LHC and HL-LHC Luminosity

Highlights of luminosity calibration, monitoring and hardware progress in recent years

Anne Dabrowski (CERN)

Thank you for material from all experiments and the LLCMWG (w/chairs W. Kozanecki, D. Stickland)

Presentations at ICHEP_2024 by E. Franzoso (LHCb), P. Major (CMS), G. Contreras (ALICE); LHCp_2024, CERN EP seminar R. Hawkings (ATLAS) serve as recent references

LHC Days Split, Hvar Croatia
30th September - 4th October 2024

Luminosity importance

Connects theory and experiment

$$\langle N_{pp\to X}\rangle = \boldsymbol{\sigma}_{pp\to X} L_{int}$$

- Among the **leading sources of experimental uncertainties in SM precision physics at LHC** e.g. fiducial cross-sections for inclusive vector-boson production, top production …

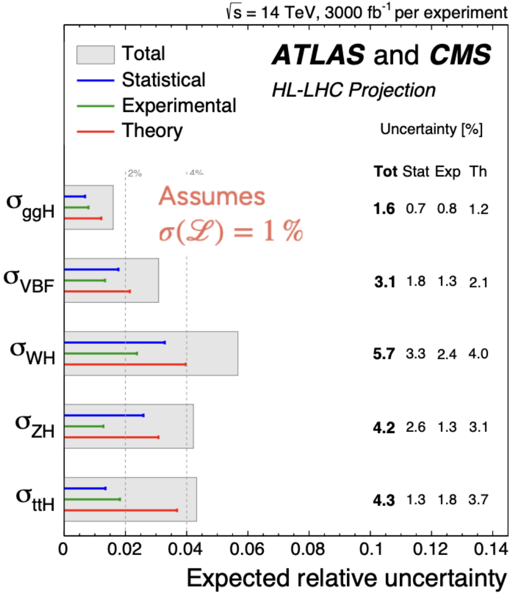
HL-LHC: CMS and ATLAS target 1% uncertainty on the yearly calibrated offline luminosity

- **1% luminosity error will dominate the experimental uncertainty** in the most precisely measured Higgs Boson production cross sections and coupling measurements and will remain significant even when including the expected theoretical uncertainties

Target per-bunch online luminosity measurement of 2% uncertainty:

- **Luminosity levelling using** combination of **β*** (1.0m – 0.015m) and separation to target pileup

ATLAS & CMS Snowmass report



Luminosity is measured using benchmark physics processes like Bhabha-scattering in lepton colliders (ΔL/L ≪0.1% at LEP1), but hadron colliders pose many challenges due to the non-trivial PDFs

S. van der Meer, CERN-ISR-PO-68-31
C. Rubbia, CERN-pp_bar-Note-38

Luminosity measurement at hadron collider

- Derive the absolute luminosity scale by *precisely measuring the LHC beam parameters*
  - Typically using van der Meer (vdM) scans pioneered at the CERN ISR
    - also beam gas imagining at LHCb
  - Determine L_{inst} under **well-controlled conditions**
  - Use it to determine the **visible cross-section** σ_{vis} for any process /**lumi-algorithm:**
    - e.g. the counting rate in a luminosity detector, seeing μ_{vis} counts per bunch crossing

- Per-bunch instantaneous luminosity:

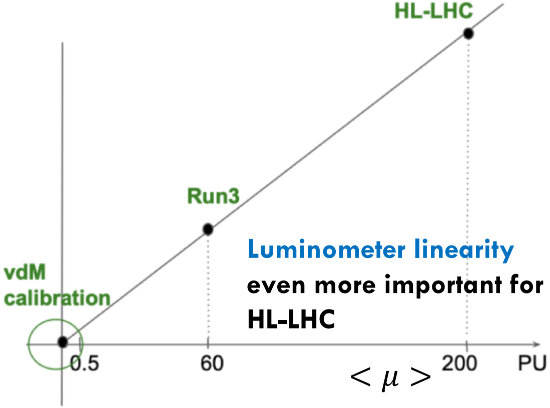
$$L_b = \frac{\mu_{vis} f}{\sigma_{vis}}$$

- Luminosity summed over all bunches:

$$L_{inst} = n_b * <L_b> = \frac{<\mu> f}{\sigma_{inel}}$$

<μ> is the pileup parameter

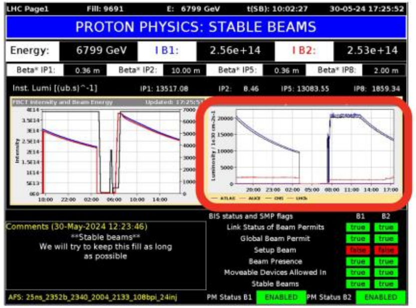
- Design a linear, stable detector, calibrate σ_{vis}, measure μ_{vis} at all times and add the measurements of L_b



Luminometer linearity
even more important for HL-LHC

Run 3: Typical Bunch Luminosity Fluctuations in Collisions

Selected 2024 fill, 14h in SB, bunches : 2352 total, 2340 IP15, 2004 IP2, 2133 IP8)



LHC Page1 Fill: 9691 E: 6799 GeV t(SB): 10:02:27 30-05-24 17:25:52

PROTON PHYSICS: STABLE BEAMS

Energy:	6799 GeV	I B1:	2.56e+14	I B2:	2.53e+14

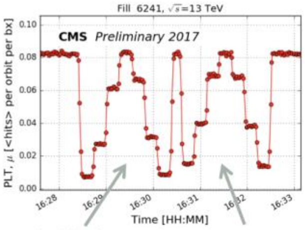
Beta* IP1:	0.36 m	Beta* IP2:	10.00 m	Beta* IP5:	0.36 m	Beta* IP8:	2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 13517.08 IP2: 8.46 IP5: 13083.55 IP8: 1859.34

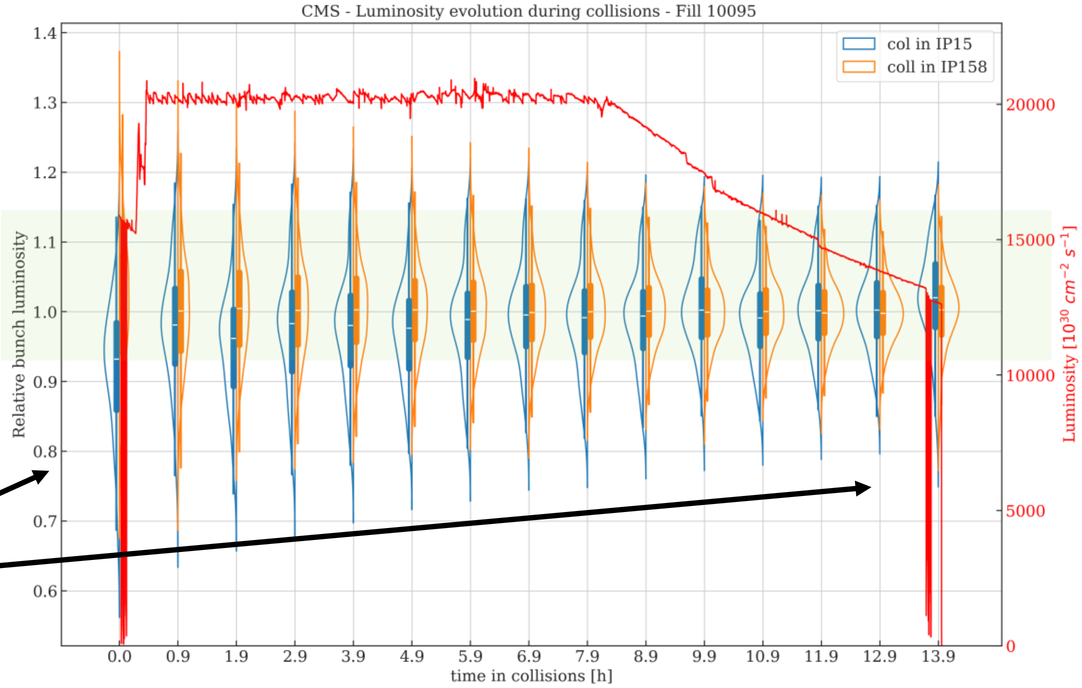
Comments (30-May-2024 12:23:46)
Stable beams
We will try to keep this fill as long
as possible

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2352b_2340_2004_2133_108bpi_24inj PM Status B1 ENABLED PM Status B2 ENABLED



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



Bunch luminosities normalized to the mean at each time stamp

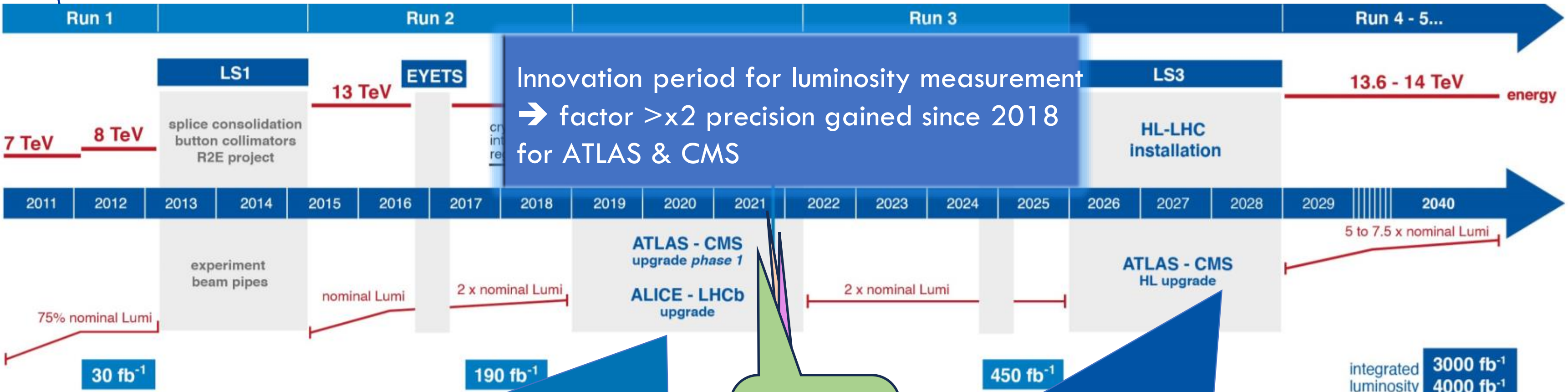
"Emittance" scans; each fill for CMS to monitor efficiency and linearity vs time/fb^{-1} and $<\mu>$ for all luminometers

https://doi.org/10.1051/epjconf/201920104001

Ilias Efthymiopoulos BE/ABP

Luminosity Run 3 and towards HL-LHC

Schedule shift of 1 year foreseen

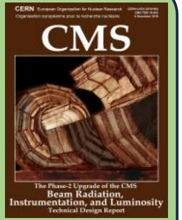


Innovation period for luminosity measurement
➔ factor >x2 precision gained since 2018 for ATLAS & CMS

LS2 Hardware for Run 3 Luminosity:

- **LHCb:** New inner tracker, new GPU based trigger 30 MHz w/luminosity flexibility, new PLUME (Cherenkov) online luminometer, new SMOG-2 gas injection for BGI & fixed target
- **ALICE:** New inner tracker, new ZDC electronics, continuous readout mode, new FTO (Cherenkov) detector for online luminosity, new FVO and FDD scintillators
- **CMS:** New silicon BCM1F w/new electronics & new PLT

e-cloud is reduced with the filling schemes (& intensities)



CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CMS

The Phase-2 Upgrade of the CMS
Beam Radiation, Instrumentation, and Luminosity
Technical Design Report

CMS BRIL Phase 2 TDR

ATLAS LUCID-3 Technical Proposal

HL-LHC BPM specifications

LS3 ATLAS& CMS Luminosity Upgrade:

- Complete upgrade/replacement of online per BX luminometers
- New ATLAS tracker, new CMS Tracker with online luminosity exploitation
- New timing detectors, electronics upgrades to various systems allowing resources for luminosity application + …

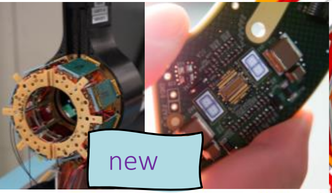
HL-LHC Machine

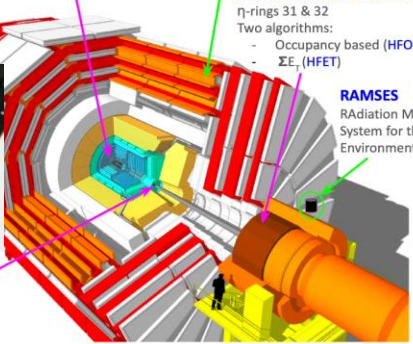
- New LHC BPMs IP5/1
- Beam screen coating for electron cloud mitigation

Multiple Run-2/3 luminometers for best handle on systematics

Multiple independent systems (*luminometers*) are utilized for best accuracy

	Independently calibrated	Cross-calibrated
Online	BCM1F*, HF*, PLT	DT, RAMSES (Run3)
Offline	PCC	RAMSES (Run2)


new



Pixel Cluster Counting (PCC)
On all except the first barrel layer
+ veto list of modules

Drift Tubes (DT)
L1 trigger primitives/objects

Hadron Forward Calorimeter (HF)
η-rings 31 & 32
Two algorithms:
- Occupancy based (HFOC)
- ΣE_T (HFET)

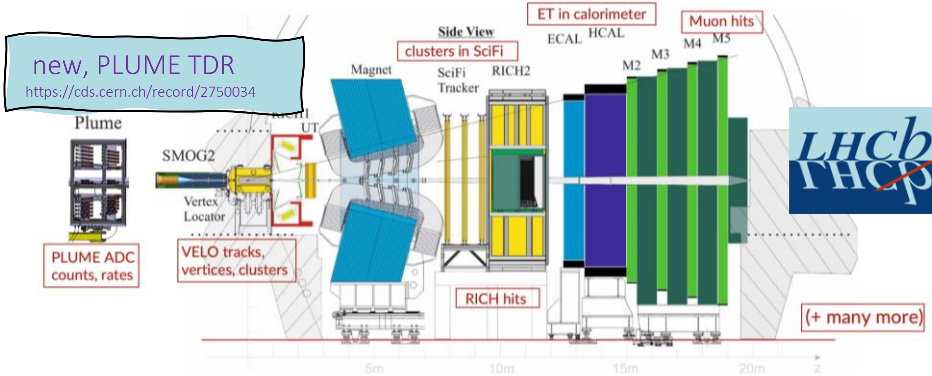
RAMSES
RAdiation Monitoring
System for the
Environment Safety

Pixel Luminosity Telescope (PLT),
Beam Condition Monitor (BCM1F)
Luminosity + beam induced background
BCM1F has multiple backends

