-factorizability (2D scans)	0.3	0.1
beam-beam	**0.5**	**0.5**

Beam-beam uncertainty is set to 0.5 % (correction +0.18 % / +0.15 % @ 13 and 5 TeV).
Orbit drifts have not yet been estimated, but expected to be small.

https://indico.cern.ch/event/813285/contributions/3406071/attachments/1854567/3047106/Overview_of_LHCb_luminosity_determination_methodology_in_Run_2_balagura.pdf

LHCb Results

Method	σ_{vis} (mb)	Absolute calibration Weight	Absolute calibration Uncertainty (correlated)	Relative calibration uncertainty	Total uncertainty
pp at $\sqrt{s} = 8$ TeV					
BGI	60.62 ± 0.87	0.50	1.43% (0.59%)		
VDM	60.63 ± 0.89	0.50	1.47% (0.65%)		
Average	60.62 ± 0.68		1.12%	0.31%	1.16%
pp at $\sqrt{s} = 7$ TeV					
BGI	63.00 ± 2.22	0.13	3.52% (1.00%)		
VDM	60.01 ± 1.03	0.87	1.71% (1.00%)		
Average	60.40 ± 0.99		1.63%	0.53%	1.71%
pp at $\sqrt{s} = 2.76$ TeV					
BGI	52.7 ± 1.2		2.20%	0.25%	2.21%
pPb at $\sqrt{s_{NN}} = 5$ TeV					
VDM	2126 ± 49		2.05%	1.03%	2.29%
Pbp at $\sqrt{s_{NN}} = 5$ TeV					
VDM	2120 ± 53		2.36%	0.82%	2.50%

Preliminary result from Run II, BGI pp:
σ_{vis} = 63.4 mb (3.9% precision) at 13 TeV and 56.4 mb (3.8% precision) at 5 TeV.

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https://cds.cern.ch/record/2255091/files/LHCb-TALK-2017-034.pdf

ALICE

Uncertainty	pp 13 TeV 2015	pp 5 TeV 2015	p-Pb 8 TeV 2016	Pb-p 8 TeV 2016	pp 5 TeV 2017	*Other periods*
Non-factorisation	0.9%	1%	0.6%	0.9%	0.1%	
Orbit drift	0.8%	<0.1%	0.7%	0.3%	0.1%	
Beam-beam deflection	0.8%	0.4%	<0.1%	0.4%	0.5%	
Dynamic β^*	0.3%	0.2%	<0.1%	<0.1%	0.2%	
Background	0.1% (T0), 0.7% (V0)	0.3% (T0), 1.1% (V0)	<0.1% (T0), 0.5% (V0)	0.3% (T0), 0.6% (V0)	0.2% (T0), 1.1% (V0)	
Pile-up	0.7%	0.7%	included in *	included in *	0.5%	
Length-scale calibration	0.5%	1%	0.5%	0.8%	0.2%	
Fit model	0.6%	0.7%	0.5% (T0), 0.4% (V0)	0.6% (T0), 0.9% (V0)	0.5%	
Σ consistency (T0 vs V0)	0.6%	0.2%	0.2%	0.4%	<0.1%	
Intensity decay	0.4%	0.7%	0.6%	0.7%	0.9%	
Bunch-to-bunch consist.	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	
Scan-to-scan consist.	<0.1%	0.5%	0.6%	0.1%	0.5% (T0), 0.4% (V0)	
Beam centreing	<0.1%	0.1%	0.1%	0.1%	0.2%	
Bunch intensity	0.6%	0.4%	0.3%	0.3%	0.4%	
Long-term stability & consist.	0.6% (isol.) 2.7% (trains)	0.4%	1.1%*	0.6%*	1.1%	
Total	3.4% (T0)	2.1% (T0), 2.3% (V0)	1.8% (T0), 1.9% (V0)	1.8% (T0), 2.0% (V0)	1.8% (T0), 2.1% (V0)	*5% (prel.)*

M. Gagliardi – **Overview of ALICE luminosity-determination methodology in Run 2** – LHC Lumi days 2019 18

https://indico.cern.ch/event/813285/contributions/3406066/attachments/1855528/3047512/Gagliardi_LumiDays_040619.pdf

ATLAS

ATLAS-CONF-2019-021: https://cds.cern.ch/record/2677054

Uncertainties and combination

- Per-year uncertainty summary
  - Treating 2015+16 as one dataset
  - Absolute vdM calibration subtotal
  - +Contributions to to physics lumi.
  - Total uncertainties for individual years are 2.0-2.4%
    - Largest single uncertainty from calibration transfer
- Combination of years
  - Taking correlations into account
  - */+=fully/partially correlated
    - See talk of R. Hawkings tomorrow
- Total run 2 lumi: 139.0±2.4 fb^{-1}
  - Uncertainty **1.7%**, dominated by calibration transfer and then long-term stability

Data sample	2015+16	2017	2018	Comb.
Integrated luminosity (fb^{-1})	36.2	44.3	58.5	139.0
Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4
Uncertainty contributions (%):				
DCCT calibration†	0.2	0.2	0.2	0.1
FBCT bunch-by-bunch fractions	0.1	0.1	0.1	0.1
Ghost-charge correction*	0.0	0.0	0.0	0.0
Satellite correction†	0.0	0.0	0.0	0.0
Scan curve fit model†	0.5	0.4	0.5	0.4
Background subtraction	0.2	0.2	0.2	0.1
Orbit-drift correction	0.1	0.2	0.1	0.1
Beam position jitter†	0.3	0.3	0.2	0.2
Beam-beam effects*	0.3	0.3	0.2	0.3
Emittance growth correction*	0.2	0.2	0.2	0.2
Non-factorization effects*	0.4	0.2	0.5	0.4
Length-scale calibration	0.3	0.3	0.4	0.2
ID length scale*	0.1	0.1	0.1	0.1
Bunch-by-bunch σ_{vis} consistency	0.2	0.2	0.4	0.2
Scan-to-scan reproducibility	0.5	1.2	0.6	0.5
Reference specific luminosity	0.2	0.2	0.4	0.2
Subtotal for absolute vdM calibration	1.1	1.5	1.2	-
Calibration transfer†	1.6	1.3	1.3	1.3
Afterglow and beam-halo subtraction*	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2
Total uncertainty (%)	2.1	2.4	2.0	1.7

https://indico.cern.ch/event/813285/contributions/3406055/attachments/1855434/3047316/ATLASIntroRH_20190604_v2.pdf

ATLAS

ATLAS-CONF-2019-021:

https://cds.cern.ch/record/2677054

- Sum of individual sources with uncertainties σ_i in each year (many separate uncorrelated and correlated sources):

$$V_L = \underbrace{\begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix}}_{\text{uncorrelated}} + \underbrace{\begin{pmatrix} \sigma_1^2 & \sigma_1\sigma_2 & \sigma_1\sigma_3 \\ \sigma_1\sigma_2 & \sigma_2^2 & \sigma_2\sigma_3 \\ \sigma_1\sigma_3 & \sigma_2\sigma_3 & \sigma_3^2 \end{pmatrix}}_{\text{correlated}} + \ldots$$

- Some sources are not relevant in all years, so have some σ_i=0
- Sources with both correlated and uncorrelated parts are handled by being broken into two separate contributions to V_L

June 2019 Richard Hawkings 3

vdM uncertainty correlations

- Separate vdM scan session in each year
  - 'Random' uncertainties should be uncorrelated
  - 'Systematic' uncertainties should be correlated – always have the same bias
- Random/uncorrelated uncertainties
  - Bunch-to-bunch and scan-to-scan σ_{vis} consistency
  - Reference specific luminosity (i.e. comparison of Σ_x, Σ_y from different algorithms)
    - All these fluctuate a lot from year to year, depending on quality/consistency of scan sets
  - Orbit drift corrections (depend on details of what happened in each scan session)
  - Background subtraction (dominated by statistical fluctuations, small, 0.2% / year)
  - Length scale calibration (independent calibration each year, orbit drift unc.)
- Fully or partially correlated uncertainties
  - Non-factorisation – not really understood, likely same underlying cause each year
  - Beam-beam effects: common MADX-based calculation
  - Fit model – partially correlated
    - Different pairs of fit functions used to set error in 2016 and 2017+2018
  - Beam position jitter – correlated 2015-17 (from run-1), new evaluation for 2018

5th June 2019 Richard Hawkings 4

https://indico.cern.ch/event/813285/contributions/3406121/attachments/1856677/3049839/ATLASCombRH_20190605_v1.pdf

