ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Luminosity measurements of the LHC experiments

The 10th Edition of the Large Hadron Collider Physics Conference, organised from Taipei

Roman Lavička on behalf of the ALICE, ATLAS, CMS and LHCb Collaborations

May 16, 2022, virtually from Vienna, Austria

Motivation

$$\sigma = \frac{N}{\mathcal{L}_{\text{int}}}$$

σ - cross section of a process, N - seen events of the process, $\mathcal{L}_{\text{int}}$ - integrated luminosity

- Luminosity is key for:
  - experiment-independent evaluation of physics message (cross section),
  - experiment control (beam quality monitoring).
- Absolute accuracy is important:
  - challenging task with many sources of systematic uncertainties,
  - $\rightarrow$ in some cases dominates the systematic uncertainty on cross section determination.
- Last summary talk at LHCP in 2020 by O. Karacheban, see HERE.
- List of new public documents since then in the backup (page 21.)

Content

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   - Definition
   - Measurement and calibration
     - van der Meer scan
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   - Luminosity-scale calibration
     - Length-scale calibration
     - Non-factorisation
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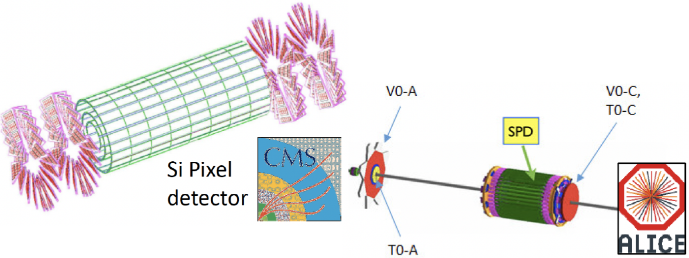
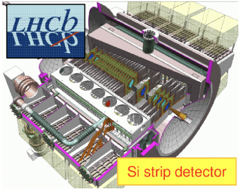
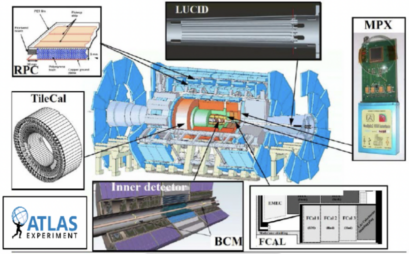
   - Integrated luminosity
     - Calibration transfer to physics runs
     - Measurement stability
3. Summary of achieved accuracy
4. Upgrades of luminometers







Luminosity definition and measurement

Luminosity definition

$$\mathcal{L} = \nu_{\mathrm{rev}} N_1 N_2 \int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y$$

ν_{rev} - revolution frequency, N_i - bunch intensity, ρ_i - bunch density distribution in (x,y) plane

$$\int \rho_1(x,y)\rho_2(x,y)\mathrm{d}x\mathrm{d}y = \frac{1}{2\pi\Sigma_x\Sigma_y}$$

Σ_x, Σ_y are the effective widths of the bunch overlap region in the two transverse directions (standard deviation if Gaussian).

$$\mathcal{L} = \nu_{\mathrm{rev}} \frac{N_1 N_2}{2\pi\Sigma_x\Sigma_y}$$

- Luminosity accuracy:
  - accuracy based on accelerator instrumentation $\mathcal{O}(10\%)$,
  - ultimate accuracy used in physics analysis is based on dedicated calibration (vdM, BGI...).

Luminosity measurement via visible cross section

- Luminosity is measured indirectly in physics data-taking using suitable reference process.

$$\mathcal{L} = \frac{\mathrm{R_{ref}}}{\sigma_{\mathrm{ref}}}$$

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$$\mathcal{L} = \frac{\mathrm{R}_{\mathrm{vis}}}{\sigma_{\mathrm{vis}}} = \frac{\mu_{\mathrm{vis}}\nu_{\mathrm{rev}}}{\sigma_{\mathrm{vis}}}$$

  - μ_{vis} is an average number of visible interactions per bunch crossing.