3

In Run 3, significant efforts to study linearity and propose new lumi counters from all subdetectors

new, PLUME TDR
https://cds.cern.ch/record/2750034



PLUME ADC counts, rates

VELO tracks, vertices, clusters

clusters in SciFi

RICH hits

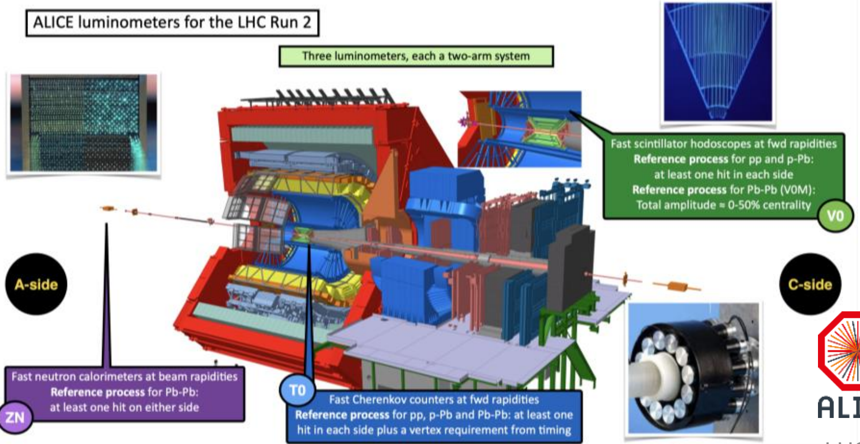
ET in calorimeter

Muon hits

(+ many more)

ALICE luminometers for the LHC Run 2

Three luminometers, each a two-arm system



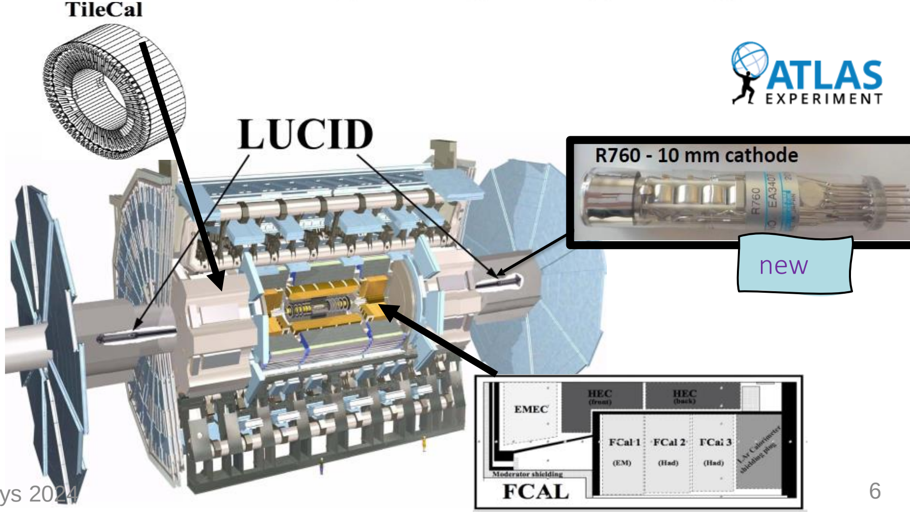
Fast scintillator hodoscopes at fwd rapidities
Reference process for pp and p-Pb:
at least one hit in each side
Reference process for Pb-Pb (V0M):
Total amplitude ≈ 0-50% centrality

Fast neutron calorimeters at beam rapidities
Reference process for Pb-Pb:
at least one hit on either side

Fast Cherenkov counters at fwd rapidities
Reference process for pp, p-Pb and Pb-Pb: at least one hit in each side plus a vertex requirement from timing

S. Acharya *et al* 2024 *JINST* **19** P05062

Guillermo Contreras, CTU in Prague



R760 - 10 mm cathode

new

Typical LHC Physics Luminosity measurement flow

1. Calibrate the absolute luminosity scale in dedicated beam conditions:

  - μ_{peak}~0.5, L_{bunch}~5x10^{28}cm^{-2}s^{-1},n_b~30-124, **β*** 19 m, L_{tot}~1-6x10^{30} cm^{-2}s^{-1}
- beam-separation vdM scans
  - → absolute luminosity scale based on factorizable vdM analysis,
  - → Measurements & corrections (non-factorization correction, length scale, beam-beam, orbit drift etc.)
- Beam-gas imaging (LHCb)
  - Independent method with many uncertainties uncorrelated to vdM method

2. Transfer calibration from vdM to physics regime (L_{tot}~10^{30}cm^{-2}s^{-1} ➔L_{tot}~10^{34}cm^{-2}s^{-1})

- correct μ, n_b & L_{tot} - dependent biases in bbb luminometers
  - requires ≥ 1 luminometer "known" to be linear wrt. L_{tot} & μ
  - best if close in time to vdM scans, monitor linearity throughout the year

3. Characterize & correct instrumental drifts over the running year

  - Radiation damage, drifts (gain, timing, efficiency ..), residual μ-dependence
  - Analysis channel-by-channel, module-by-module … w/possibility to re-calculate luminosity for optimal detector acceptance.

4. Quantify the *relative* long-term consistency & stability of as many *independent* luminosity measurements as possible

Procedure relatively standard will be **valid also for HL-LHC**

https://cds.cern.ch/record/2759074 ;
CERN-BE-2022-001

Luminosity calibration using vdM scan

- Per-bunch luminosity from beam parameters

$$\mathcal{L}_b = f_r n_1 n_2 2c \int \rho_1 \rho_2 \,\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}t$$

  - 'Geometric' definition from 4D overlap integral of the two beams, each with density $\rho_i(x,y,z,t)$
    - Bunch currents n_1, n_2 (=# protons/bunch)
    - LHC revolution frequency f_r=11246 Hz

$$\mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} \qquad \Sigma_x \approx \sqrt{\sigma_{x,1}^2 + \sigma_{x,2}^2}$$

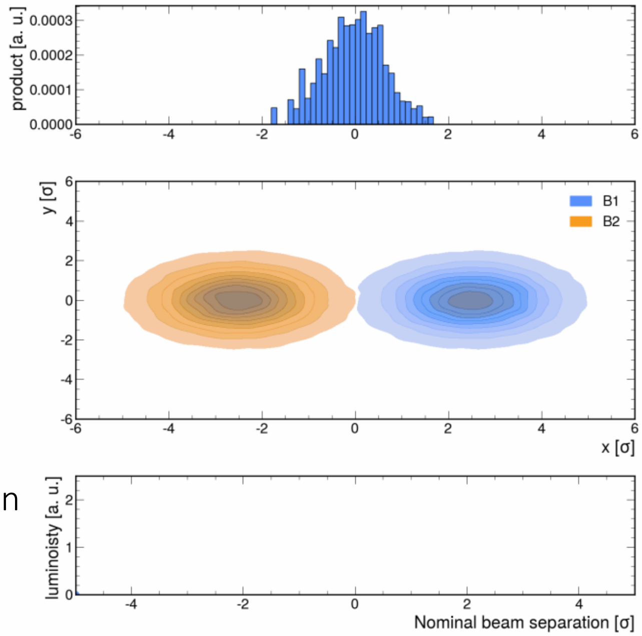
- Convolved beam widths Σ_x, Σ_y obtained from μ_{vis} vs. beam separation Δx, Δy

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int \mu_{\mathrm{vis}}(\Delta x)\,\mathrm{d}\Delta x}{\mu_{\mathrm{vis}}(\Delta x^{\mathrm{max}})}$$

- Finally obtain σ_{vis} by also using μ^{max} at peak

$$\sigma_{\mathrm{vis}} = \mu_{\mathrm{vis}}^{\mathrm{max}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

One x/y scan pair is enough to determine σ_{vis}



Slide Courtesy J. Wanczyk.
R. Hawkings

Luminosity calibration using vdM scan

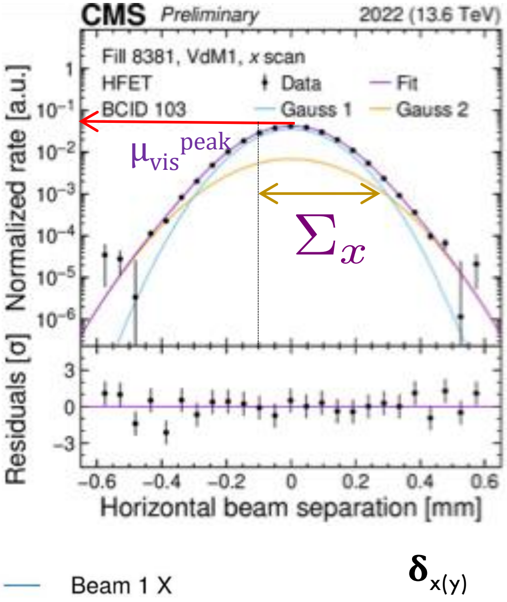
$$\sigma_{vis} = \mu_{vis}^{peak} \frac{2\pi\Sigma_x\Sigma_y}{n_1 n_2}$$

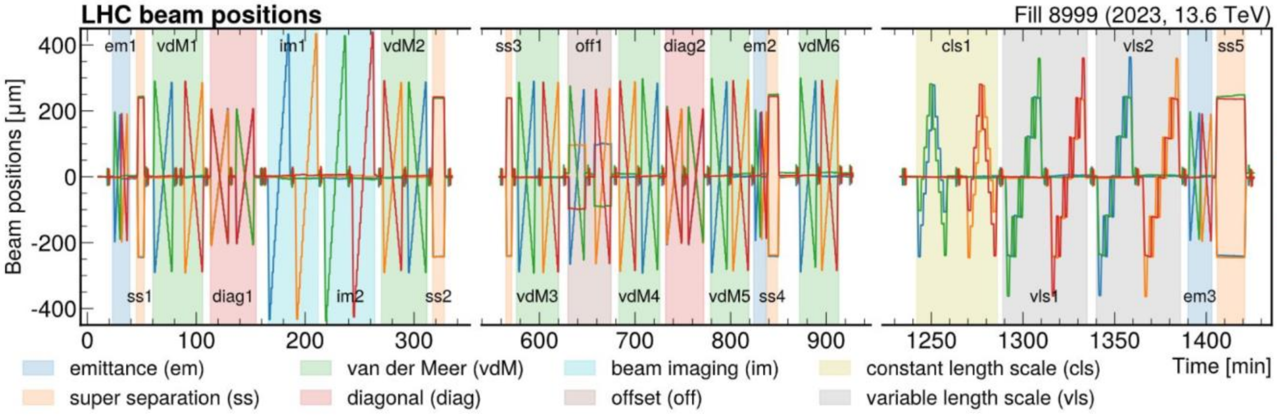
Beam overlap width

n_1 n_2 number protons/bunch

- Key assumption: factorization of bunch proton density function

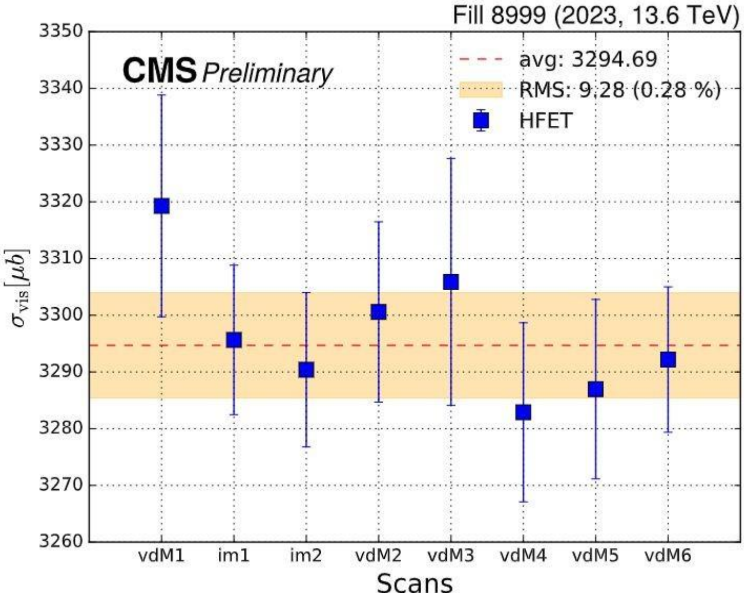
$$\mathscr{L}\left(\delta_x, \delta_y\right) = f_x\left(\delta_x\right) f_y\left(\delta_y\right)$$





The vdM method

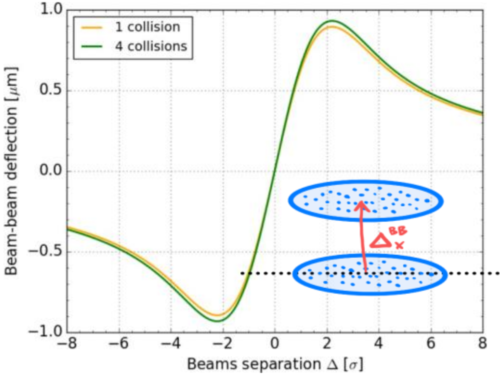
- **Challenges:**
  - Bunch shape distortion due to beam-beam EM forces
  - Factorizability of beam overlap shape
    - leading source of uncertainty)
  - Accuracy of beam position
  - Orbit drifts
  - Beam-beam deflection
  - Length scale
  - (Not covered)
    - Detector background
    - Accuracy of bunch proton count measurement

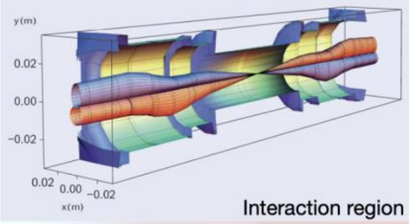


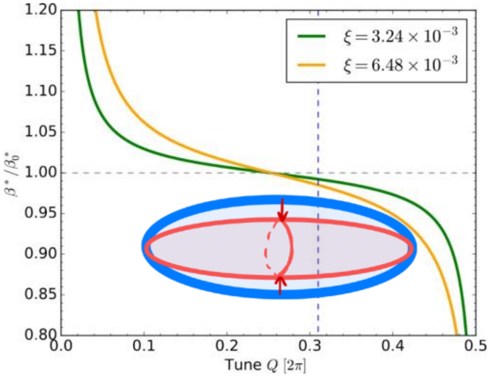
CMS DP-2024/068

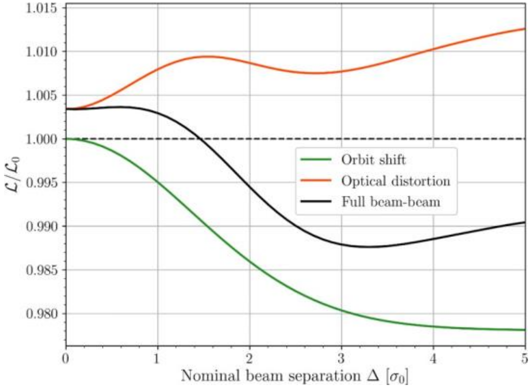
Beam-beam effects on luminosity

- Deflection
  - induces orbit changes
- Optical distortion
  - Changes in beam widths/tune (dynamic beta)
  - Amplitude-dependent changes: use lumi integrator codes (e.g., COMBI) for arbitrary bunch distributions
  - Parameterization corrections for Gaussian distribution B*B
- **LHC: Two opposing effects on luminosity;** overall calibration constant slightly negative (tune-dependent)
- **Luminosity** results published pre-2020 may have **~1% bias** due to incomplete beam-beam correction









B*B: Balagura, V. van der Meer scan luminosity measurement and beam–beam correction. *Eur. Phys. J.* C **81**, 26 (2021). https://doi.org/10.1140/epjc/s10052-021-08837-y