Uncertainties tables CMS PAS

2017 data-taking

	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

CMS-PAS-LUM-17-004

http://cds.cern.ch/record/2621960?ln=en

2018 data-taking

	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

CMS-PAS-LUM-18-002

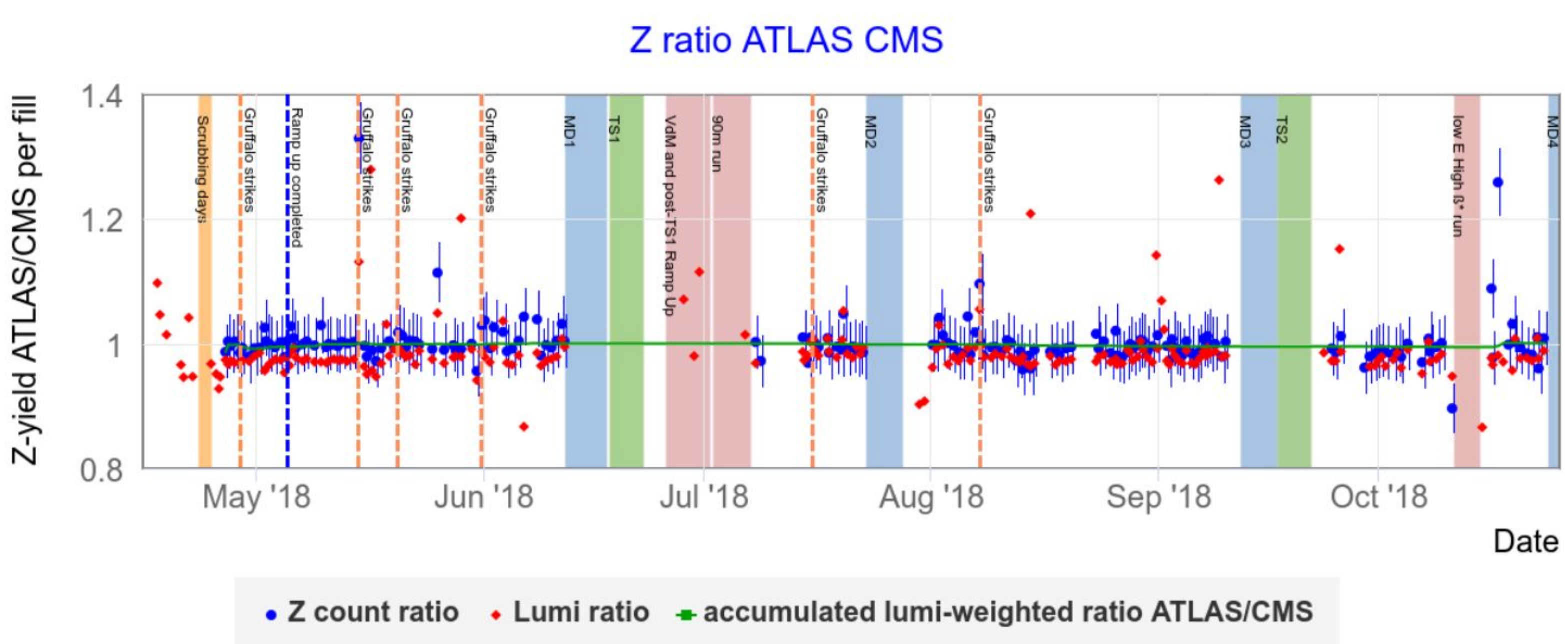
http://cds.cern.ch/record/2676164?ln=en

	2015	2016	2017	2018	2015-2018	2016-2018
Total delivered luminosity, full year (1/fb)	4.21	40.99	49.79	67.86	162.85	158.64
Recorded and certified luminosity, golden JSON (1/fb)	2.26*	35.92	41.53	59.74	139.45	137.19
Uncertainty (%)	2.3	2.5	2.3	2.5	1.8	1.8
Reference	LUM-15-001	LUM-17-001	LUM-17-004	LUM-18-002	n/a	n/a

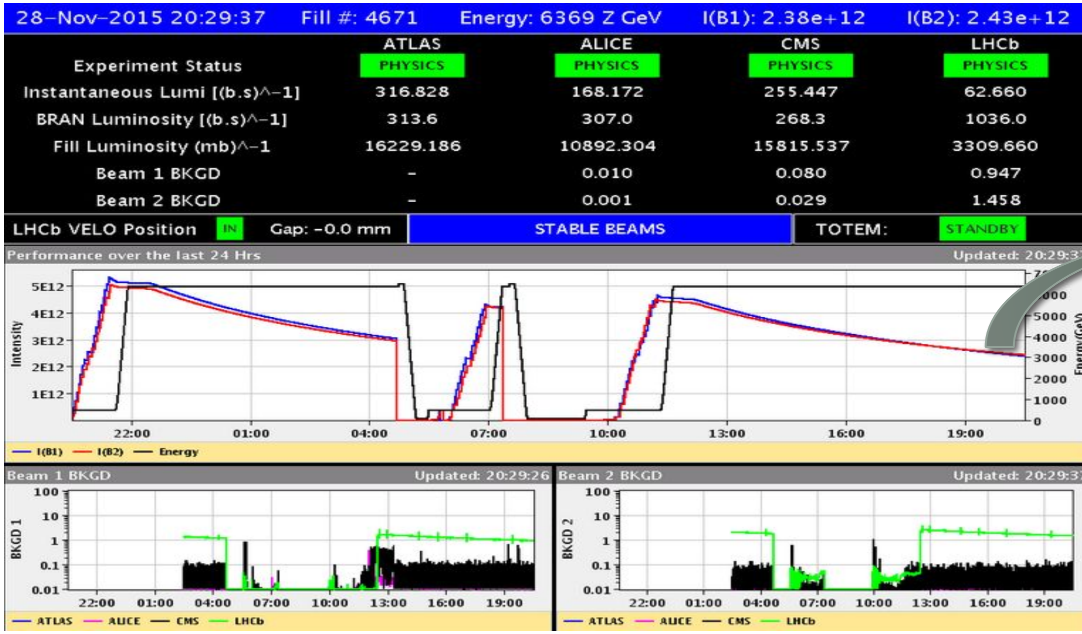
* 25 ns fills with magnet on only

Z boson counting

- Is used for ATLAS/CMS stability and luminosity cross check
- As an alternative for luminosity measurement?
  - Theoretical precision with NNLO+NLO predictions and latest pdf's is around **3-5%.**
  - $Z \rightarrow \mu^+\mu^-$ counting reaches 1% stat. precision every 20 minutes, with a latency of several days in Run 2 (delay of prompt reconstruction). Can not be used for online luminosity, where seconds/minutes latency is required.
  - There is ongoing effort to probe possibility of precision luminosity measurements at LHC with prospects to HL-LHC (arXiv:1806.02184).

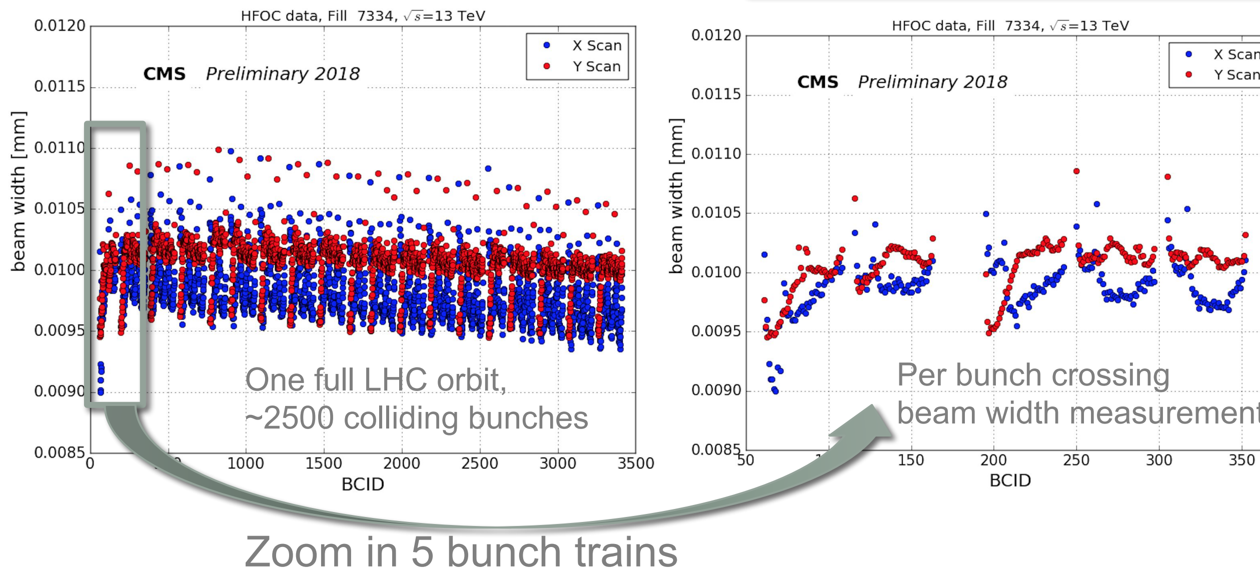


Online luminosity and background measurement



Per-bunch luminosity measurement opens a new doorway to understanding of our data:

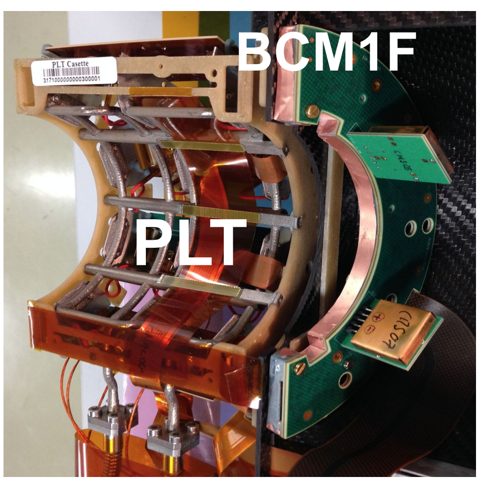
Bunch train structure and evolution in time:



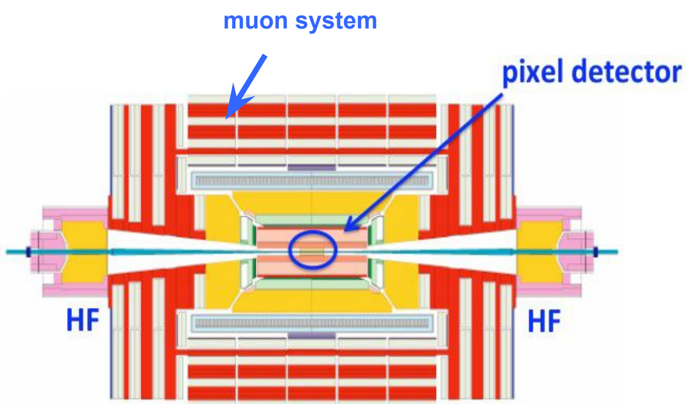
Luminometers

- *Forward calorimeter (**HFOC and HFET**)*
- *Fast Beam Conditions Monitor (**BCM1F**)*
- *Pixel Luminosity Telescope (**PLT**)*
- *Pixel Detector (cluster counting **PCC**)*
- *Muon system drift tubes (DT) and radiation protection system (RAMSES) for integrated lumi stability measurement (cross calibrated to one of the main luminometers).*

$$L = R / \sigma_{vis}$$

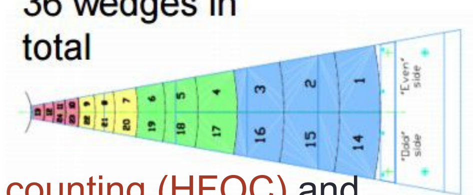


Triple coincidence counting (PLT), zero counting (BCM1F)



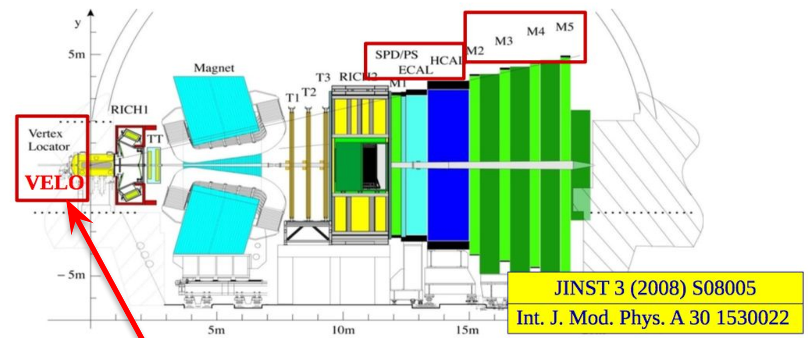
HF wedge

36 wedges in total

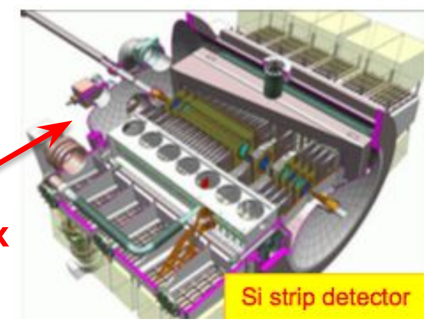


Zero counting (HFOC) and transverse energy sum (HFET)

LHCb Luminometers

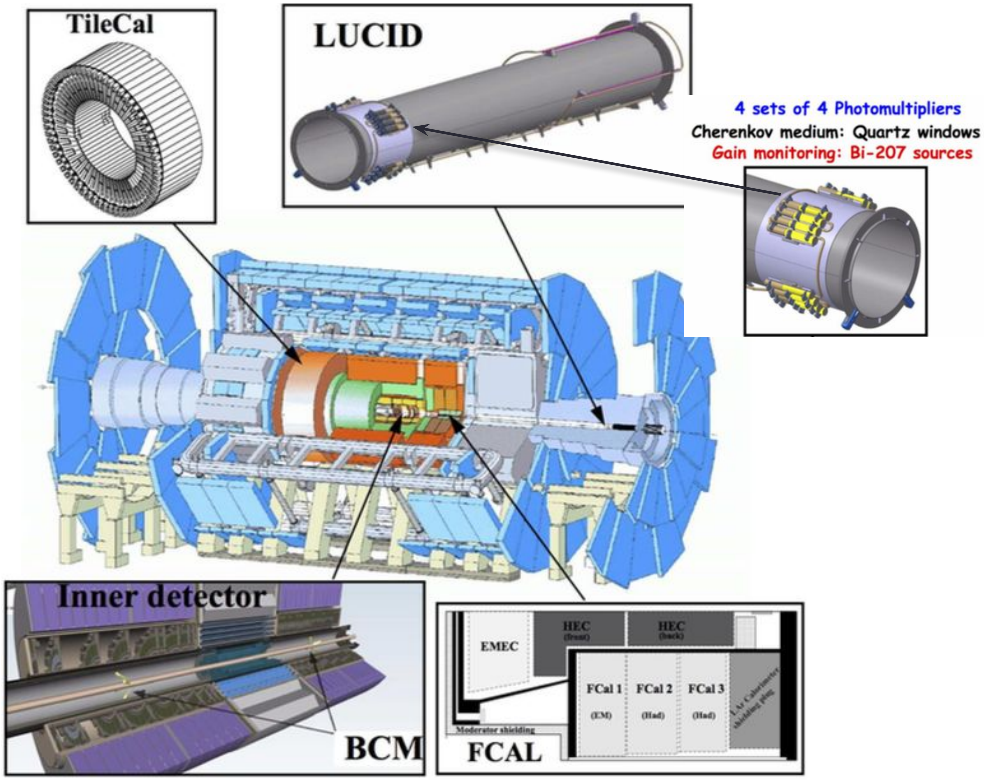


LHCb vertex locator



- Vertex locator (**VELO**): **N tracks**, vertices, upstream hits, backward tracks
- SPD preshower: N hits
- Calorimeters: transverse energy
- Muon system: N muons

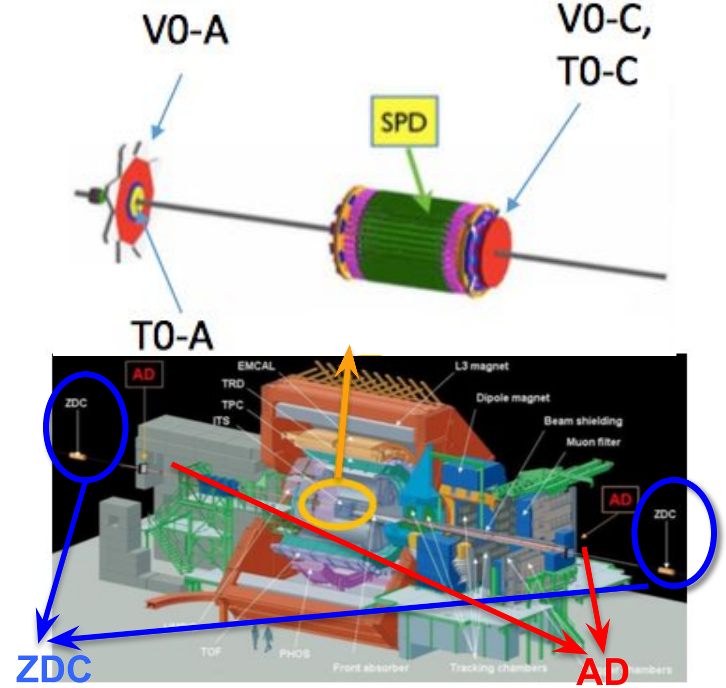
ATLAS Luminometers



- Luminosity measurement using a **Cherenkov integrating detector (LUCID)**: publishes b-b-b integrated lumi over 60 s.
- **Track counting** is used for LUCID calibration transfer.
- Beam Conditions Monitor (BCM) based on diamond sensors. (Secondary, not used in 13TeV, only for cross checks in HI running period.)