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$$\mathcal{L} = \nu_{\mathrm{rev}}\frac{N_1 N_2}{2\pi\Sigma_x\Sigma_y} \quad \mathcal{L} = \frac{\mu_{\mathrm{vis}}\nu_{\mathrm{rev}}}{\sigma_{\mathrm{vis}}} \quad \rightarrow \quad \sigma_{\mathrm{vis}} = \frac{2\pi\mu_{\mathrm{vis}}\Sigma_x\Sigma_y}{N_1 N_2}$$

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- We need a session where we can measure μ_{vis}, N_i and Σ_i simultaneously!

Bunch intensity measurement

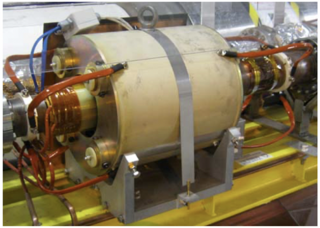
$$\mathcal{L} = \nu_{\text{rev}} \frac{N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

Bunch intensity measurement

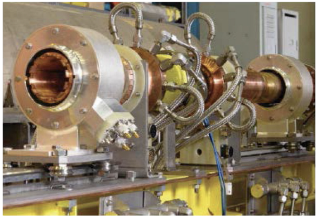
$$\mathcal{L} = \nu_{\text{rev}} \frac{N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

- Provided by LHC via current transformers:
  - DC current transformer (DCCT)
    - total beam intensities,
  - fast beam current transformer (fBCT)
    - relative bunch intensities.

DCCT

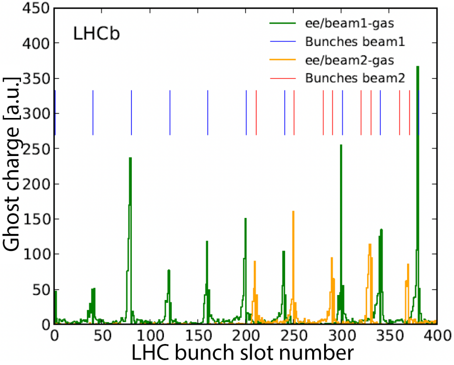


fBCT



- Parasitic-charge correction:
  - ghost charge (LHC, LHCb),
  - satellite charge (LHC).

JINST 9 P12005 (2014)



- Currently, per-mil level uncertainties.

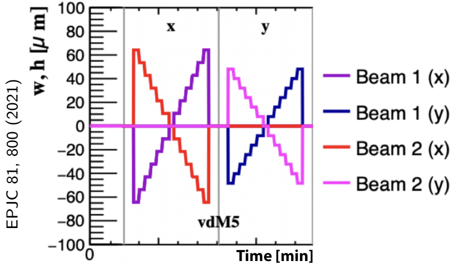
Bunch overlap region measurement

$$\mathcal{L} = \nu_{\mathrm{rev}} \frac{N_1 N_2 / 2\pi}{\Sigma_x \Sigma_y}$$

Bunch overlap region measurement

$$\mathcal{L} = \nu_{\text{rev}} \frac{N_1 N_2 / 2\pi}{\Sigma_x \Sigma_y}$$

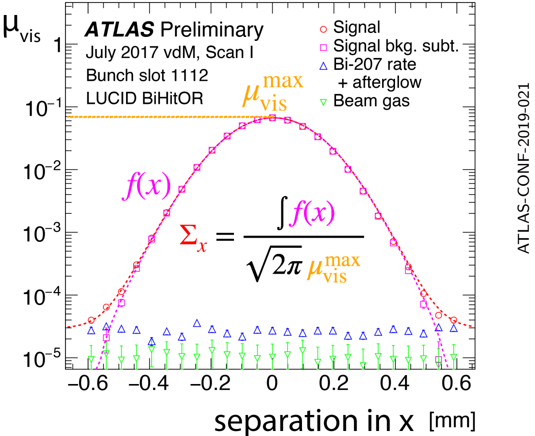
- Dedicated sessions: van der Meer scans (all experiments), beam-gas imaging (LHCb).
- vdM: displaced beams move against each other in x and then in y direction.