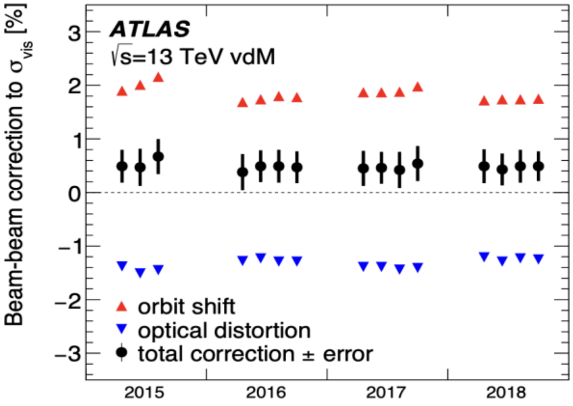
Babaev, A.*et al*. Impact of beam–beam effects on absolute luminosity calibrations at the CERN Large Hadron Collider. *Eur. Phys. J.* C **84**, 17 (2024). https://doi.org/10.1140/epjc/s10052-023-12192-5

See: J. Wanczyk ECFA mini-workshop on beam-beam effects in circular colliders

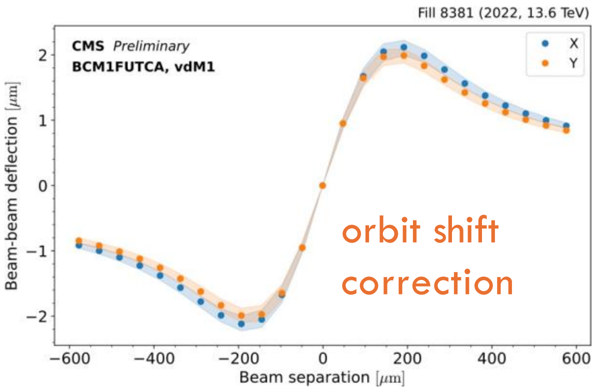
Beam Beam correction – Luminometer calibration corrections

- vdM is the case of very special beam conditions that results in the increase of ξ over time in collision, standard ξ~0.003 - 0.006

$$\frac{L_{\mathrm{no-bb}}}{L}(\Delta x) = f(\Delta x, Q_x, Q_y, \xi_{\mathrm{R}}) \qquad \xi_{\mathrm{R}} = \frac{r_p \bar{n} \beta^*}{2\pi\gamma\Sigma_x\Sigma_y}$$

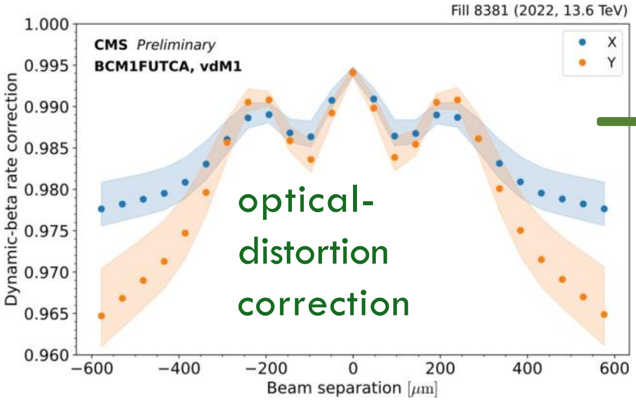


DOI: 10.1140/epjc/s10052-023-11747-w



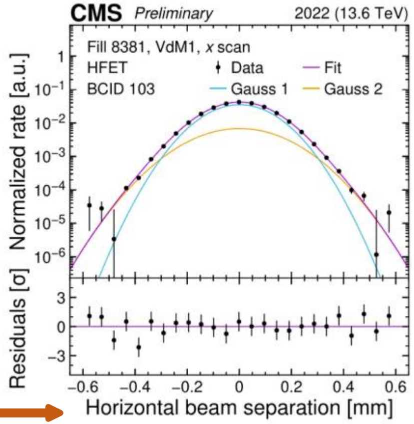
orbit shift correction

CMS-PAS-LUM-22-001



optical-distortion correction

CMS-PAS-LUM-22-001



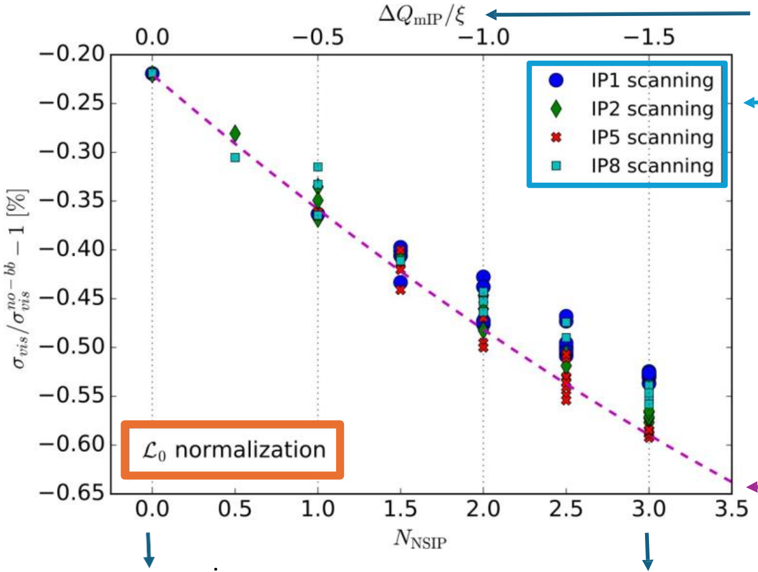
CMS-PAS-LUM-22-001

Impact of multi-IP effects on luminosity calibration

- Luminosity bias correction model based on the single- IP parametrization dependent on beams separation Δ, BB parameter and tunes $\mathcal{L}/\mathcal{L}_0(\Delta, \xi, Q_x, Q_y)$
- effective multi-IP tune shift ΔQ_{mIP} can be used to obtain the equivalent σ_{vis} bias
- simple scaling law derived from strong-strong simulations:

$$\Delta Q_{mIP} = -0.5 \times \xi N_{NSIP}$$

- valid for all LHC IPs
- verified in simulation for vdM regime (ξ<0.01)
- when considering more than single collision there is an ambiguity related to the normalization
    - ‘witness’ collision perturbed $\mathcal{L}_u$
    - absolute $\mathcal{L}_0$ (no beam-beam interaction anywhere)
    - phase advance dependence, covered in uncertainty



tune shift for single-IP calculation

full multi-collision simulation

single-IP calculation

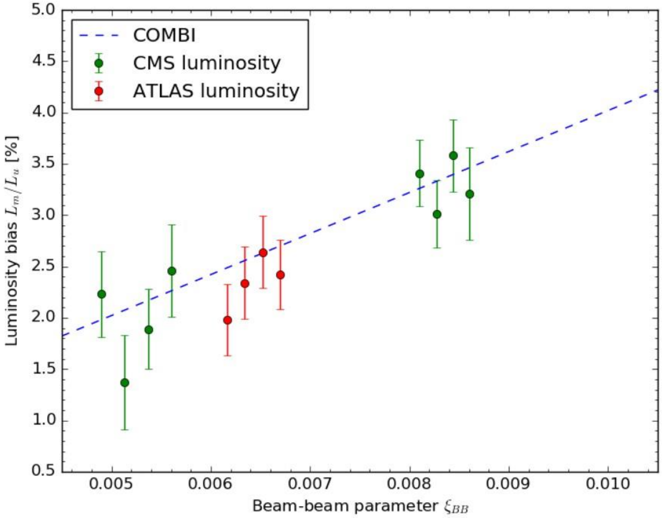
scanning-IP only

scanning-IP + 3 extra collisions

https://doi.org/10.1140/epjc/s10052-021-08837-y

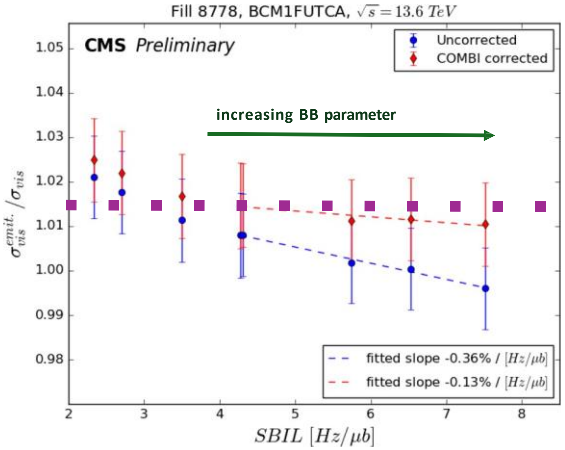
Machine development: benchmark beam-beam simulations

- Aimed at validation of the correction strategy used in the vdM calibration
- phase advance between IP1 C IP5 optimized for **maximizing** the effect on luminosity 1 → 3% at the witness IP at LHC injection energy 450 GeV
- methodology using the **witness IP** with configuration changes at other location
- repetitive steps used for validation
- **first measurement of the impact of BB effects on the luminosity at the LHC**
- **scaling law with BB parameter verified**
  - wire scanner measurements used as a reference to evaluate ξ_{BB}
  - **very good agreement with simulation**

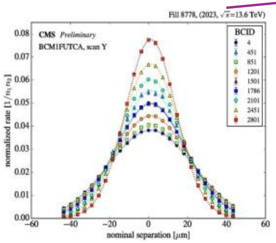


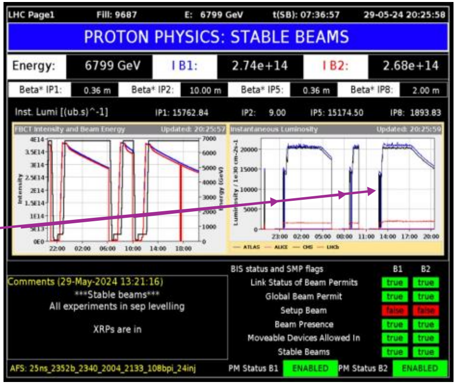
J. Wanczyk DOI: 10.5075/epfl-thesis-10500

Application of beam-beam corrections in nominal conditions



perfectly linear luminometer = flat response across SBIL





LHC Page1 Fill: 9687 E: 6799 GeV t(SB): 07:36:57 29-05-24 20:25:58

PROTON PHYSICS: STABLE BEAMS

Energy:	6799 GeV	I B1:	2.74e+14	I B2:	2.68e+14

Beta* IP1:	0.36 m	Beta* IP2:	10.00 m	Beta* IP5:	0.36 m	Beta* IP8:	2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 15762.84 IP2: 9.00 IP5: 15174.50 IP8: 1893.83

Comments (29-May-2024 13:21:16)
Stable beams
All experiments in sep levelling

XRPs are in

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2352b_2340_2004_2133_108bpi_24inj PM Status B1 ENABLED PM Status B2 ENABLED

DOI: https://doi.org/10.22323/1.449.0624

- main contributions to the measured non-linearity:
  - apparent BB-induced slope - removed with COMBI simulation
  - intrinsic detector response inefficiencies

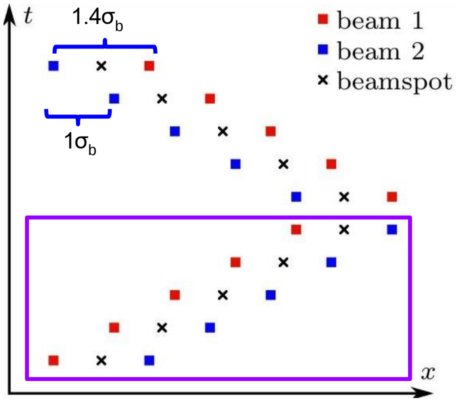
- possible additional biases from non-factorisation
- challenging fit quality
- operational limitations - to be improved in the future

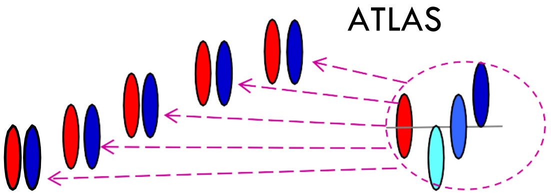
- possibility for an independent measurement
- valuable for HL-LHC
- further studies needed to make it precise

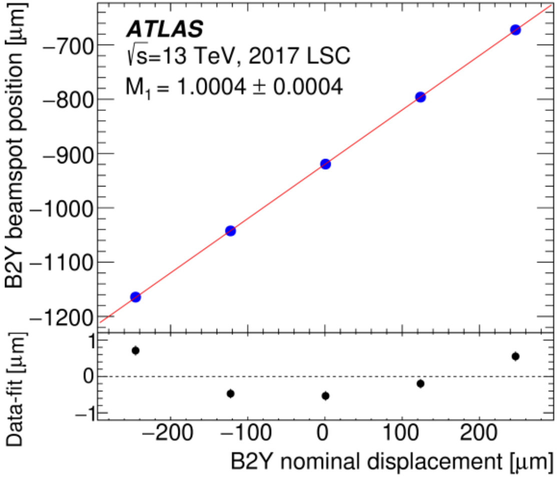
J. Wanczyk DOI: 10.5075/epfl-thesis-10500

Length scale calibration

- Neither the nominal magnet settings predictions nor the BPM measurement positions close the the IP correspond to the real value of the bunch during the scan
- The reconstructed beam-spot from tracker is taken as a reference
- The relation is linear $X_{true} = \alpha X_{nominal}$
- Two special scans use for the LSC
  - Constant separation LS scan ➔ average LS for B1&B2





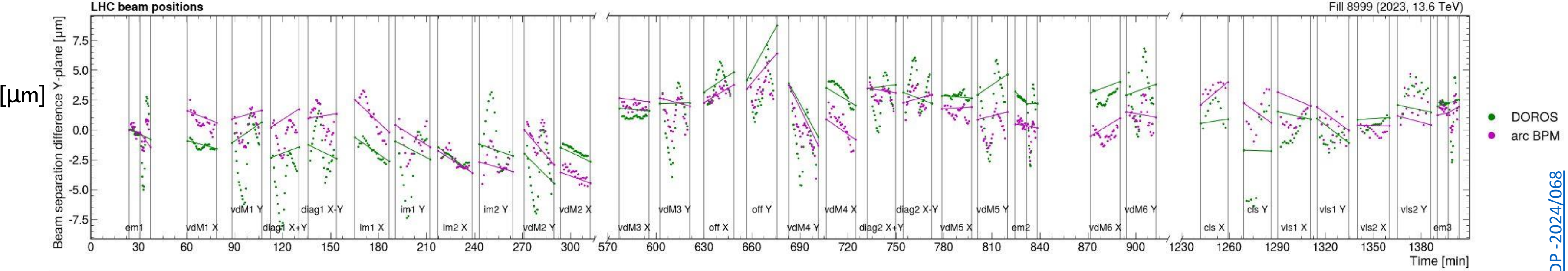


3-point "mini" variable separation scan for B1 x/y and B2 x/y at each position to interpolate to head-on collisions

Length scale factors depend on experiment ±0.4% of unit for ATLAS for all directions

BPM systematics

Deviation from nominal position during the vdM scan program are measured



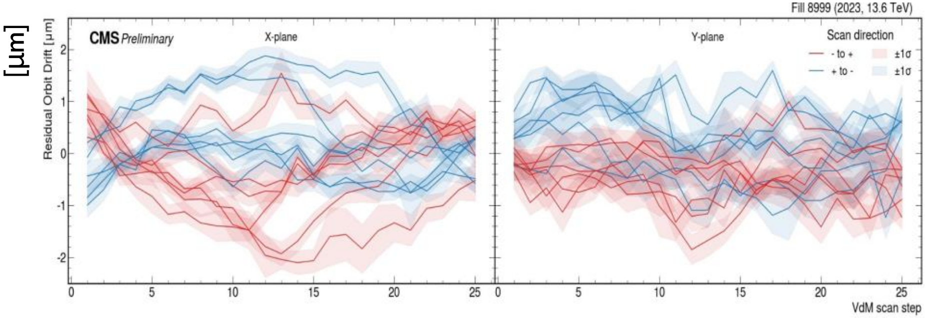
CMS DP -2024/068

Measured using

- Arc beam position monitor (BPM)
- DOROS BPM

Contributions to measurements:

- Linear orbit drift
- beam-beam deflection (partial effect from Bassetti-Erskine formula)
- **Residual effects** after correcting for above ← clear difference based on scan direction: - → + vs + → e



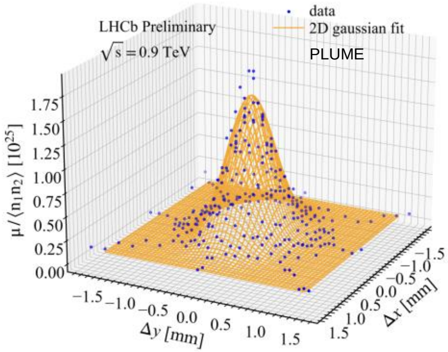
Typical OD uncertainty for CMS in 2022-2023: ~0.2%
Large improvement since 2015-16 papers (0.5-0.8%)

Lab B-field measurements on spare LHC corrector show clear hysteresis effects

CERN-ACC-NOTE-2022-0013

Non-factorization

Signature: Dependence of vertical convolved beam size and/or vertical luminous width on horizontal separation (and vice-versa) $\rho(x,y) \neq or = \rho(x)\,\rho(y)$

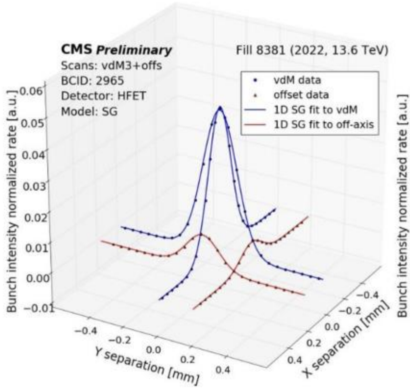


Multiple Methods used

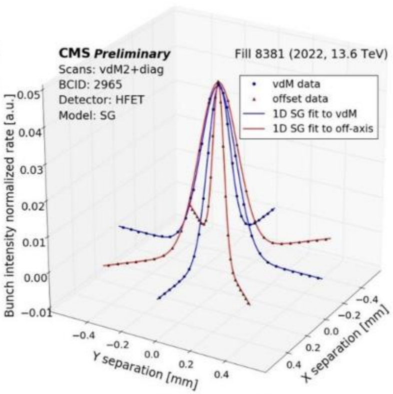
2D scans (CMS)

- Fits the bunch overlap shape directly
- Using complementary scans for off-axis sampling
- All BCIDs are used, all luminometers

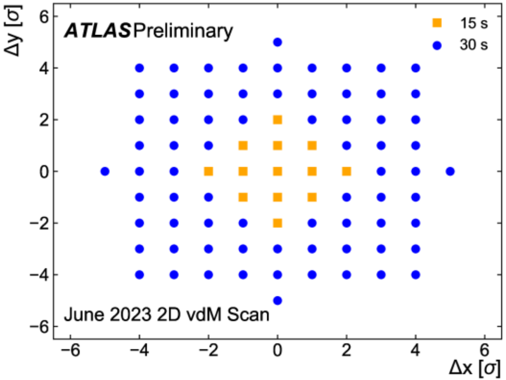
Luminous region analysis

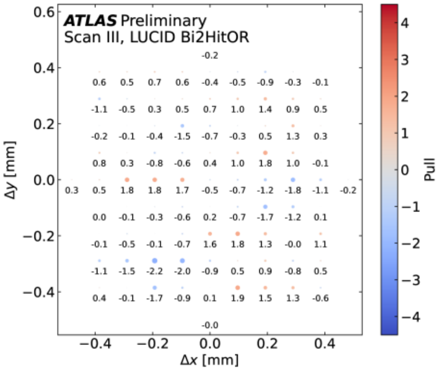


offset scan



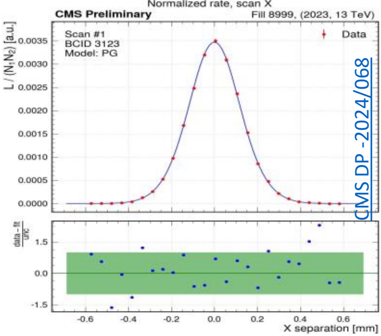
diagonal scan





Non-factorization

Non-factorization uncertainty: 2022 (prelim): 0.8%
2023 (prelim): 0.7%

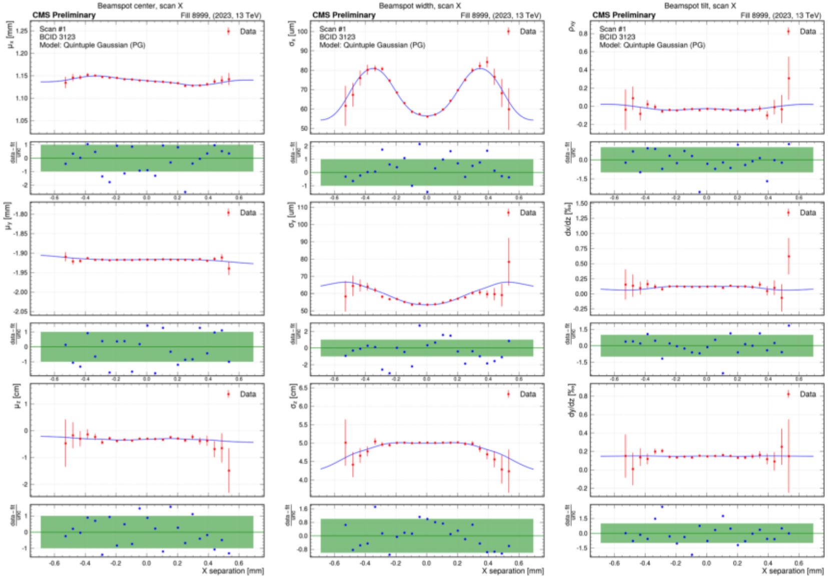


CMS DP -2024/068

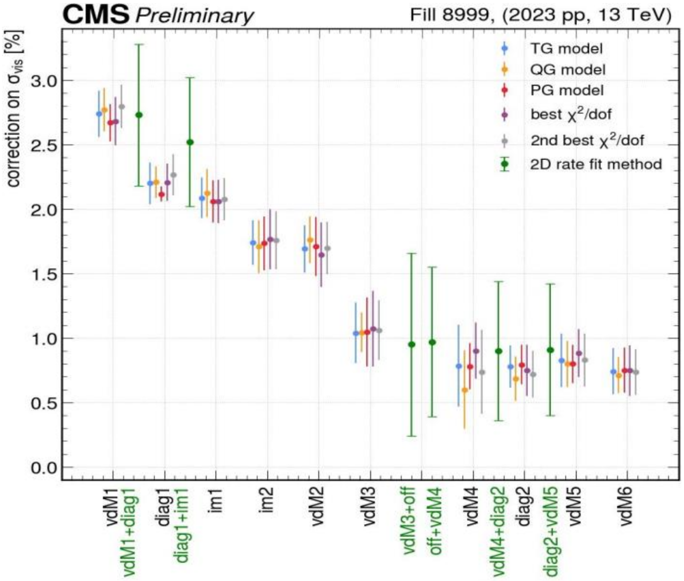
2D scans (CMS)

Luminous region analysis

- Fits the 3D bunch density function for the two beams
- Use any scans, few BCID with high rate
- Extract parameters of 3D beamspot ellipsoids under various model assumptions



CMS DP -2024/068

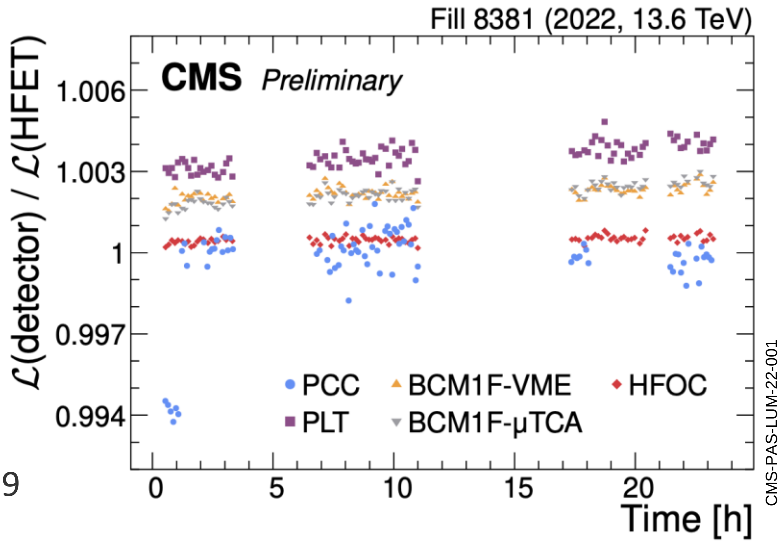


CMS DP -2024/068

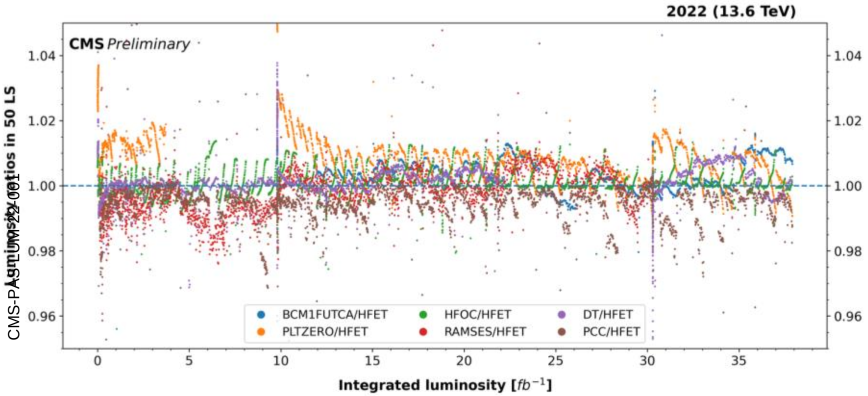
Cross-check of two different methods over the 2023 fill.

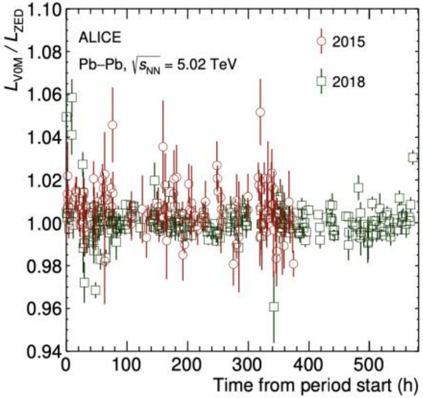
Cross detector consistency

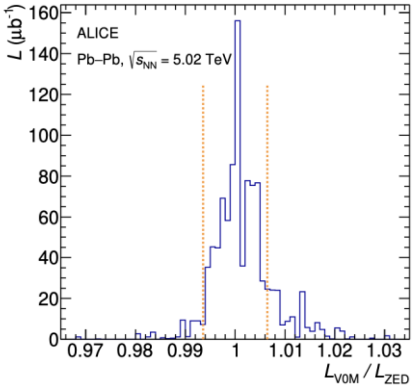
- Closure of detectors checked in the vdM fill
- Efficiency and linearity of detectors is tracked and corrected for independently using “emittance” scans (CMS)
- Spread of detectors is tracked throughout the whole year



S. Acharya *et al* 2024 *JINST* **19** P02039



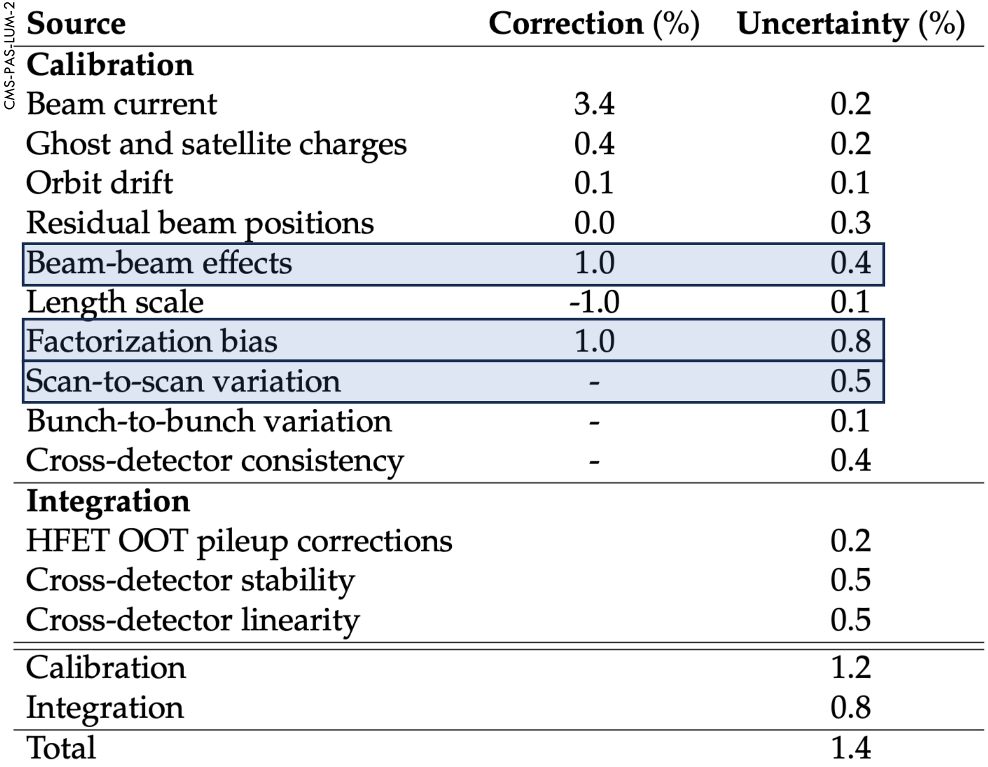




vdM calibration systematics: an LHC example

Example CMS 2022 pp 13.6 TeV

CMS-PAS-LUM-22-001



Source	Correction (%)	Uncertainty (%)
Calibration		
Beam current	3.4	0.2
Ghost and satellite charges	0.4	0.2
Orbit drift	0.1	0.1
Residual beam positions	0.0	0.3
Beam-beam effects	1.0	0.4
Length scale	-1.0	0.1
Factorization bias	1.0	0.8
Scan-to-scan variation	-	0.5
Bunch-to-bunch variation	-	0.1
Cross-detector consistency	-	0.4
Integration		
HFET OOT pileup corrections		0.2
Cross-detector stability		0.5
Cross-detector linearity		0.5
Calibration		1.2
Integration		0.8
Total		1.4

LHC Machine Developments in 2023/2024 and extended vdM scans dedicated to addressing leading systematics:

- benchmarking beam-beam effects, incl. the effects of collisions at multiple IPs
- beam preparation to minimize the factorization bias
- novel scan methods to measure time dependent non-factorization corrections