Hit counting is used for luminosity measurement.

ALICE Luminometers



- Two **T0 Cherenkov** detector arrays [pp, p-Pb];
- Two **scintillator arrays V0** on opposite side A and C [pp, p-Pb, Pb-Pb];
- **Neutron Zero Degree Calorimeters (ZDC)** [p-Pb, Pb-Pb]: two **spaghetti calorimeters**;
- **ALICE diffractive (AD)** detector [pp]: two **scintillators**.

Luminosity algorithms based on event counting.

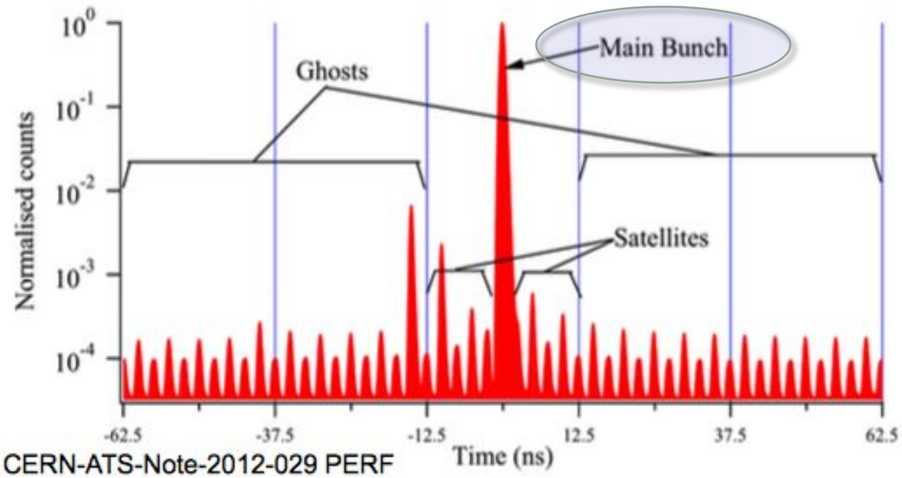
Bunch current normalization. Ghosts & satellites.

Satellite charge subtracted from FBCT measurement →

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

$$\sigma_{\mathrm{vis}_j} = \mu^{\max}_{\mathrm{vis}_j} \frac{2\pi \Sigma_{x_j} \Sigma_{y_j}}{n_{j1} n_{j2}} \quad \mathit{BCID = j}$$

Calibration using ghost subtracted DCCT



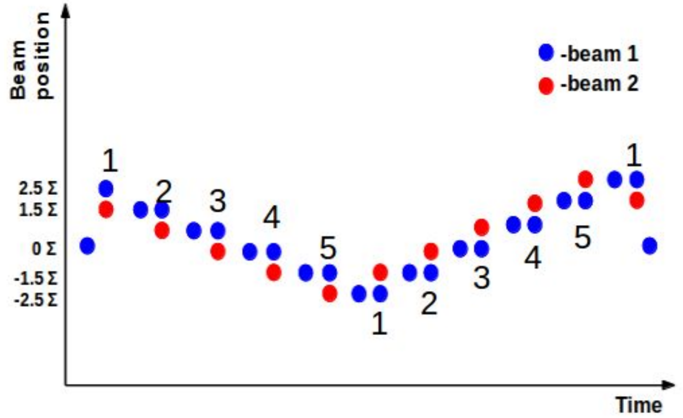
CERN-ATS-Note-2012-029 PERF

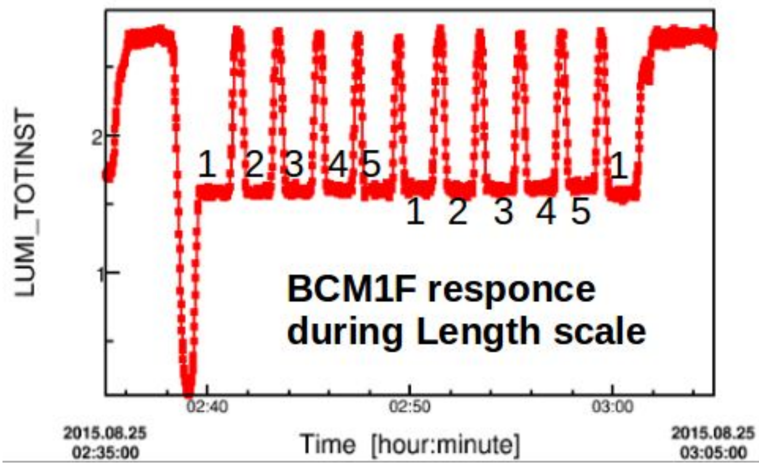
Magnitude of effect in pp vdM 2017-18:
correction [none– 0.4%]
uncertainty [0.1 – 0.3%]

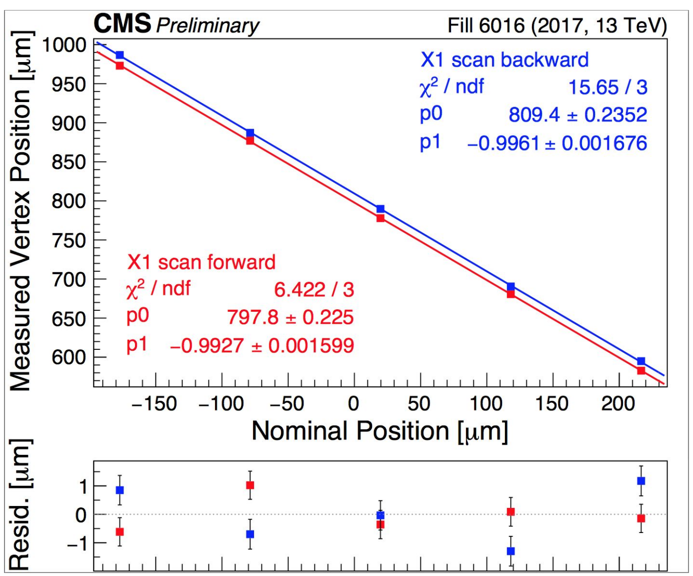
- Total beam current is measured by Direct Current Current Transformers (DCCT): 0.2% uncertainty, but too slow for per bunch crossing measurements.
- Per bunch crossing current is measured by Fast Beam Current Transformers (FBCT): fast, but not the best precision, re-normalized to DCCT.
- Ghost and satellites fractions are measured by BSRL (Beam Synchrotron Radiation – Longitudinal monitors).
- **Requirements** on bunch bunch current precision: 0.1-0.2% and on ghost (f_{ghost}) and satellites fraction (f_{sat}) measurement precision: at the level of <0.05%.

Length scale calibration (CMS)

- **Length scale calibration** is a correction to nominal beam separation derived using measured by CMS tracker vertex position.
  - needed in the VdM scan, as beams are steered in the range wider than the range for normal operation (where magnets are calibrated).
- **Contributions to uncertainty**: orbit drift, stability of the LHC magnet settings, and the vertex reconstruction.