- Beam conditions (vdM vs. pp physics):
  - low pile-up (~ 0.5 vs. 30-60),
  - isolated bunches vs. bunch trains,
  - low luminosity ($\sim 10^{30}$ vs. $\sim 10^{34}$).

- Factorization assumption applied

$$\rho(x, y) = \rho(x)\rho(y)$$

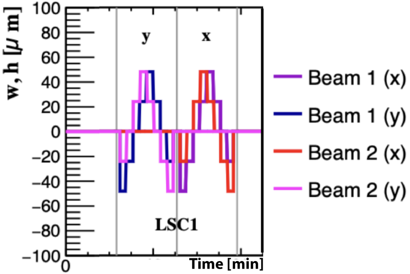


Selected topics

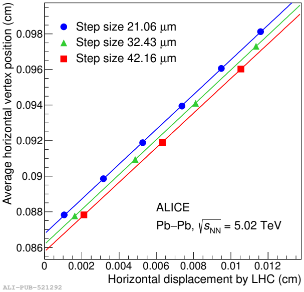
Length-scale calibration

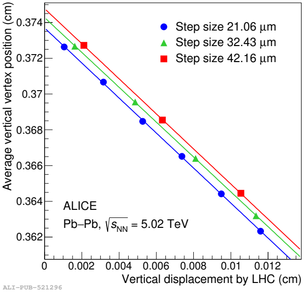
- Measures the scale factor between nominal beam displacement to actual one.
- Measurement of vertex position while moving beams with fixed distance.

EPJC 81, 800 (2021)



arXiv:2204.10148v1



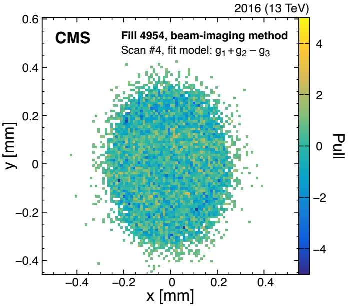


- Alternatively, beam-gas imaging can be used (large beam-gas vertex sample required).

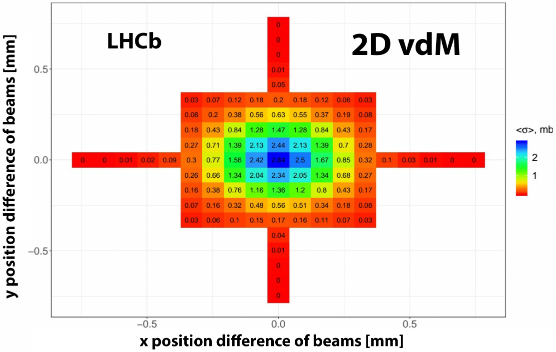
Non-factorisation

$$\rho(x, y) \neq \rho(x)\rho(y)$$

- Differs from bunch to bunch and in time. Effect up to $\sim 5\%$ in Run 1.
- Beam tailoring in the LHC injection chain reduces this effect under 2%.



EPJC 81, 800 (2021)

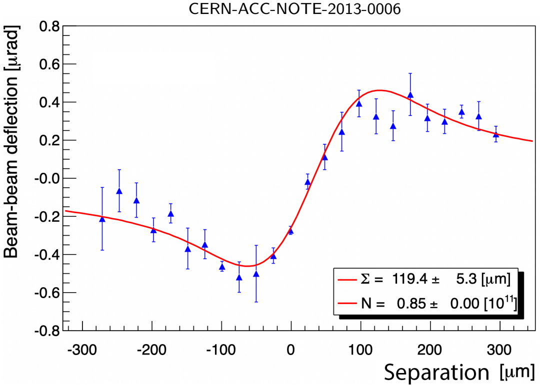


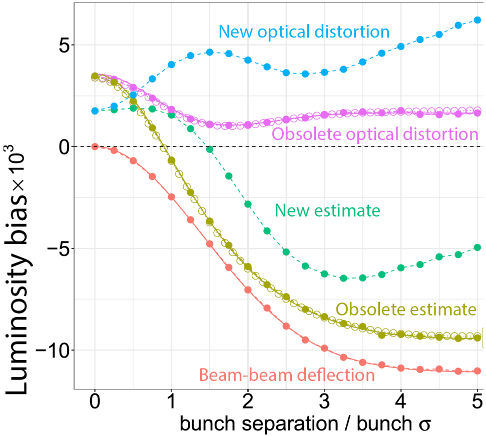
From talk by V. Balagura at Lumi Days 2019

- ALICE, ATLAS: combined fit to the beam-separation dependence of the luminosity and of the luminous-region parameters.
- CMS: beam-beam imaging.
- LHCb: beam-gas imaging, 2D vdM (Run 3?).
- Uncertainty now tamed to $0.5 - 1\%$ in Run 2.