Common and relevant for all LHC Experiments, incl. HL-LHC era

Z-counting rates

Z→μμ (& Z→ee) are “standard” candle processes for luminosity monitoring

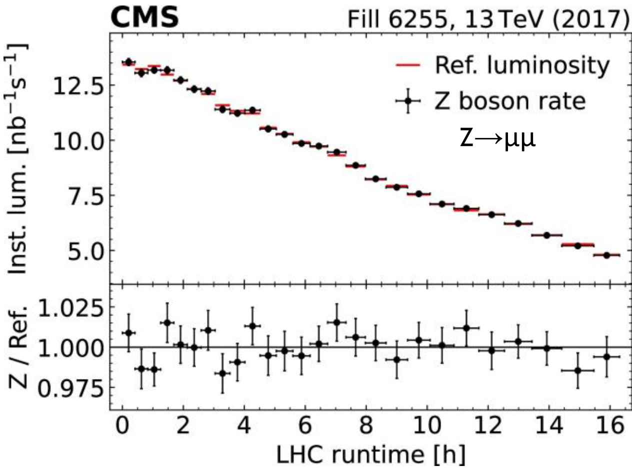
- ➢ a clean signature
- ➢ large cross section
- ➢ But σ_Z is only known to 3-4% (PDFs) – cannot use for absolute luminosity scale

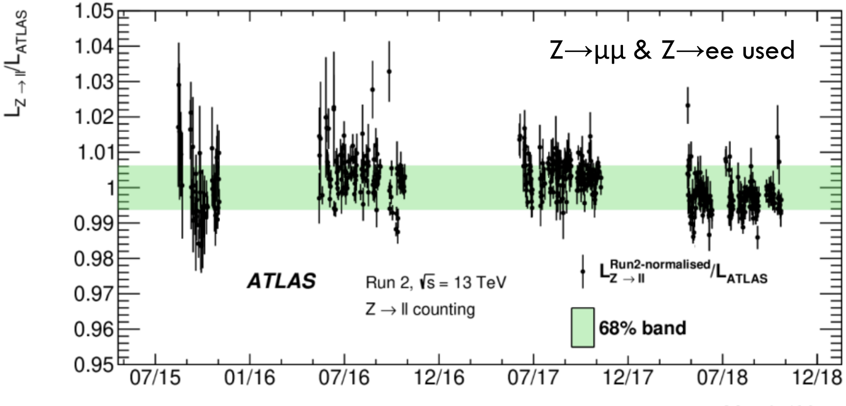
Trigger and selection efficiencies are measured in situ every 20/pb

Main goal: anchoring the measurement at low PU

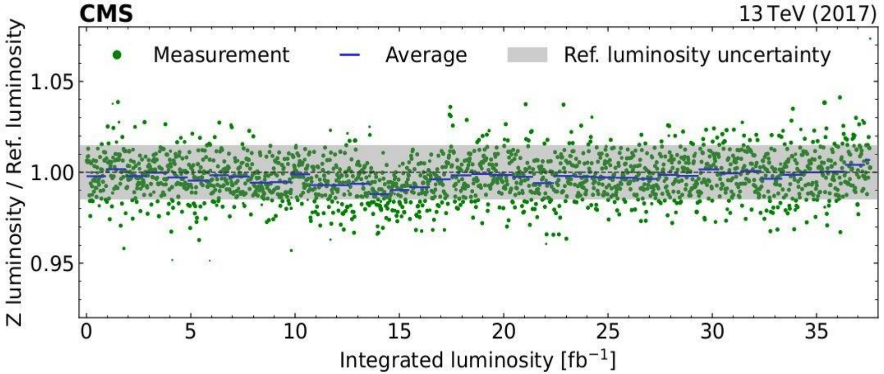
- → extrapolate to high PU

$$\mathcal{L}_{\mathrm{highPU}} = \frac{N^{Z}_{\mathrm{highPU}}}{N^{Z}_{\mathrm{lowPU}}}\mathcal{L}_{\mathrm{lowPU}}.$$





ATL-DAPR-PUB-2021-001



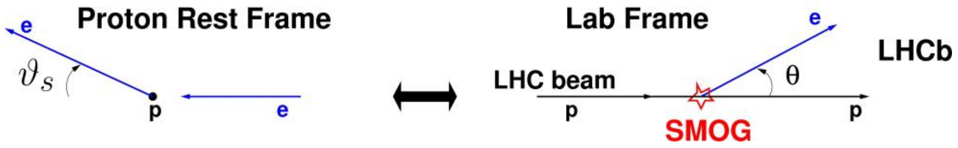
Luminosity determination using Z boson production at the CMS experiment. *Eur. Phys. J.* C **84**, 26 (2024).

Luminosity for LHCb fixed target – Run 2

Elastically scattered atomic electrons (from fixed target He atoms), w/ theoretically known cross-section

Using SMOG as fixed target

- Gas pressure too small, BGI-lumi not feasible



- **Count Number of such electrons** (minus N positrons estimating the backgrounds), **divided by the known cross-section.** Allows to measure **the luminosity** (and SMOG gas density) **with 6% accuracy**

Phys. Rev. Lett. 121 (2018) 222001

Results using this luminosity measurement

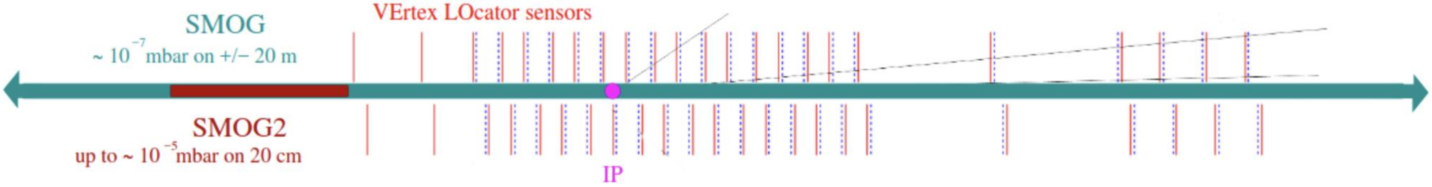
- the antiproton cross-section in sqrt(s) range relevant for astrophysics
- J/psi, D0 cross-section measurements in p-He and the extrapolation to the full cc-bar production

Phys. Rev. Lett. 122 (2019) 132002

Similar luminosity measurements were performed with the neon target; **p-Ne luminosity also has 6% accuracy**

- Open charm production and asymmetry in pNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV

Eur. Phys. J. C83 (2023) 625541

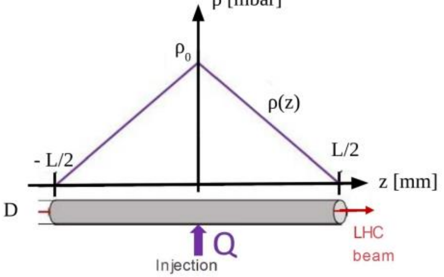


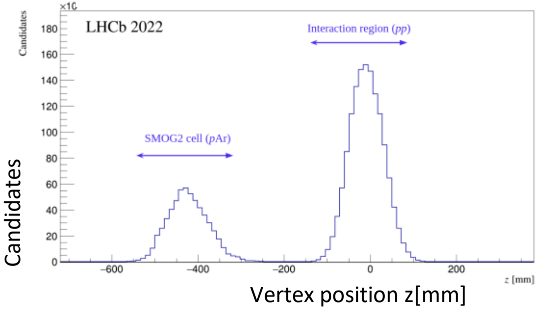
Luminosity for LHCb fixed target – Run 3

Run 3, Expectations using SMOG-2 as fixed target luminometer

- Installed in 2020, located 40 cm upstream of IP8, inside the beam pipe. It injects gas, and the beam passes through this localized gas volume.
  - By localizing the interaction volume, the local density is increased by a factor of 100 (compared to SMOG) using the same amount of gas.
  - **Density $\rho(0)$ is calculated from the the particle flux using the gas flow (Φ) and C_{tot} the total conductance of the cell from the center upwards, considering gas temperature measured by dedicated probes.**
  - The correction factor, k, is ~2.5% (based on Molflow+ simulations), independent of gas type and for gas fluxes ranging between 2 and 10 × 10^{-5} mbar·l/s
  - **Gas flow simulations and monitoring instruments enable luminosity calculation accuracy better than 2%.**

$$\rho_0 = \frac{\Phi}{C_{tot}}, \qquad \theta = \rho_0 \cdot L/2, \qquad \mathcal{L} = k \cdot \theta N_p f_{rev};$$





SMOG - System for Measuring Overlap With Gas

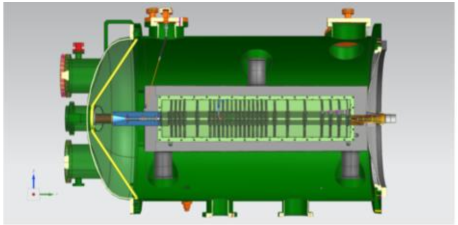


Figure 3: Overall view of the VELO vessel with the storage cell (in blue) just upstream of the RF boxes (light green).

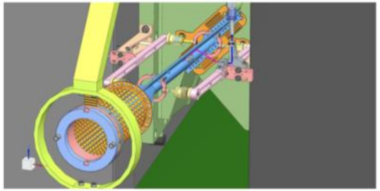
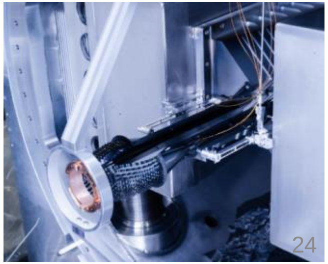


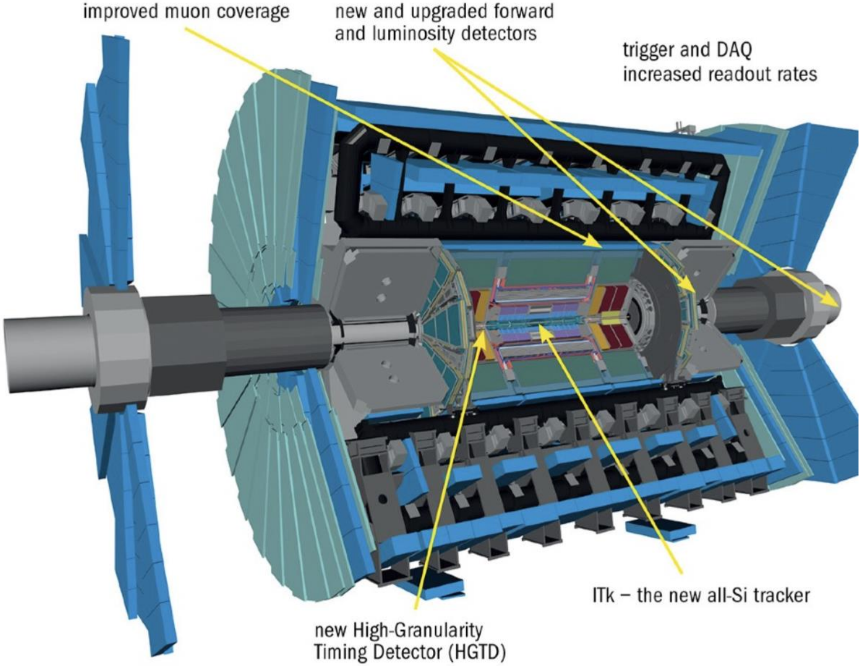
Figure 4: Zoom on the storage cell to show the supports and attachment to the VELO RF boxes and upstream beam pipe ring (light blue) via wake field suppressors (in gold).



arXiv:2407.14200

ATLAS Upgrade & New Luminosity Measurement @ HL-LHC

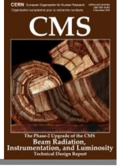
- Comprehensive Phase-II detector upgrades, many which provide key improvements for luminosity:
  - New Luminosity Cherenkov Integrating Detector — LUCID-3
  - High-Granularity Timing Detector (HGTD)
  - New all-silicon Inner Tracker (ITk)
  - BCM’ - updated Beam Conditions Monitors
  - Additional systems considered
    - BMA - Beam Monitoring for ATLAS
    - Pixel Luminosity Rings
  - Improved trigger & data acquisition increases the capacity for offline readout



Lucid-3 https://cds.cern.ch/record/2780604?ln=en

More details: see talk C. Ohm ICHEP

CMS Strategy Luminosity Measurement @ HL-LHC

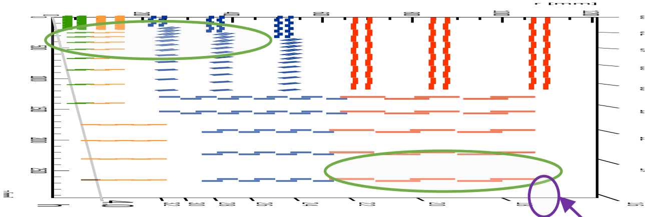

CMS

The Phase-2 Upgrade of the CMS Beam Radiation, Instrumentation, and Luminosity Technical Design Report

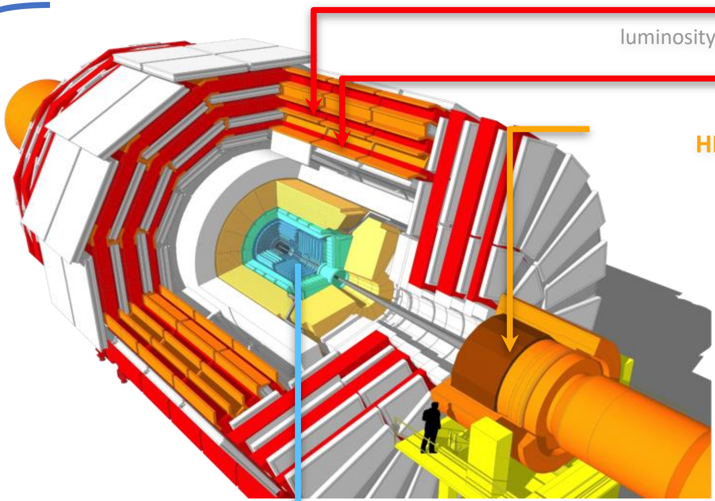
CMS Sub-detector frontends

- **With dedicated luminosity readout**
- Exploit SoC & FPGAs in backend electronics for dedicated, real-time luminosity object processing

OT (Outer Tracker Layer 6)


TEPX-Disk4-Ring1

FBCM


40 MHz trigger scouting

luminosity (L1 muons, tracks, calorimeter objects)

Muon Barrel

luminosity (L1 trigger primitives)

HF (Hadronic Forward Calorimeter)

luminosity (Transverse energy sum, quartz fibers)

OT (Outer Tracker Layer 6)

luminosity (Si strip sensor coincidences stubs)

TPEX (Tracker Endcap Pixel Detector)

luminosity (Si pixel cluster counting)

FBCM (Fast Beam Condition Monitor)

luminosity (Si pad zero-counting)

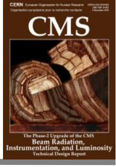
TPEX_Disk4_Ring1 (outside eta=4)

luminosity (Si pixel cluster counting)

detectors exclusive for luminosity beam monitoring

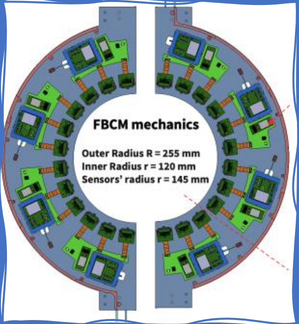
https://cds.cern.ch/record/2759074

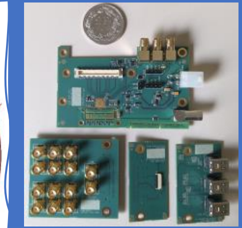
CMS Strategy Luminosity Measurement @ HL-LHC