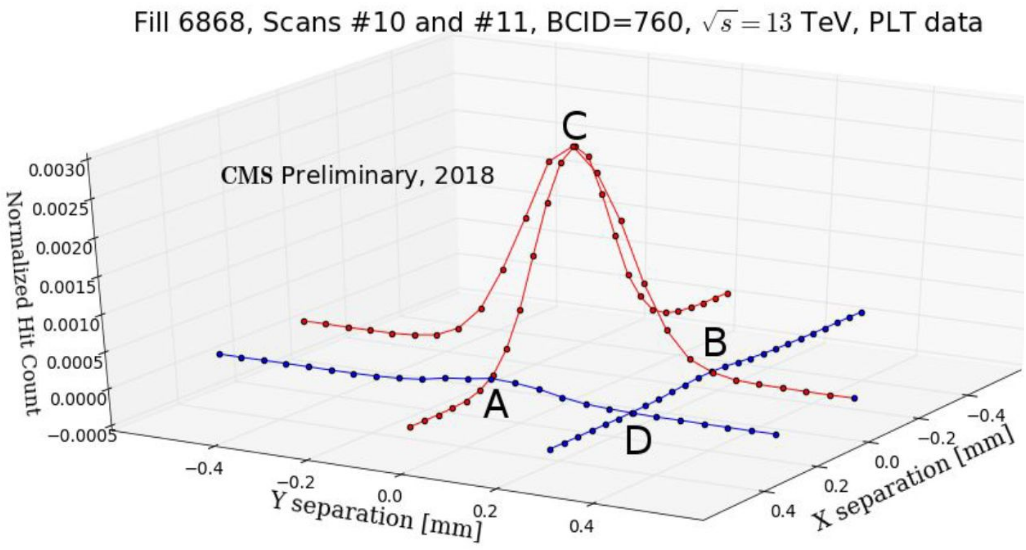


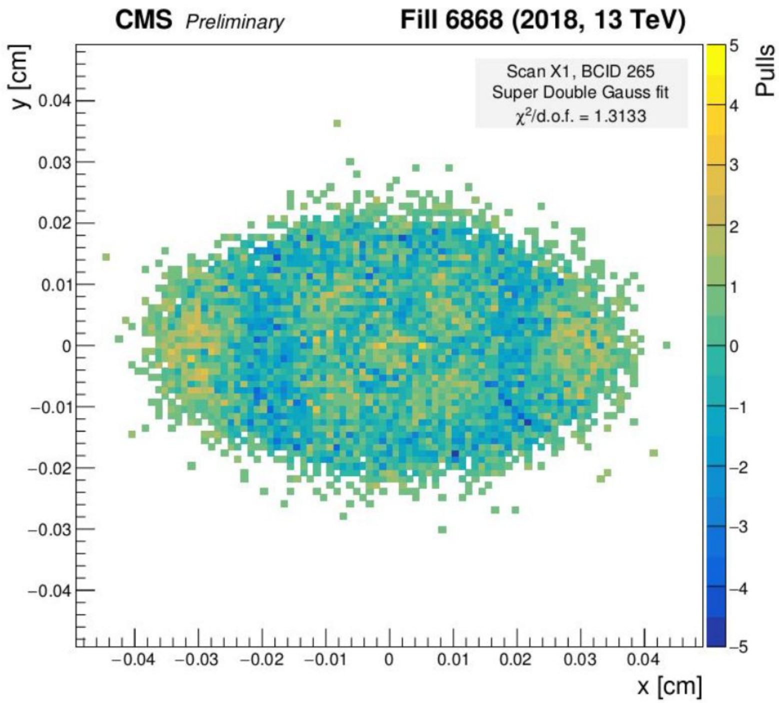
Magnitude of effect in pp vdM 2017-18:
correction [0.8 – 0.9%]
uncertainty [0.2 – 0.3%]

CMS: correlations on the beam shape (X-Y)

- VdM method assumes factorization of the proton densities in X and Y plane: ρ(x,y) = ρ(x)ρ(y).
- To test non-factorization of the beam (***x-y* correlations**) multiple methods are employed by CMS:
  - Beam Imaging analyses, where the image of each beam obtained in X and Y **using vertex information** from 4 special scans;
  - Offset scans allowing for better understanding of the "tails" of VdM scans;
- **Contributions to uncertainty**: fit model, difference between toy Monte-Carlo simulation and true correction values, bunch-to-bunch difference.

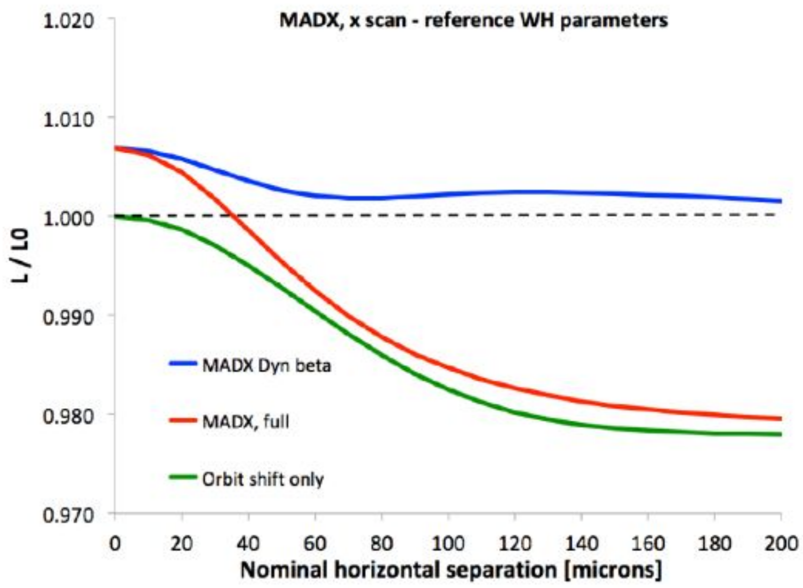
Magnitude of effect in pp vdM 2017-18: correction [none – 0.8%] uncertainty [0.8 – 2.0%]

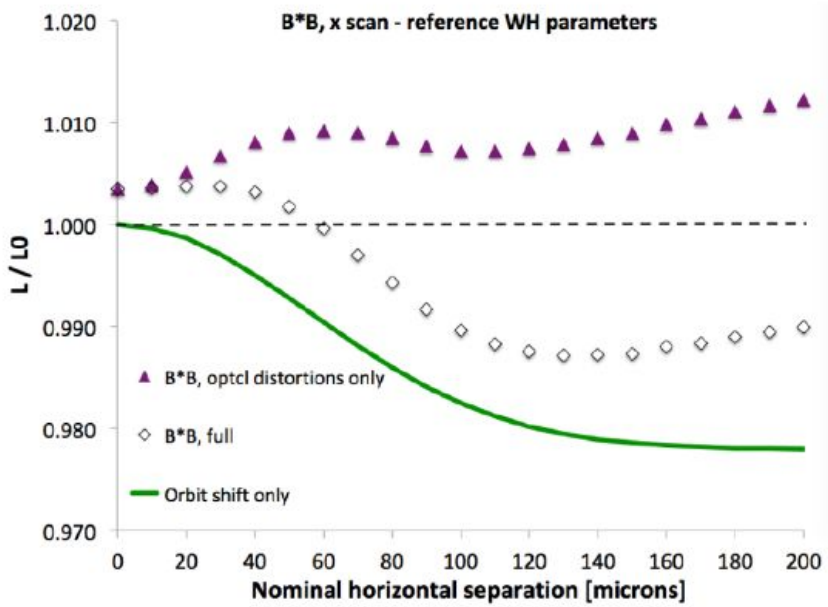




Comparison of old beam-beam correction with new

Beam parameters from previous 2012 simulation for direct comparison w/ MADX



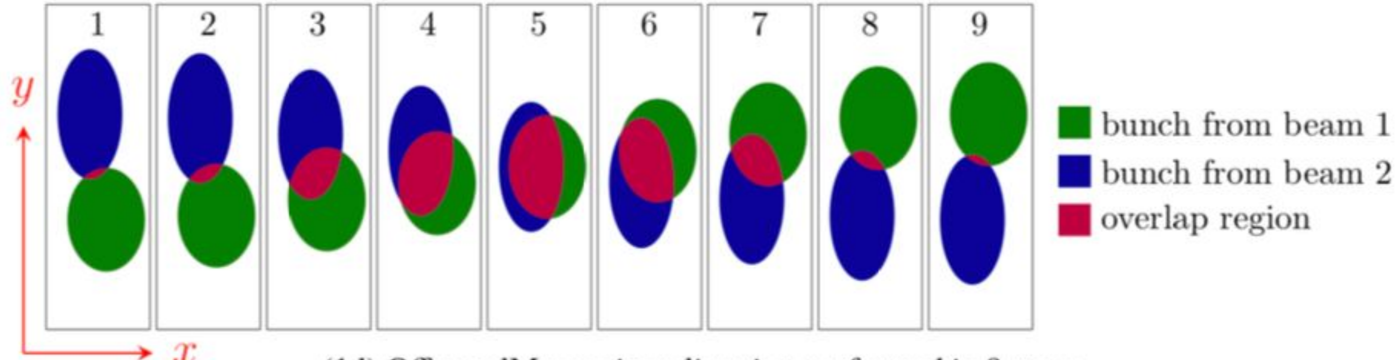


Note: the cancellation between optical distortions orbit shift leads to anticorrelations that will help cancel systematic errors