Beam-beam interaction

- Orbit and shape of colliding bunches distorted by mutual electromagnetic interaction.
- Beam-beam deflection: change in beam separation; estimated analytically.
- Optical distortion: change in beam profile; estimated with simulations.
- Beam-beam deflection + optical distortion = full effect; is estimated with simulation.

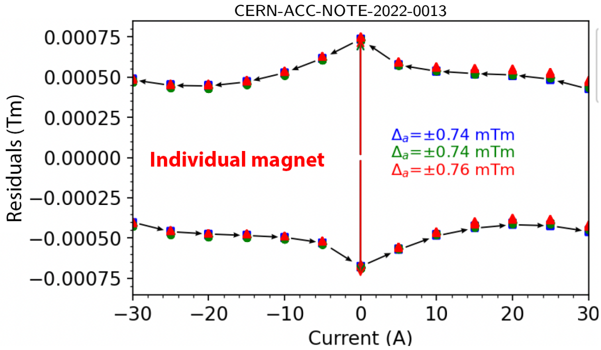


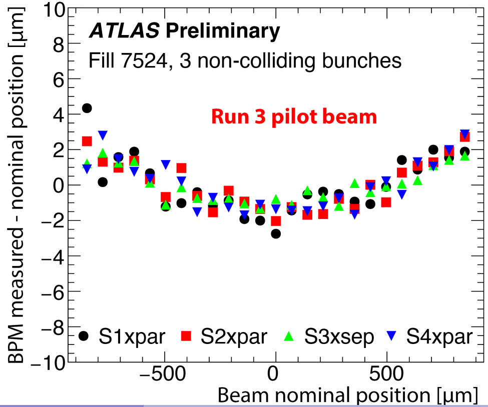


Balagura, EPJC 81, 26 (2021)

Magnetic non-linearities

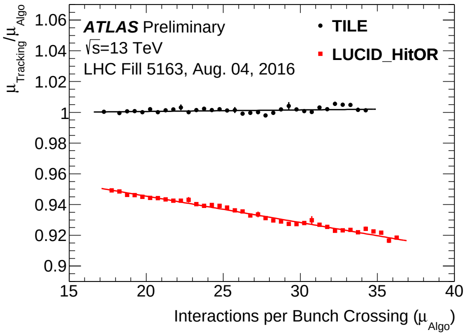
- Difference between expected and measured positions with Beam-Position Monitors.
- Points to non-linear behaviour of steering magnets → hysteresis.
- Impact on calibration precision is several per mil, currently being assessed.
- Precision calibration of BPMs could cure this problem.
- Effect studied with dedicated tests on Run 3 pilot run → reproducible within that session.



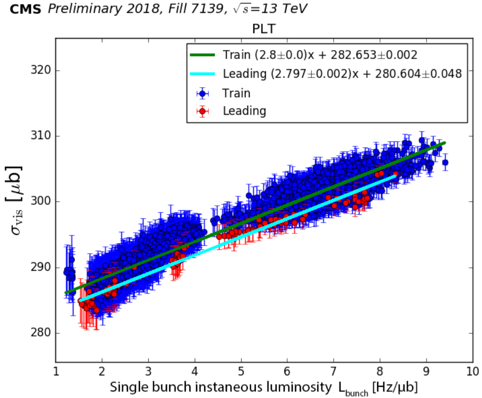


Calibration transfer to physics conditions

- vdM condition: low pile-up and isolated bunches → correction needed for ATLAS/CMS.
- ATLAS: calibration transfer based on track-counting luminosity.
- CMS: calibration transfer based on emittance scans (short vdM in physics conditions).
- Typical effect up to 10% and uncertainty up to 1%.