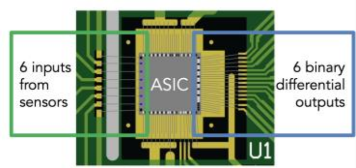


CMS Sub-detector frontends

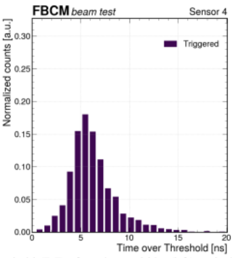
- **With dedicated luminosity readout**
- Exploit SoC & FPGAs in backend electronics for





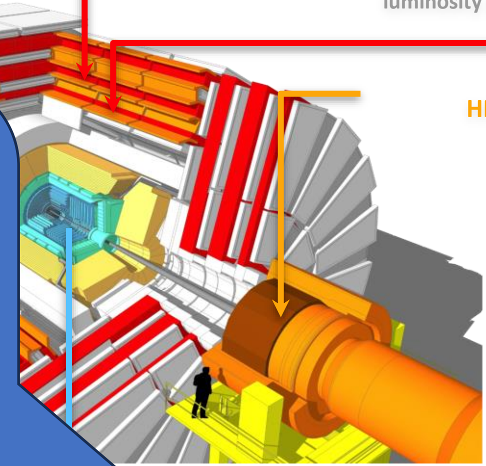


FBCM ASIC top view on test board



Dedicated, triggerless frontend ASIC designed in 65 nm and produced. Performance characterized [arXiv:2312.02834](https://arxiv.org/abs/2312.02834)

Two test beams in 2024 - data being analyzed



40 MHz trigger scouting
luminosity (L1 muons, tracks, calorimeter objects)

Muon Barrel
luminosity (L1 trigger primitives)

HF (Hadronic Forward Calorimeter)
luminosity (Transverse energy sum, quartz fibers)

OT (Outer Tracker Layer 6)
luminosity (Si strip sensor coincidences stubs)

TPEX (Tracker Endcap Pixel Detector)
luminosity (Si pixel cluster counting)

FBCM (Fast Beam Condition Monitor)
luminosity (Si pad zero-counting)

TPEX_Disk4_Ring1 (outside eta=4)
luminosity (Si pixel cluster counting)

detectors exclusive for luminosity and beam monitoring

https://cds.cern.ch/record/2759074

Summary

- **Leaps in progress over the last 5 years**
  - ✓ Beam-beam corrections incl. benchmaking and parameterization for collisions in multiple IPs
  - ✓ Non-factorization measurement methods, corrections and machine preparation
  - ✓ Bunch current normalization
  - ✓ Quantifying and correction of orbit drift and BPM performance specifications for HL-LHC
  - ✓ Efficiency and linearity measurements using "emittance" scans in nominal physics conditions

✓ **Luminosity precision has improved by a factor of x2 from ~2% from preliminary Run 2 analysis to ~1% for final Run 2 papers and preliminary Run 3 results**

  - **"Luminosity determination in** pp **collisions at** s√=13 **TeV using the ATLAS detector at the LHC**" Eur. Phys. J. C 83 (2023) 982
  - **"Precision luminosity measurement in proton-proton collisions at s√= 13 TeV in 2015 and 2016 at CMS" Eur. Phys. J. C 81 (2021) 80**
  - **"ALICE luminosity determination for Pb–Pb collisions" at √sNN= 5.02 TeV S. 2024 JINST 19 P02039**
  - **"Precision luminosity measurements at LHCb"** 2014 JINST 9 P12005

- Detector stability and non-linearity and methods to measure it will be crucial for HL-LHC as extrapolation in pileup from vdM to nominal conditions

- **Many studies ongoing to refine systematics**
  - Beam-beam corrections in 2D, offset scans
  - Beam-beam effects on non-factorization
  - Origins of non-factorization and scan-to-scan and fill-to-fill reproducibility
  - … LHC machine developments to be devoted in the future to achieve necessary understanding and precision

Next Lumi Days 11th-12th March '25

- **Luminosity analysis and hardware design is challenging, long and collaborative effort!**

Extra slides

Biography & acknowledgements (I)

- **Special Thanks**
  - J. Wanczyk, W. Kozanecki, Vladislav Balagura, Tatiana Pieloni, G. Pasztor, I. Efthymiopoulos
  - Eric Torrence, Klaus Monig, R. Hawkings, R. Matev
  - M. Gagliardi, M. Hostettler, D. Stickland, O. Karacheban
  - Christian Ohm, Ivan Kralik, Fabio Ferrari, Edoardo Franzoso,
  - P. Major, Rogelio Tomas Garcia, Elisabeth Maria Niel
- **General References**
  - **S. van der Meer**, *Calibration of the Effective Beam Height in the ISR*, CERN-ISR-PO-68-31 (1968)
  - **C. Rubbia**, *Measurement of the Luminosity of pp Collider with a (Generalized) Van der Meer Method*, CERN-pp-Note-38 (1977)
  - **V. Balagura**, *Notes on Van der Meer Scan for Absolute Luminosity Measurements*, Nucl. Instrum. Meth. A654 (2011) 634
  - **P. Grafstrom & W. Kozanecki**, *Luminosity Determination at Proton Colliders*, Progr. Nucl. Part. Phys. 81 (2015) 97–148 *Detailed Experimental Review of Luminosity Determination Methodology, from the ISR to the LHC*
- **Precision Goals at HL-LHC**
  - **G. P. Salam**, *Theoretical Perspective on SM and Higgs Physics at HL-LHC* Link to Document

Biography & acknowledgements – ATLAS (II)

- **Analysis References from ATLAS Collaboration**
  - **Improved luminosity determination in pp collisions at √s =7 TeV using the ATLAS detector at the LHC**
    Eur. Phys. J. C73 (2013) 2518
  - **Luminosity determination in pp collisions at √s =8 TeV using the ATLAS detector at the LHC**
    Eur. Phys. J. C76 (2016) 653
  - **Luminosity determination in pp collisions at √s =13 TeV using the ATLAS detector at the LHC**
    Eur. Phys. J. C 83 (2023) 982
    Link to Paper
- **Preliminary Luminosity Calibration Analysis**
  - **Preliminary analysis of the luminosity calibration of the ATLAS 13.6 TeV data recorded in 2022**
    ATL-DAPR-PUB-2023-001
    Link to Paper
  - **Preliminary analysis of the luminosity calibration for the ATLAS 13.6 TeV data recorded in 2023**
    ATL-DAPR-PUB-2024-001
    Link to Paper
- **Additional Resources**
- **ATLAS Public Luminosity Plots**
  Link to Webpage

Biography & acknowledgements – LHCb (III)

- **LHCb Collaboration: Key References on Luminosity Measurements**
  - **Precision luminosity measurements at LHCb**
    JINST 9 (2014) P12005
    Link to Paper
  - **Proposal for an absolute luminosity determination using vertex detection of beam-gas interactions**
    M. Ferro-Luzzi, Nucl. Instrum. Meth. A553 (2005) 388
  - **Absolute luminosity measurements with the LHCb detector at the LHC**
    LHCb Collaboration, R. Aaij et al., JINST 7 (2012) P01010, arXiv:1110.2866
  - **Precision luminosity measurements at LHCb with beam-gas imaging**
    C. Barschel, PhD Thesis, RWTH Aachen University, CERN-THESIS-2013-301 (2014)
  - **PLUME Calibration**
- PLUME :
  - **LHCb PLUME: Probe for LUminosity Measurement , Technical Design Report** https://cds.cern.ch/record/2750034/files/LHCB-TDR-022.pdf
  - First Calibration reference
- **Ghost and Satellite Measurements Using Beam-Gas**
  - **Ghost Charge Measurements with Beam-Gas Imaging in November 2022**
    Link to Figures
    LHCB-FIGURE-2023-003
  - **Ghost Charge Measurements for Fills 8997 and 8999**
    Link to Figures
    LHCB-FIGURE-2024-001
- **Papers Using LHCb Fixed Target Luminosity**
  - **Measurement of antiproton production in pHe collisions at $\sqrt{s_{\rm NN}}=110$ GeV**
    Phys. Rev. Lett. 121 (2018) 222001
  - **First measurement of charm production in fixed-target configuration at the LHC**
    Phys. Rev. Lett. 122 (2019) 132002
  - **Open charm production and asymmetry in pNe collisions at $\sqrt{s_{NN}}=68.5$ GeV**
    Eur. Phys. J. C83 (2023) 541
  - **Charmonium production in pNe collisions at $\sqrt{s_{NN}}=68.5$ GeV**
    Eur. Phys. J. C83 (2023) 625

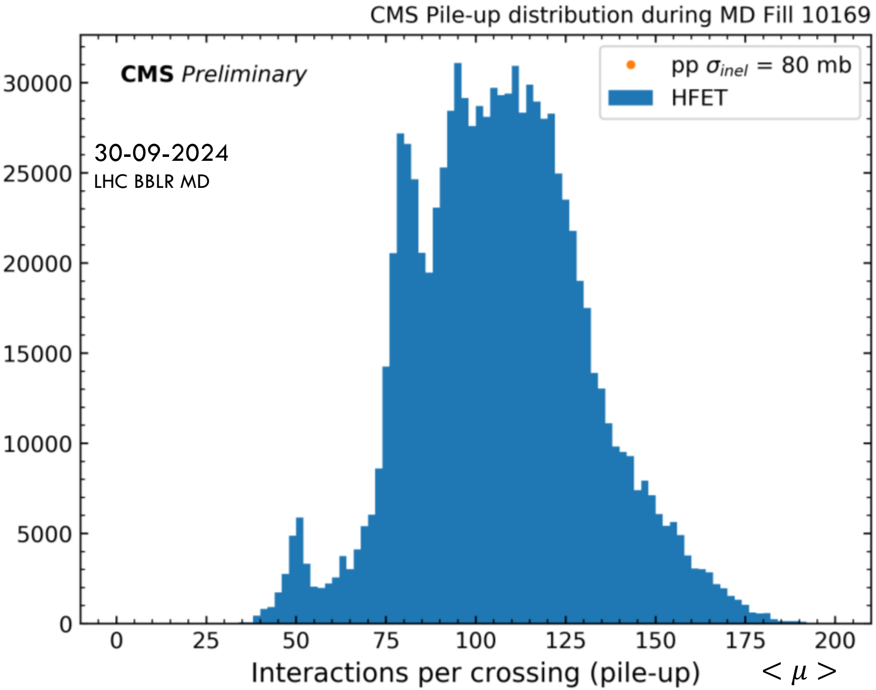
Biography & acknowledgements – CMS (III)

- **CMS Collaboration Luminosity Measurements**
- **CMS Luminosity Based on Pixel Cluster Counting**
  CMS-PAS-LUM-13-001 (Sep. 2013)
- **Luminosity Calibration for the 2013 Proton-Lead and Proton-Proton Data Taking**
  CMS-PAS-LUM-13-002 (Jan. 2014)
- **Inclusive and Differential Z Boson Production Cross Sections in pp Collisions at √s = 13 TeV**
  CMS PAS SMP-15-011 (March 2016)
- **CMS Luminosity Measurement for the 2015 Data Taking Period**
  CMS-PAS-LUM-15-001 (March 2016, rev. Feb 2017)
- **CMS Luminosity Measurements for the 2016 Data Taking Period**
  CMS-PAS-LUM-17-001 (March 2017)
- **CMS Luminosity Measurements for the 2017 Data-Taking Period at 13 TeV**
  Link to Paper
  June 2018
- **Papers Since 2018**
  - **Precision Luminosity Measurement in Proton-Proton Collisions at √s = 13 TeV in 2015 and 2016 at CMS**
    Eur. Phys. J. C 81 (2021) 80
  - **Measurement of the Offline Integrated Luminosity for the CMS Proton-Proton Collision Dataset (2023)**
    CMS-DP-2024-068; CERN-CMS-DP-2024-068
  - **XY-Factorization Correction for Luminosity Calibration Using Off-Axis Scans (2022 pp Data at 13.6 TeV)**
    CMS-DP-2024-004; CERN-CMS-DP-2024-004
  - **Luminosity Determination Using Z Boson Production at CMS**
    Eur. Phys. J. C 84 (2024) 26
  - **CMS Luminosity Measurement for Nucleus-Nucleus Collisions at √sNN = 5.02 TeV (Run 2)**
    CMS-PAS-LUM-20-002
  - **Offline Luminosity Measurement for the 2022 pp Collisions at 13.6 TeV**
    CMS-PAS-LUM-22-001
  - **CMS Luminosity Measurement Using Nucleus-Nucleus Collisions at √sNN = 5.02 TeV (2018)**
    CMS-PAS-LUM-18-001
  - **Luminosity Measurement in Proton-Proton Collisions at 5.02 TeV (2017)**
    CMS-PAS-LUM-19-001
  - **CMS Luminosity Measurement for the 2018 Data-Taking Period at √s = 13 TeV**
    CMS-PAS-LUM-18-002
  - **CMS Luminosity Measurement Using 2016 Proton-Nucleus Collisions at √sNN = 8.16 TeV**
  - **Additional Resources**
- **CMS Public Luminosity Results**
  Link to Webpage

Biography & acknowledgements (II)

- **ALICE Collaboration References**
  - **Performance of the ALICE VZERO system**
    - JINST 8 (2013) P10016 arXiv:1306.3130 [nucl-ex]
  - **Performance of the ALICE Experiment at the CERN LHC**
    - Int. J. Mod. Phys. A 29 (2014) 1430044
  - **Measurement of visible cross sections in proton-lead collisions at √sNN = 5.02 TeV in van der Meer scans with the ALICE detector**
    - JINST 9 (2014) 1100
  - **ALICE luminosity determination for pp collisions at √s = 13 TeV**
    - ALICE-PUBLIC-2016-002
  - **Luminosity**
    - **pp Collisions**
      - 13 TeV 2015 https://cds.cern.ch/record/2160174/
      - 13 TeV 2016-17-18 https://cds.cern.ch/record/2776672/
      - 5 TeV 2015 https://cds.cern.ch/record/2202638
      - 5 TeV 2017 https://cds.cern.ch/record/2648933
    - **p-Pb Collisions**
      - ALICE Data https://cds.cern.ch/record/2314660
    - **Pb-Pb Collisions**
      - IOP Journal Article https://iopscience.iop.org/article/10.1088/1748-0221/19/02/P02039