Black: new, red: old'2012 – large difference

	Old'2012	new Jan'2019
$\sigma(bb)/\sigma(no\ bb) - 1$	-1.2%	-0.3%

Offset scans



(1d) Offset vdM scan in y direction performed in 9 steps

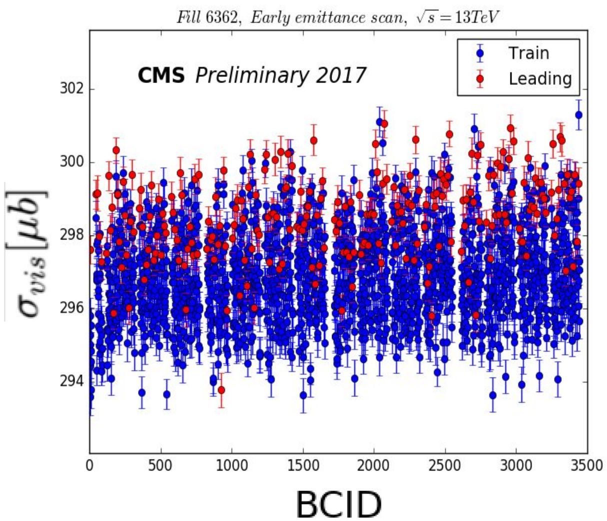
- Powerful method to probe non-factorization
  - Stat. uncertainties are larger (wrt on-axis scans) due to decrease of the interaction rate

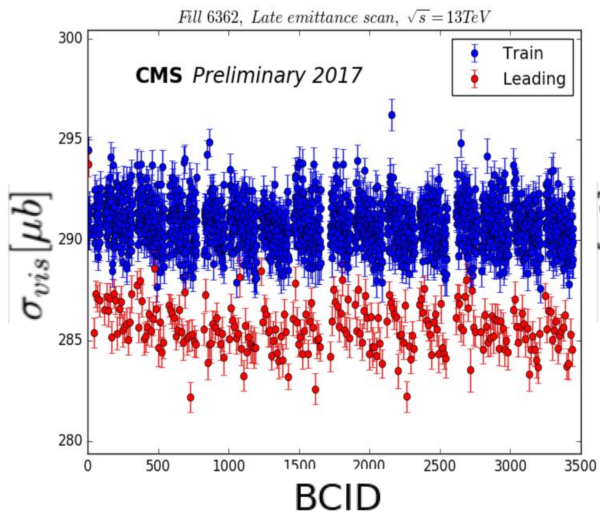
- **ALICE:** combined fit: offset + on-axis scans (often bunch-averaged due to limited statistics)
- **ATLAS:** combined fit with close-in-time on-axis scan (always done bunch-by-bunch)
- Combination improves overall fit stability

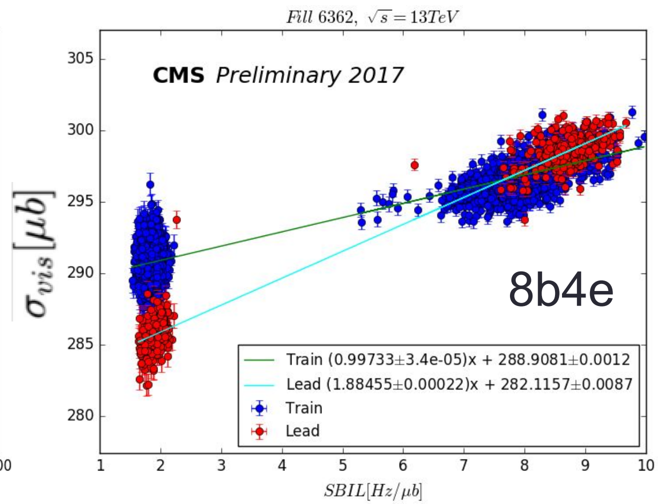
https://indico.cern.ch/event/813285/contributions/3406094/attachments/1855833/3048867/mdyndal_2019-06-05-lumiDays.pdf

Emittance scans for non-linearity measurement

- Wide range of single bunch instantaneous luminosity (SBIL) in physics fills allows for non-linearity measurement.

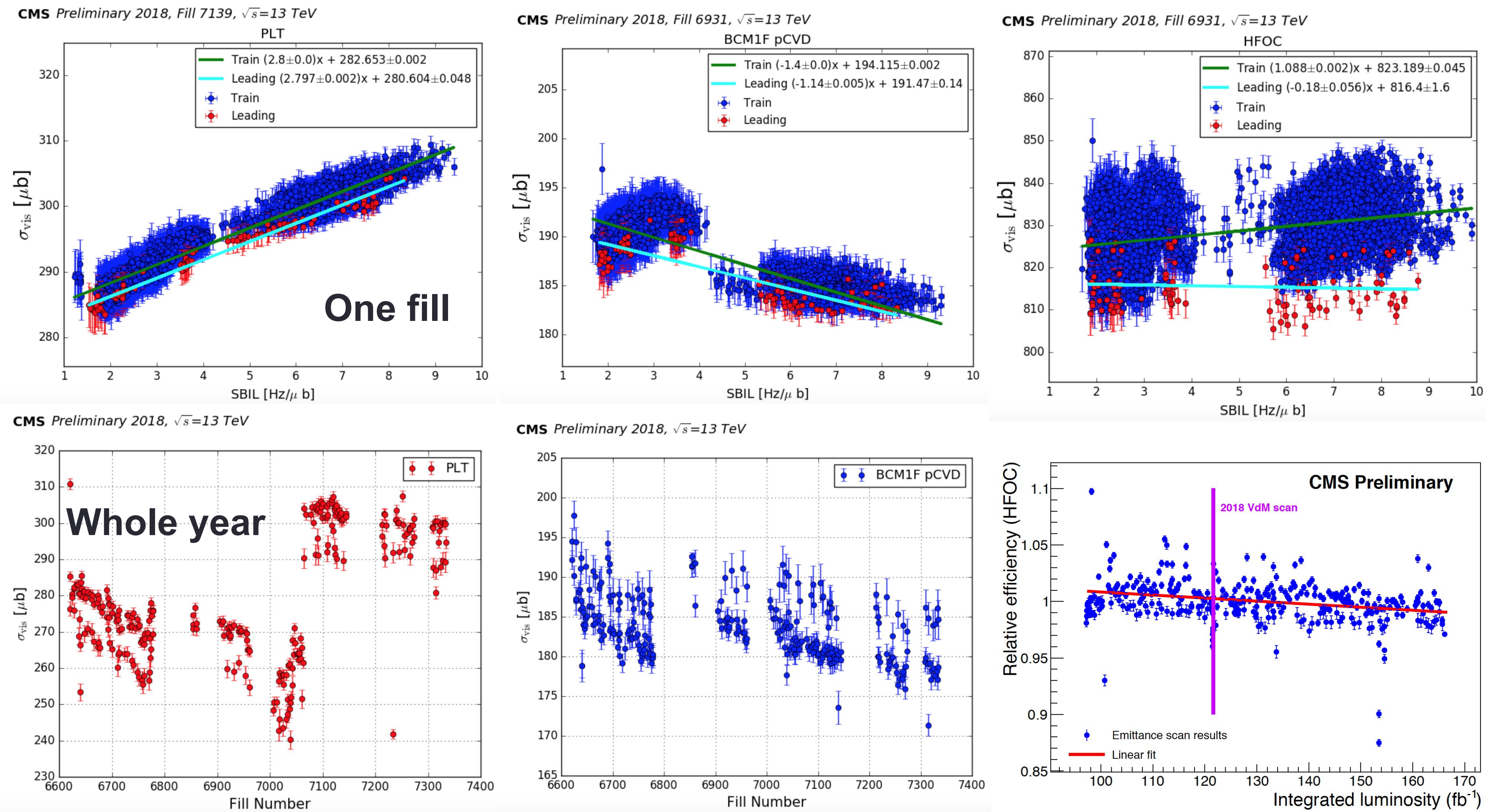






- Non-linearity correction is extracted:
  - per detector $\Rightarrow$ self-consistent check
  - per fill / per scan $\Rightarrow$ early and late scans can be used separately (next slide)
  - per bunch crossing $\Rightarrow$ leading and train bunches have different evolution of emittance and also show different linearity

Is non-linearity always the same?