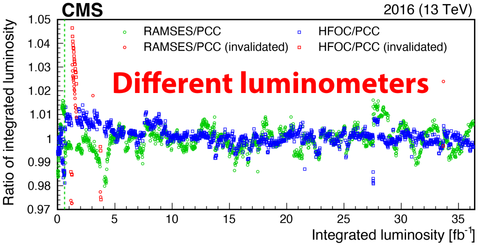


ATLAS-CONF-2019-021

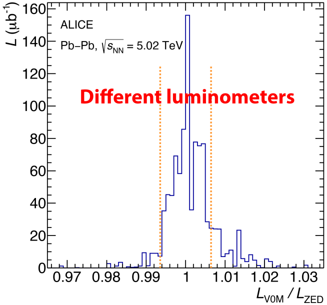


CMS-DP-2019-016

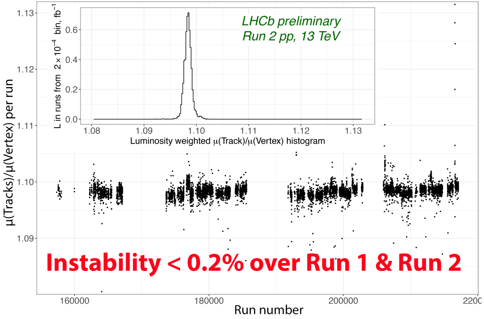
Stability and reproducibility over time



EPJC 81, 800 (2021)

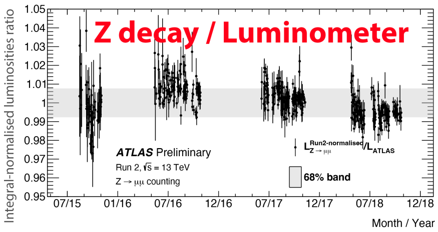


arXiv:2204.10148v1



CERN-LHCC-2021-002

ATLAS tested luminosity calibration stability using Z bosons.



ATL-DAPR-PUB-2021-001

Summary of achieved accuracy

Summary: achieved uncertainties in pp collisions

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for pp at 8 TeV	2012	Run 1
ALICE	2.4	
ATLAS	1.9	
CMS	2.6	
LHCb		**1.16**

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for pp at 2.76 TeV	2013
ALICE	3.8
ATLAS	3.1
CMS	3.7
LHCb	2.2

←Run 1

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for pp at 13 TeV	2015	2016	2017	2018	Run 2
ALICE	3.4	1.9	2.7	2.1	1.6
ATLAS	*2.1*		*2.4*	*2.0*	*1.7*
ATLAS low-μ			*1.5*		
CMS	1.6	1.2	*2.3*	*2.5*	*1.6*
CMS low-μ			*1.7*		
LHCb	*2.0*				

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for pp at 5 TeV	2015	2017
ALICE	2.3	2.1
ATLAS	*1.5*	
CMS	*2.3*	*1.9*
LHCb	*2.0*	

←Run 2

Preliminary in italics. Numbers without hypertext link are internal.

Summary: achieved uncertainties in heavy-ion collisions

- Larger uncertainties:
  - no time to tune vdM setup,
  - larger ghost charge,
  - large satellite charge,
  - statistical limitations.
- Smaller uncertainties:
  - beam-beam effects,
  - calibration transfer.