MD: beam-beam long range – online pileup distribution



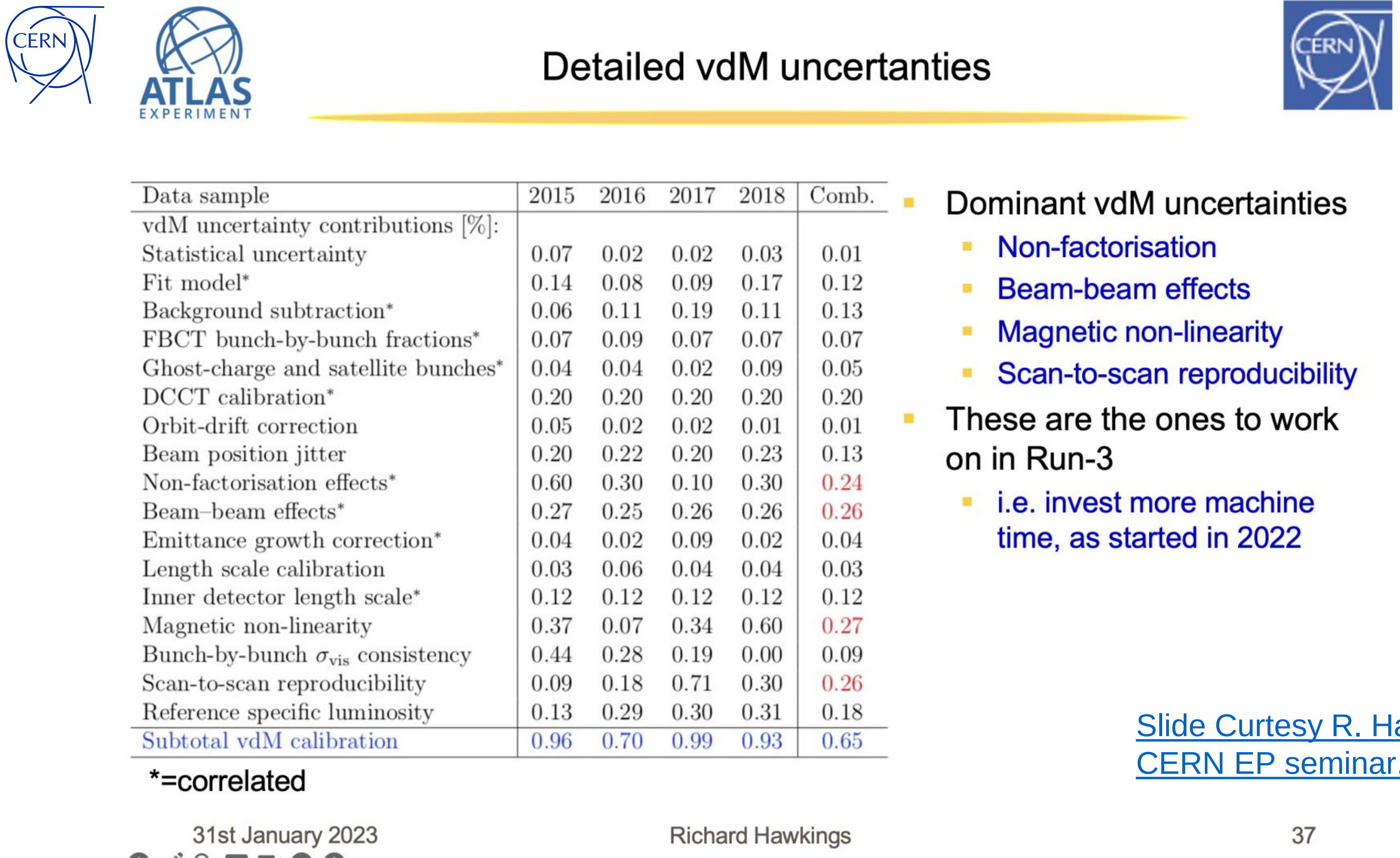
Results for the high-pileup sample

Data sample	2015	2016	2017	2018	**Comb.**
Integrated luminosity [fb^{-1}]	3.24	33.40	44.63	58.79	**140.07**
Total uncertainty [fb^{-1}]	0.04	0.30	0.50	0.64	**1.17**
Uncertainty contributions [%]:					
Subtotal vdM calibration	0.96	0.70	0.99	0.93	0.65
Calibration transfer*	0.50	0.50	0.50	0.50	0.50
Calibration anchoring	0.22	0.18	0.14	0.26	0.13
Long-term stability	0.23	0.12	0.16	0.12	0.08
Total uncertainty [%]	1.13	0.89	1.13	1.10	**0.83**

*=correlated

Slide Curtesy R. Hawkings
CERN EP seminar, 31/1/23

- Total per-year uncertainties of 0.9-1.1%
- Total Run-2 uncertainty of 0.83%; L_{int}=140.1±1.2 fb^{-1} for standard GRL
  - Absolute calibration uncertainty (vdM) slightly larger than calibration transfer and stability uncertainties
  - Largest single uncertainty from calibration transfer (correlated between years)



Detailed vdM uncertanties

Data sample	2015	2016	2017	2018	Comb.
vdM uncertainty contributions [%]:					
Statistical uncertainty	0.07	0.02	0.02	0.03	0.01
Fit model*	0.14	0.08	0.09	0.17	0.12
Background subtraction*	0.06	0.11	0.19	0.11	0.13
FBCT bunch-by-bunch fractions*	0.07	0.09	0.07	0.07	0.07
Ghost-charge and satellite bunches*	0.04	0.04	0.02	0.09	0.05
DCCT calibration*	0.20	0.20	0.20	0.20	0.20
Orbit-drift correction	0.05	0.02	0.02	0.01	0.01
Beam position jitter	0.20	0.22	0.20	0.23	0.13
Non-factorisation effects*	0.60	0.30	0.10	0.30	0.24
Beam–beam effects*	0.27	0.25	0.26	0.26	0.26
Emittance growth correction*	0.04	0.02	0.09	0.02	0.04
Length scale calibration	0.03	0.06	0.04	0.04	0.03
Inner detector length scale*	0.12	0.12	0.12	0.12	0.12
Magnetic non-linearity	0.37	0.07	0.34	0.60	0.27
Bunch-by-bunch σ_{vis} consistency	0.44	0.28	0.19	0.00	0.09
Scan-to-scan reproducibility	0.09	0.18	0.71	0.30	0.26
Reference specific luminosity	0.13	0.29	0.30	0.31	0.18
Subtotal vdM calibration	0.96	0.70	0.99	0.93	0.65

*=correlated

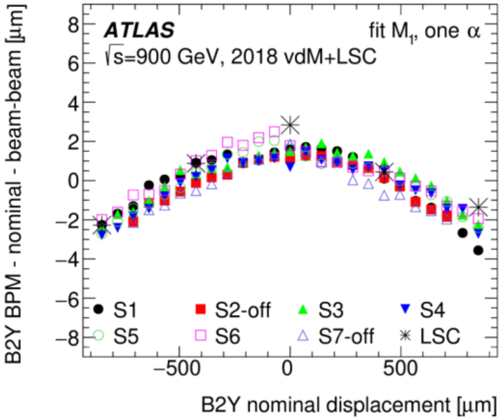
- Dominant vdM uncertainties
  - Non-factorisation
  - Beam-beam effects
  - Magnetic non-linearity
  - Scan-to-scan reproducibility
- These are the ones to work on in Run-3
  - i.e. invest more machine time, as started in 2022

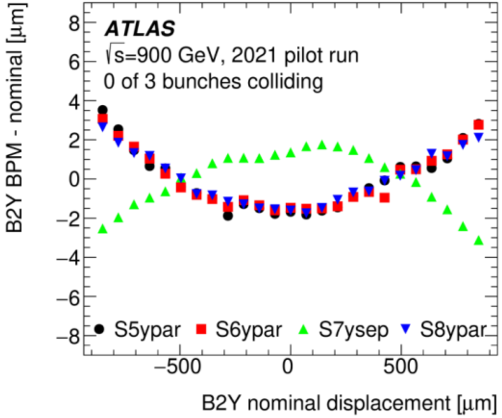
Slide Curtesy R. Hawkings
CERN EP seminar, 31/1/23

Slide Curtesy R. Hawkings
CERN EP seminar, 31/1/23

Magnetic non-linearity at $\sqrt{s}$=900 GeV

- Also studied using LHC DOROS beam position monitors during vdM scans
  - BPMs mounted on the inner faces of the final-focus triplets at z=±21.7m – see the scan displacements
  - Several 25-point scans per vdM scan session
  - Need to correct for beam-beam deflections
    - Not trivial, especially when not all bunches collide
  - 900 GeV scans show clear reproducible effects
    - Consistent between LSC-beamspot / vdM-DOROS
- Lab measurements on spare LHC correctors
  - B-fields reproducible to 10^{-4}, but clear hysteresis effects – could produce observed non-linearities
    - CERN-ACC-NOTE-2022-0013, thanks !
- Dedicated measurements in 2021 pilot run
  - No bunches colliding in ATLAS – no beam-beam
- Effect parameterised with 2nd/3rd order LSC terms
  - Only odd terms affect σ_{vis}





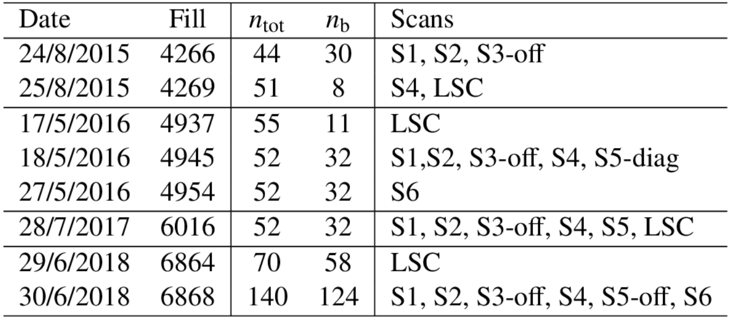
vdM scan fills

Slide Curtesy R. Hawkings
CERN EP seminar, 31/1/23

- vdM scans performed in dedicated fills with specially-tailored LHC conditions
  - 44-140 **isolated** bunches
    - Allows zero beam crossing angle – reduces orbit drift and beam-beam uncertainties
    - LHC beam focusing parameter β^* =19.2 m, increased beam emittance 3-4 µm
    - Larger beam sizes – luminous region RMS ($=\Sigma_{x,y}/2$) ≈ 60µm
  - Beam tailoring in injectors to get Gaussian profiles – reduces non-factorisation
  - Reduced bunch currents ~0.8 10^{11} p/bunch
  - Setup gives $<\mu^{max}> \approx 0.5$, and measurable tail rates at $\Delta x = \pm\, 6\sigma_{nom}$

- One vdM session per year: σ_{vis}/year
  - Several on-axis x-y scan pairs
  - Off-axis / offset scans to sample tails
  - Length-scale calibration (LSC)
  - Diagnonal scans
  - Emittance scans
- 2x20 minutes per scan pair
  - 25 steps of $0.5\sigma_{nom}$, $\pm 6\sigma_{nom}$
  - ~24 hour vdM fills, alternating ATLAS and CMS scan periods

Summary of vdM sessions



Date	Fill	n_{tot}	n_b	Scans
24/8/2015	4266	44	30	S1, S2, S3-off
25/8/2015	4269	51	8	S4, LSC
17/5/2016	4937	55	11	LSC
18/5/2016	4945	52	32	S1,S2, S3-off, S4, S5-diag
27/5/2016	4954	52	32	S6
28/7/2017	6016	52	32	S1, S2, S3-off, S4, S5, LSC
29/6/2018	6864	70	58	LSC
30/6/2018	6868	140	124	S1, S2, S3-off, S4, S5-off, S6

ATLAS scan example

Luminosity Results

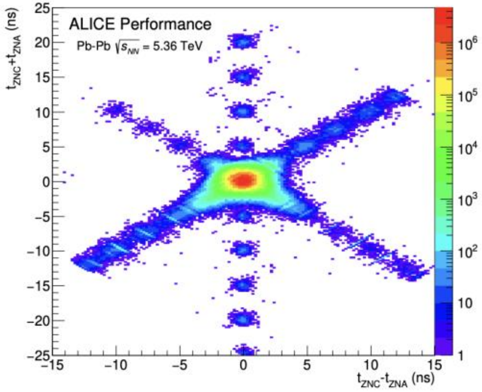
Selection subset of p-p

	LHCb	ALICE	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Run 1, 2	2012 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp	2017 pp	2017 pp	2018 pp	2018 pp
√s [TeV]	8	13	13	13	13	13	13	13	13	13
σ_L /L [%] (normalization)	1.1	2.1	0.95	1.8	0.70	1.6	0.99	1.6	0.93	2.1
σ_L /L [%] (total)	**1.2** (paper)	3.4	**1.13** (paper)	**1.6** (paper)	**0.89** (paper)	**1.2** (paper)	**1.13** (paper)	2.3 (prelim)	1.10 (paper)	2.5 (prelim)

	LHCb	ALICE	ALICE	ALICE	ATLAS	CMS	CMS
Run 3	2022	2016	2017	2018	2022	2022	2023
√s [TeV]		13	13	13	13.6	13.6	13.6
σ_L /L [%] (normalization)		1.0	1.2	1.1	1.42	1.2	0.89
σ_L /L [%] (total)		1.8	2.6	1.9	2.19 (prelim)	1.4 (prelim)	1.28 (prelim)

ALICE Luminometers for Run 3

Luminometers for Run 3

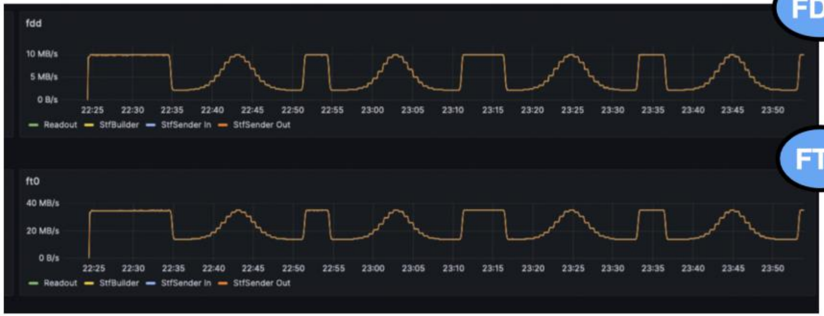


ALI-PERF-565487

ZN

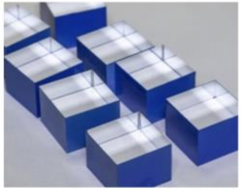
Same detector, improved electronics

pp van der Meer scan, September 2023



FDD

FT0



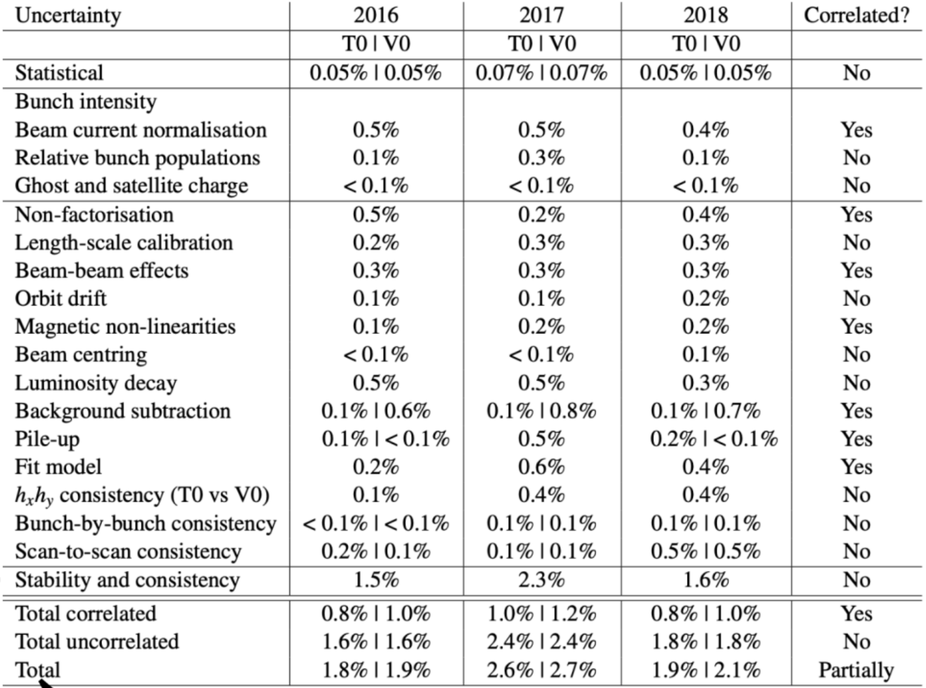
FT0

New detector (quartz Cherenkov radiators, MCP-PMT)
More channels, larger rapidity coverage