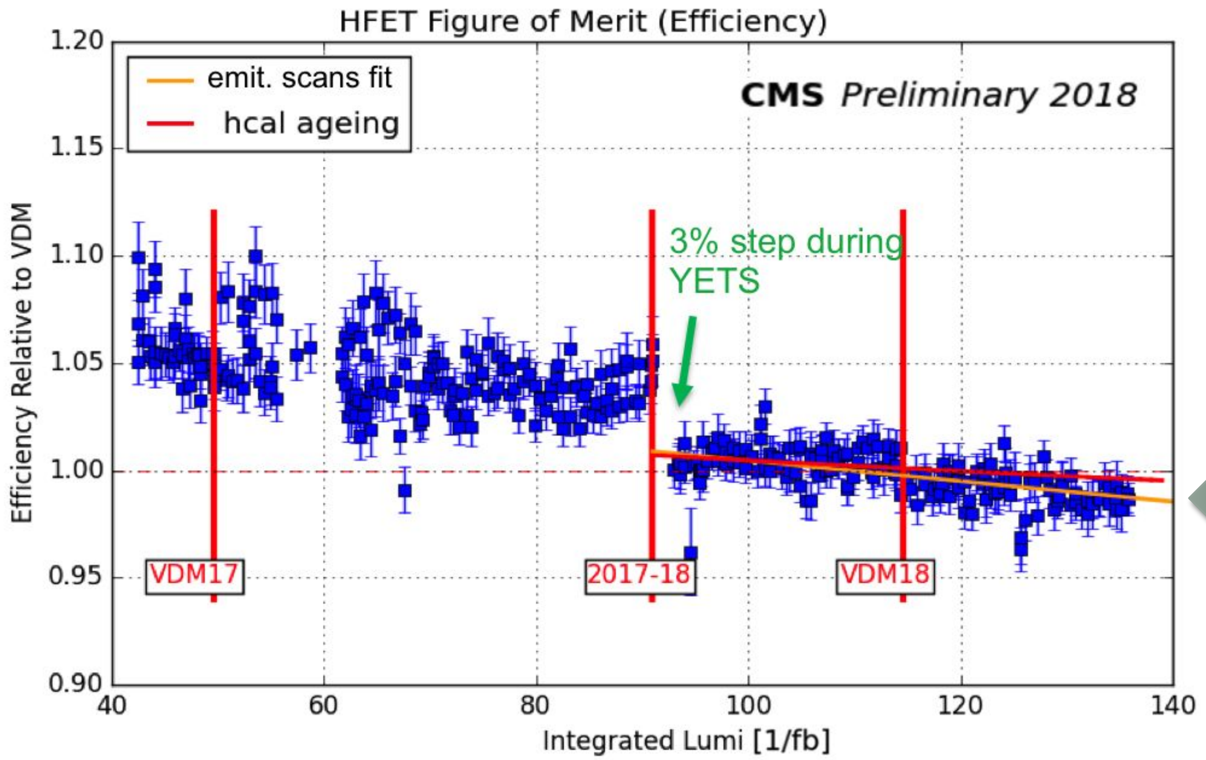


- Nonlinearity is different for each detector, but it stays constant during long period of time and similar beam conditions.

Emittance scans for stability monitoring (2/2)

- Less scatter in 2018 emittance scans
  - more optimized beam conditions and more consistent filling scheme (in 2017 filling scheme was changed several times).

- HF detector performance change was spotted from the first emittance scans in the year in 2018 after the end of year technical stop (YETS)!



Radiation damage measured from emittance scans is slightly more pronounced than predicted by HCAL ageing model.

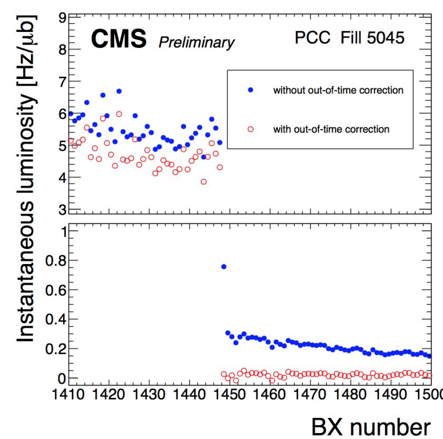
Corrections applied per bunch crossing

- Afterglow correction per bunch crossing:
  - afterglow type1 – fast component and type 2 – slow component from material activation.
  - Relevant for HF, BCM1F and PCC.

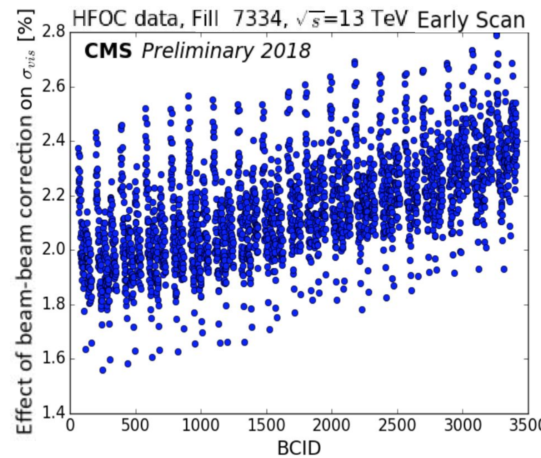
- Single beam-beam deflection correction (function of bunch intensity and bunch width);

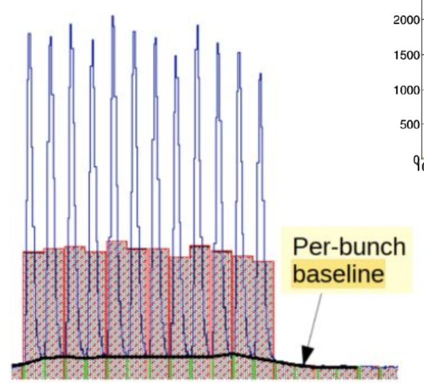
- Corrections to bunch current:
  - -1% correction to FBCT current of the fits bunch in the train;
  - FBCT/DCCT normalization in every scan;

Out of time response correction (afterglow)

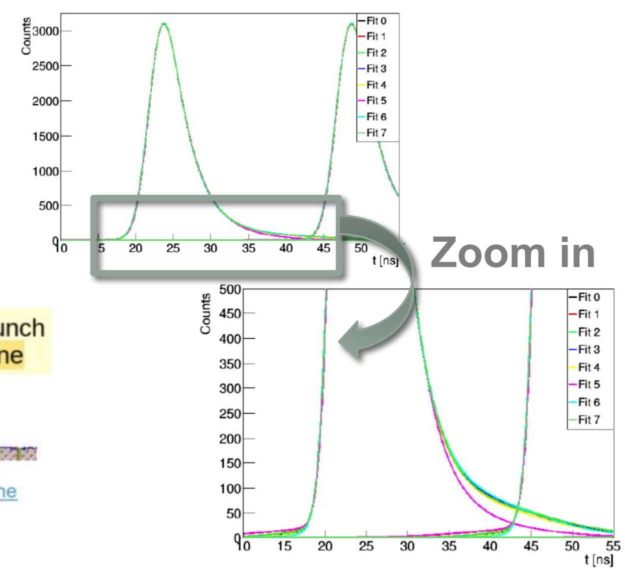


Single beam-beam deflection per BCID





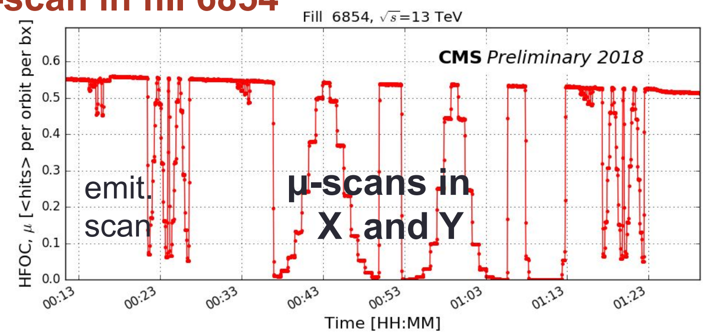
[*J. Kral, "A new Acquisition System for the SPS and LHC Fast BCTs"]