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for p–Pb/Pb–p at 5 TeV

	2013
ALICE	3.7/3.4
ATLAS	2.7
CMS	3.6/3.4
LHCb	2.3/2.5

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for Pb–Pb at 2.76 TeV

	2010	2011
ALICE	5.8	4.2

←Run 1

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for p–Pb/Pb–p at 8 TeV

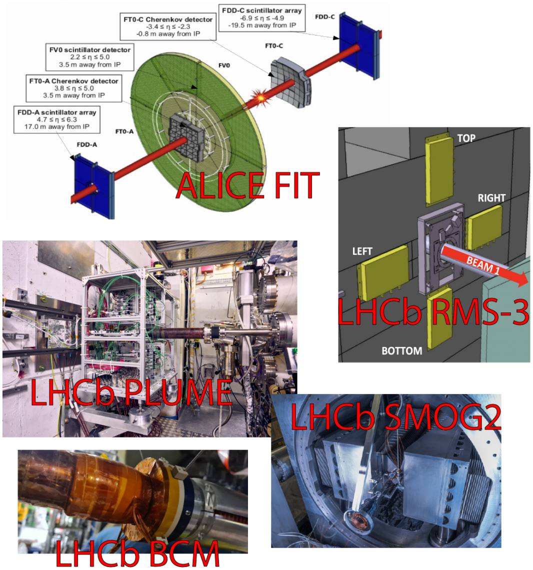
	2016
ALICE	1.9/2.0
ATLAS	2.4
CMS	*3.7/3.2*
LHCb	*2.6/2.5*

$\sigma_{\mathcal{L}}/\mathcal{L}[\%]$ for Pb–Pb at 5 TeV

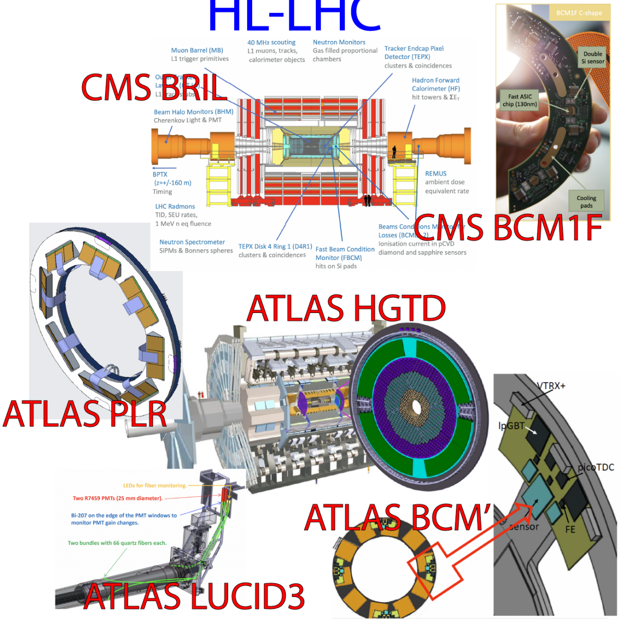
	2015	2018
ALICE	2.3	
ATLAS	1.5	1.9
CMS		*1.5*
LHCb		*4.2*

←Run 2

Run 3

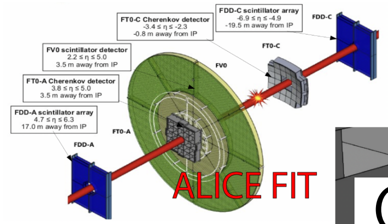

FDD-C scintillator array
-6.9 ≤ η ≤ -4.9
-19.5 m away from IP
FT0-C Cherenkov detector
-3.4 ≤ η ≤ -2.3
-0.8 m away from IP
FV0 scintillator detector
2.2 ≤ η ≤ 5.0
3.5 m away from IP
FT0-A Cherenkov detector
3.8 ≤ η ≤ 5.0
3.5 m away from IP
FDD-A scintillator array
4.7 ≤ η ≤ 6.3
17.0 m away from IP
FDD-C
FT0-C
FV0
FT0-A
FDD-A
ALICE FIT
TOP
RIGHT
LEFT
BEAM 1
BOTTOM
LHCb RMS-3
LHCb PLUME
LHCb SMOG2
LHCb BCM

HL-LHC

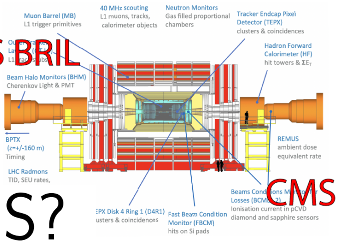

CMS BRIL
Muon Barrel (MB)
L1 trigger primitives
40 MHz scouting
L1 muons, tracks, calorimeter objects
Neutron Monitors
Gas filled proportional chambers
Tracker Endcap Pixel Detector (TEPX)
clusters & coincidences
Hadron Forward Calorimeter (HF)
hit towers & ΣE_T
Beam Halo Monitors (BHM)
Cherenkov Light & PMT
BPTX
(z=+/-160 m)
Timing
REMUS
ambient dose equivalent rate
LHC Radmons
TID, SEU rates,
1 MeV n eq fluence
Neutron Spectrometer
SiPMs & Bonners spheres
TEPX Disk 4 Ring 1 (D4R1)
clusters & coincidences
Fast Beam Condition Monitor (FBCM)
hits on Si pads
Ionisation current in pCVD diamond and sapphire sensors
BCM1F C-shape
Double Si sensor
Fast ASIC chip (130nm)
Cooling pads
CMS BCM1F
ATLAS HGTD
ATLAS PLR
LEDs for fiber monitoring.
Two R7459 PMTs (25 mm diameter).
Bi-207 on the edge of the PMT windows to monitor PMT gain changes.
Two bundles with 66 quartz fibers each.
ATLAS LUCID3
VTRX+
lpGBT
picoTDC
sensor
FE
ATLAS BCM'

Run 3

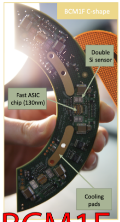
HL-LHC



ALICE FIT

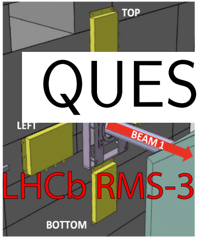


CMS BRIL

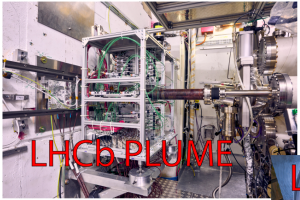


CMS BCM1F

QUESTIONS?

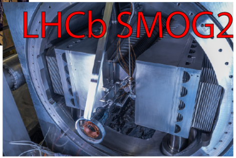


LHCb RMS-3

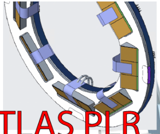


LHCb PLUME

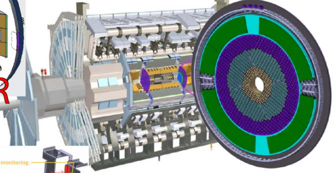
LHCb BCM



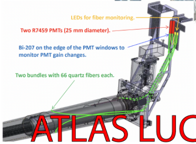
LHCb SMOG2



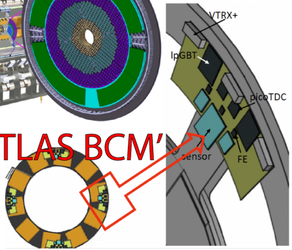
ATLAS PLR



ATLAS HGTD



ATLAS LUCID3



ATLAS BCM'

BACK UP

References

Luminosity measurements

ALICE: pp 13 TeV 2016-2018: ALICE-PUBLIC-2021-005.
ALICE: Pb–Pb 5 TeV 2015/2018: arXiv:2204.10148v1.
ATLAS: low-pileup pp 5/13 TeV: ATLAS-CONF-2020-023.
ATLAS: pp via Z-boson 13 TeV: ATL-DAPR-PUB-2021-001.

CMS: pp 13 TeV 2015/2016: EPJC 81, 800 (2021).
CMS: pp 5 TeV 2017: CMS-PAS-LUM-19-001 (2021)
CMS: Pb–Pb 5 TeV 2018: CMS-PAS-LUM-18-001 (2022).

Detector upgrades

ALICE FIT: CERN-LHCC-2013-019.

CMS BCM1F: CMS-PHO-GEN-2022-001.
CMS BRIL: CERN-LHCC-2021-008 (2021).

ATLAS BCM': internal communication.
ATLAS HGTD: CERN-LHCC-2020-007.
also poster by Fatima Bendebba at LHCP22.
ATLAS LUCID-3: LHCC-2021-016.
also poster by Jack Lindon at LHCP22.
ATLAS PLR: internal communication.