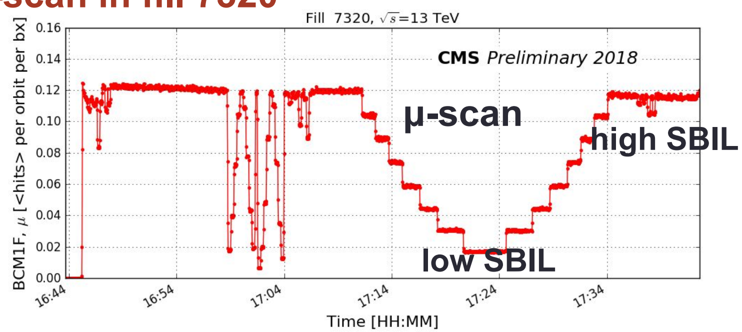
μ-scans for cross-detector linearity comparison

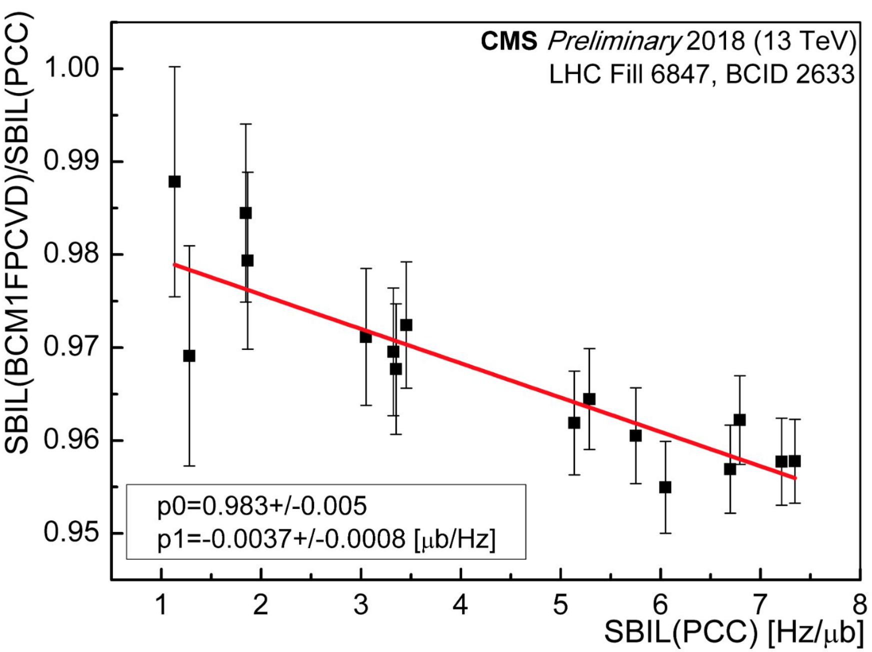
- μ-scans are similar to emittance scans, however often with equal steps in SBIL and longer step duration for better statistics.
- Ratio of measured by two independent detectors luminosity (SBIL) in every step of **μ-scan** is the measure of cross-detector linearity. Additional cross check for emittance scans method.

μ-scan in fill 6854



μ-scan in fill 7320





Example of impact of $\sigma_{\mathcal{L}}$ on SM precision tests: W & Z fiducial cross-sections at 7 TeV

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ATLAS Collaboration, Eur. Phys. J. C 77 (2017) 367

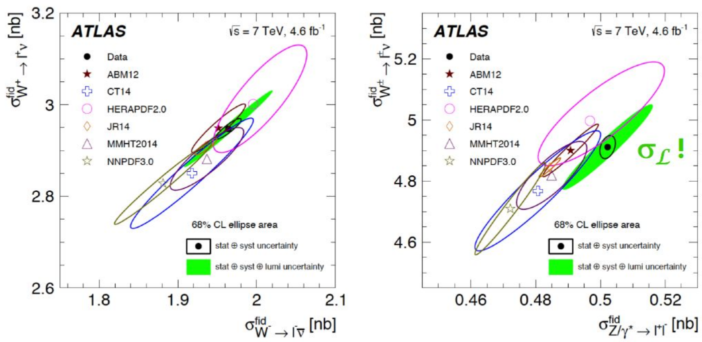


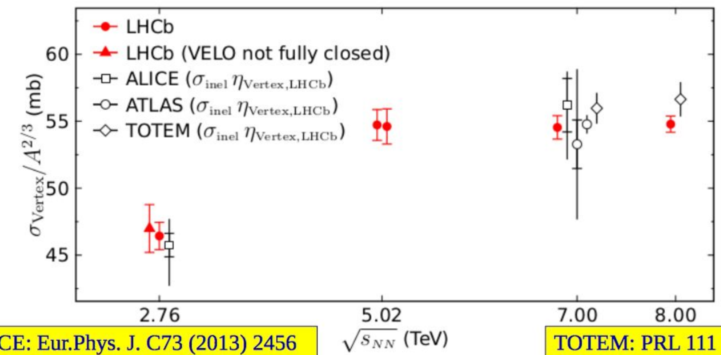
Figure 19: Integrated fiducial cross sections times leptonic branching ratios of $\sigma^{\rm fid}_{W^+\to\ell^+\nu}$ vs. $\sigma^{\rm fid}_{W^-\to\ell^-\bar\nu}$ (left) and $\sigma^{\rm fid}_{W^\pm\to\ell^\pm\nu}$ vs. $\sigma^{\rm fid}_{Z/\gamma^*\to\ell^+\ell^-}$ (right). The data ellipses illustrate the 68% CL coverage for the total uncertainties (full green) and total excluding the luminosity uncertainty (open black). Theoretical predictions based on various PDF sets are shown with open symbols of different colours. The uncertainties of the theoretical calculations correspond to the PDF uncertainties only.

W. Kozanecki 6 Dec 2019

http://indico.hep.manchester.ac.uk/conferenceDisplay.py?confId=5556

Comparison with other experiments

Inelastic σ scaled to LHCb "Vertex" lumi-counter acceptance using MC efficiency $\eta_{\rm Vertex}$.
p-Pb cross-section at 5.02 TeV is scaled by $A^{-2/3}$. From J. Instrum. 9 (2014) P12005



ALICE: Eur.Phys. J. C73 (2013) 2456

ATLAS: Nature Com. 2 (2011) 463; Nucl.Phys. B889 (2014) 486-548

TOTEM: PRL 111 (2013) 012001; Europhys. Lett. 101 (2013) 21004)

Most recent results (not plotted, 1.9% precision for 2012 data) ATLAS: Eur. Phys. J. C 76 (2016) 653

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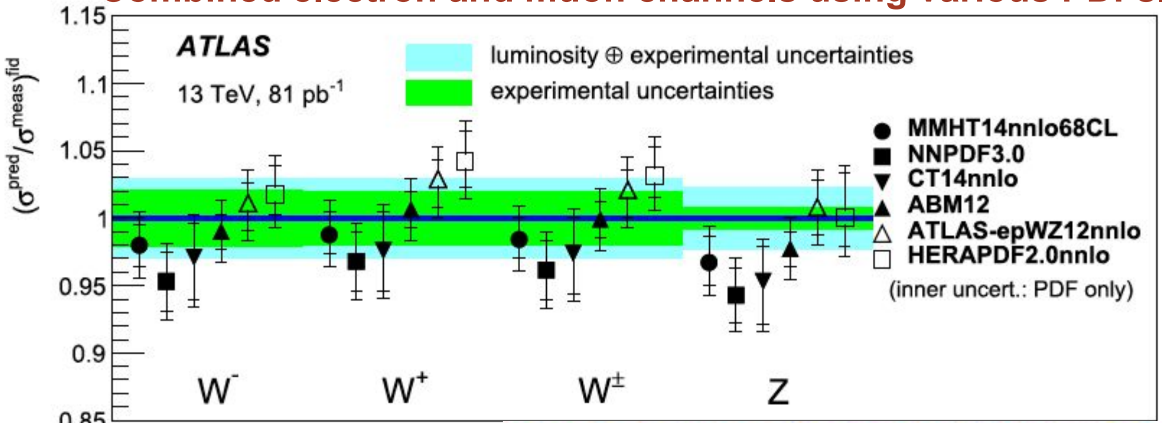
https://cds.cern.ch/record/2255091/files/LHCb-TALK-2017-034.pdf

Combined electron and muon channels using various PDFs.



Physics Letters B 759 (2016) 601–621