LHCb BCM: internal communication.
LHCb PLUME: CERN-LHCC-2021-002.
LHCb RMS-3: CERN-Poster-2021-1046.
LHCb SMOG2: CERN-LHCC-2019-005.

ATLAS uncertainties for pp 13 TeV (2015-2018)

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

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ALICE uncertainties for Pb–Pb 5 TeV (2015 and 2018)

Source	Uncertainty (%) ZED | V0M
Statistical	0.04 | 0.09
$h_{x0}h_{y0}$ consistency (V0M vs ZED)	0.13
Length-scale calibration	1
Non-factorisation	1.1
Bunch-to-bunch consistency	0.4 | 0.1
Scan-to-scan consistency	1
Background subtraction	0.8 | 0.5
Bunch intensity	0.8
Magnetic non-linearities	0.2
Orbit drift	0.15
Beam–beam deflection and distortion	0.1
Fitting scheme	0.4
Total of visible cross section	2.2 | 2.1
Stability and consistency	0.7
Total of luminosities	2.3 | 2.2

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CMS uncertainties for pp 13 TeV (2015 and 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	—

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LHCb uncertainties for all collision systems in Run 1

Source	BGI	VDM	Correlated
Bunch population uncertainties (section 3)			
FBCT offset	0.04	0.05	yes
BPTX cross-check	n.a.	0.09	yes
DCCT population product	0.22	0.23	yes
Ghost charge	0.02	0.04	yes
Satellite charge	0.06	0.02	yes
Missing satellite measurements	n.a.	0.23	no
Rate measurement			
Background subtraction	0.20	0.14	yes
Ratio of observables *Track* to *Vertex*	0.20	n.a.	no
Efficiency of rate observables	negl.	0.09	no
Fit model	0.50	0.50	yes
VELO transverse scale	0.05	0.05	yes
BGI specific (section 6)			
Beam-beam resolution	0.93		no
Beam-gas resolution	0.55		no
Detector alignment	0.45		no
Measurement spread	0.54		no
Bunch length	0.05		no
Reconstruction efficiency	0.04		no
Pressure gradient	0.03		no
VDM specific (section 7)			
Length scale		0.50	no
Beam-beam effects		0.28	no
Fit bias		0.20	no
Linear correlation		0.08	no
Parameter assumptions		0.74	no
Constraints from BGI		0.30	yes
Scan variation and drift		0.32	no
Non-reproducibility		0.80	no
Statistical		0.04	no
Uncorrelated	1.31	1.32	
Correlated	0.59	0.65	

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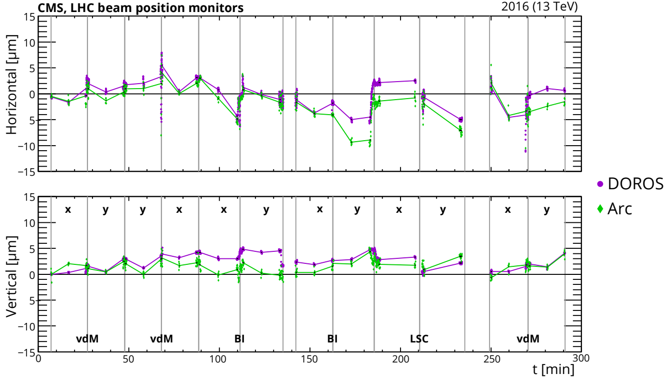
Orbit drift and beam-satellite event by event separation



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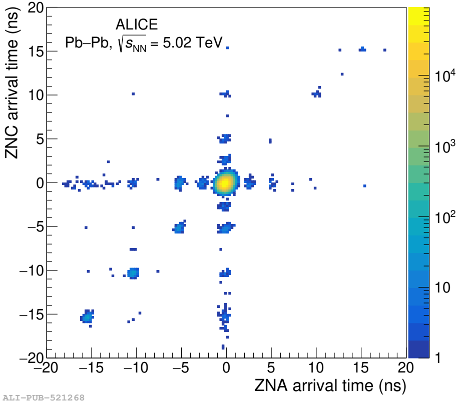

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