Other new detectors being evaluated as luminometers

Furthermore, ALICE now operates in continuous readout mode → New possibilities to define reference processes

Summary of pp collisions at 13 TeV from 2016 to 2018



Uncertainty	2016	2017	2018	Correlated?
	T0 | V0	T0 | V0	T0 | V0	
Statistical	0.05% | 0.05%	0.07% | 0.07%	0.05% | 0.05%	No
Bunch intensity				
Beam current normalisation	0.5%	0.5%	0.4%	Yes
Relative bunch populations	0.1%	0.3%	0.1%	No
Ghost and satellite charge	< 0.1%	< 0.1%	< 0.1%	No
Non-factorisation	0.5%	0.2%	0.4%	Yes
Length-scale calibration	0.2%	0.3%	0.3%	No
Beam-beam effects	0.3%	0.3%	0.3%	Yes
Orbit drift	0.1%	0.1%	0.2%	No
Magnetic non-linearities	0.1%	0.2%	0.2%	Yes
Beam centring	< 0.1%	< 0.1%	0.1%	No
Luminosity decay	0.5%	0.5%	0.3%	No
Background subtraction	0.1% | 0.6%	0.1% | 0.8%	0.1% | 0.7%	Yes
Pile-up	0.1% | < 0.1%	0.5%	0.2% | < 0.1%	Yes
Fit model	0.2%	0.6%	0.4%	Yes
$h_x h_y$ consistency (T0 vs V0)	0.1%	0.4%	0.4%	No
Bunch-by-bunch consistency	< 0.1% | < 0.1%	0.1% | 0.1%	0.1% | 0.1%	No
Scan-to-scan consistency	0.2% | 0.1%	0.1% | 0.1%	0.5% | 0.5%	No
Stability and consistency	1.5%	2.3%	1.6%	No
Total correlated	0.8% | 1.0%	1.0% | 1.2%	0.8% | 1.0%	Yes
Total uncorrelated	1.6% | 1.6%	2.4% | 2.4%	1.8% | 1.8%	No
Total	1.8% | 1.9%	2.6% | 2.7%	1.9% | 2.1%	Partially

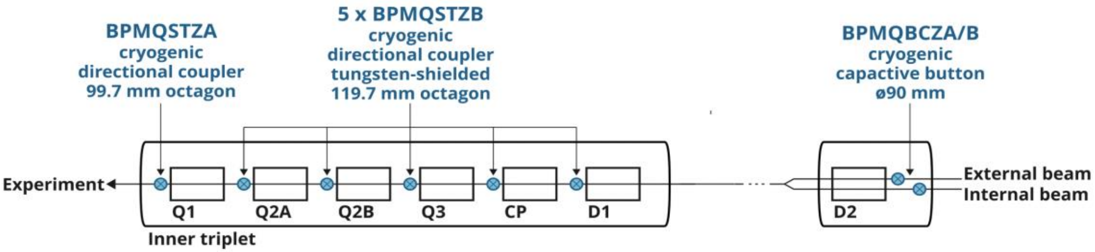
Main contribution to uncertainty

Uncertainty from combined sample slightly better than 2%

ALICE-PUBLIC-2021-005

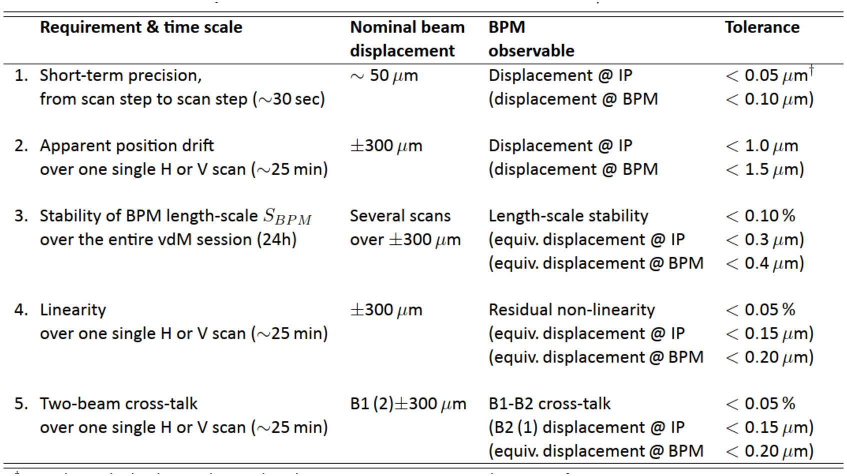
BPM’s for HL-LHC for orbit drift measurements

44 newly designed** Beam Position Monitors (BPM) to be installed around the ATLAS and CMS experiments in **LS3



vdM scans

- Fill duration (~20 hours)
- 1 Hz continuous measurement
- Requirements on relative displacement
- Linearity over large displacements
- Position cross talk contribution from instrumentation
- Precision in lower than nominal bunch charge



	Requirement & time scale	Nominal beam displacement	BPM observable	Tolerance
1.	Short-term precision, from scan step to scan step (~30 sec)	$\sim 50\,\mu$m	Displacement @ IP (displacement @ BPM	$< 0.05\,\mu$m[†] $< 0.10\,\mu$m)
2.	Apparent position drift over one single H or V scan (~25 min)	$\pm300\,\mu$m	Displacement @ IP (displacement @ BPM	$< 1.0\,\mu$m $< 1.5\,\mu$m)
3.	Stability of BPM length-scale S_{BPM} over the entire vdM session (24h)	Several scans over $\pm300\,\mu$m	Length-scale stability (equiv. displacement @ IP (equiv. displacement @ BPM	$< 0.10\,\%$ $< 0.3\,\mu$m) $< 0.4\,\mu$m)
4.	Linearity over one single H or V scan (~25 min)	$\pm300\,\mu$m	Residual non-linearity (equiv. displacement @ IP (equiv. displacement @ BPM	$< 0.05\,\%$ $< 0.15\,\mu$m) $< 0.20\,\mu$m)
5.	Two-beam cross-talk over one single H or V scan (~25 min)	B1 (2)$\pm300\,\mu$m	B1-B2 cross-talk (B2 (1) displacement @ IP (equiv. displacement @ BPM	$< 0.05\,\%$ $< 0.15\,\mu$m) $< 0.20\,\mu$m)

D. Gamba *et al.*, “Conceptual Specifications for the HL-LHC BPMs”, Geneva, Switzerland, Rep. LHC-BPM-ES-0013, Apr. 2022. `https://edms.cern.ch/document/2387369`

Bunch Current normalization

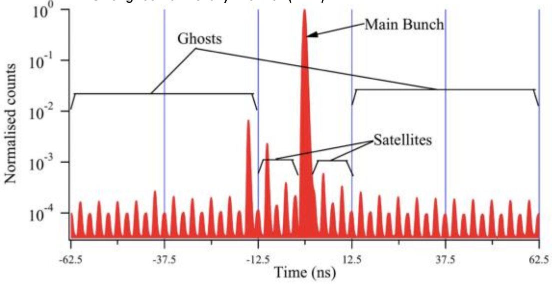
Measure n_1 and n_2 for each bunch in colliding RF bucket to ≪1%

- DC Current Transformer (DCCT) with absolute accuracy << 1%
  - Calibrated against precision current source without beam
  - Measures all charge in the LHC orbit
- Fast Beam Current Transformer (FBCT) measures relative bunched charge in 25 ns integration window above a threshold with limited absolute accuracy
- Longitudinal Density Monitor (LDM or BSRL), LHCb BGI and ALICE ZDC to estimate ghosts and satellites population around each filled bunch and subtract

LHC-DCCT

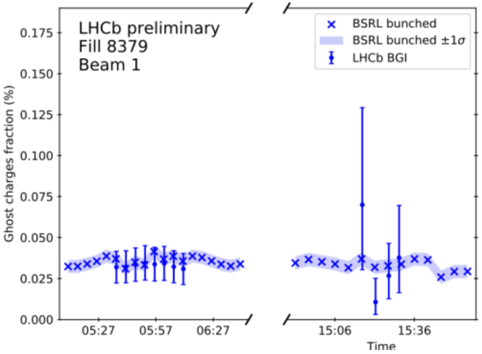
LHC-FBCT

LHC Longitudinal Density Monitor (LDM)

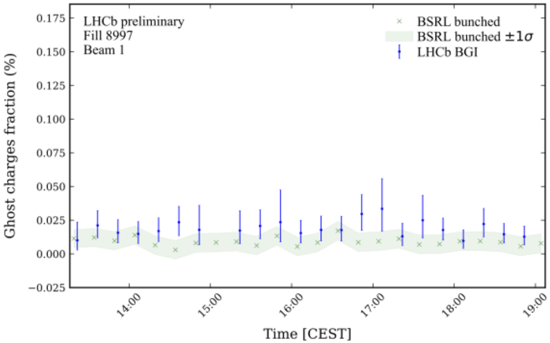


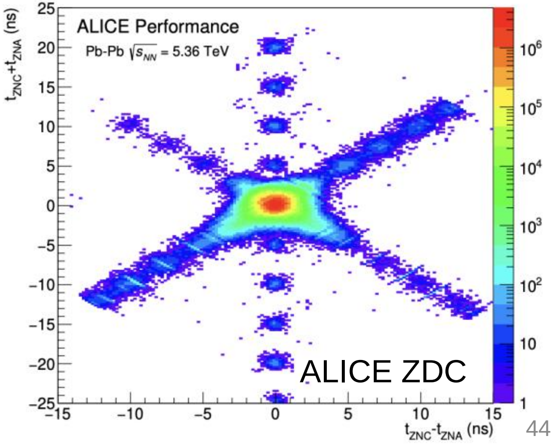
CERN-ATS-Note-2013-034 TECH

https://cds.cern.ch/record/2852922



https://cds.cern.ch/record/2888045





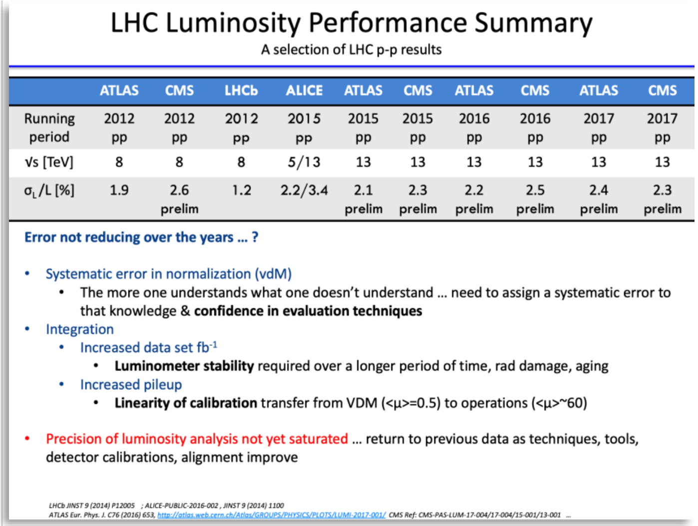
Typical correction 0.1-0.4% (for pp) and higher for PbPb on σvis uncertainties <0.1%

Professional effort from LHC SY/BI, LHCb & all involved

Luminosity determination at HL-LHC: a first discussion

Anne Dabrowski (CERN)
On behalf of the LHC Experiments

Workshop on the physics of HL-LHC, and perspectives
at HE-LHC, 18-20 Jun 2018, CERN, Geneva



LHC Luminosity Performance Summary

A selection of LHC p-p results

	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Running period	2012 pp	2012 pp	2012 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp	2017 pp	2017 pp
√s [TeV]	8	8	8	5/13	13	13	13	13	13	13
σ_L/L [%]	1.9	2.6 prelim	1.2	2.2/3.4	2.1 prelim	2.3 prelim	2.2 prelim	2.5 prelim	2.4 prelim	2.3 prelim

Error not reducing over the years … ?

- Systematic error in normalization (vdM)
  - The more one understands what one doesn't understand … need to assign a systematic error to that knowledge & **confidence in evaluation techniques**
- Integration
  - Increased data set fb^{-1}
    - **Luminometer stability** required over a longer period of time, rad damage, aging
  - Increased pileup
    - **Linearity of calibration** transfer from VDM (<μ>=0.5) to operations (<μ>~60)

- Precision of luminosity analysis not yet saturated … return to previous data as techniques, tools, detector calibrations, alignment improve

LHCb JINST 9 (2014) P12005 ; ALICE-PUBLIC-2016-002 , JINST 9 (2014) 1100
ATLAS Eur. Phys. J. C76 (2016) 653, http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/ CMS Ref: CMS-PAS-LUM-17-004/17-004/15-001/13-001 …

LLCMWG strategy for work on systematics common to all experiments refined during [Lumi day 2019 workshop]

Intensive work since 2018 on vdM calibration systematics and luminosity monitoring (LLCMWG)

- Beam-beam corrections
- Non factorisation (e.g., 2D scans, beam imaging, beam gas)
- Orbit drift, magnetic non-linearity, LHC beam instrumentation
- Monitoring of luminometer efficiency and linearity
  - $<\mu>$ and emittance scans
- Z-counting rate measurements

Machine development: Non-factorization studies

- In efforts to reduce the uncertainty from non-factorization for the luminosity calibration and any contribution from the injectors, a joint program between accelerator-experiments (13th-14th May 2024) was proposed to determine:
- Does non-factorization (NF) from coupling resonances (can be excited by machine imperfections) in the PSB translate to high NF in the LHC at injection energy? → If betatronic tune of the particles match resonance conditions, there can be a change in the phase space structure, which is non-factorizable for coupling resonances
- This was done with two experiments, one at injection energy (accelerator only), and one at top energy (vdM measurements, imaging and accelerator measurements).
- Is the NF measurable at LHC injection energy with scraping and profile measurements?
- Does high NF at injection translate to high NF at LHC stable beams? How does the NF evolve during stable beams?

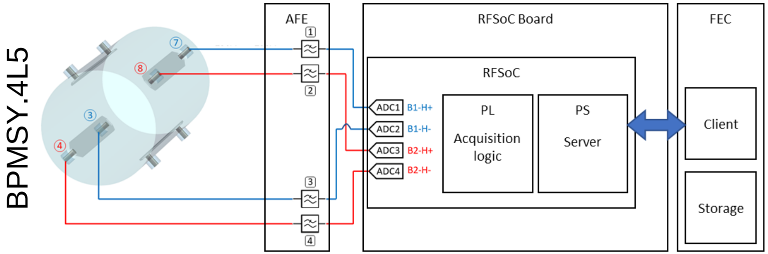
Preliminary results being presented in LLCMWG

E. Lamb, F. Asvesta, H. Bartosik, G. Sterbini, S. Kostoglou

HL-LHC BPMs - Electronics

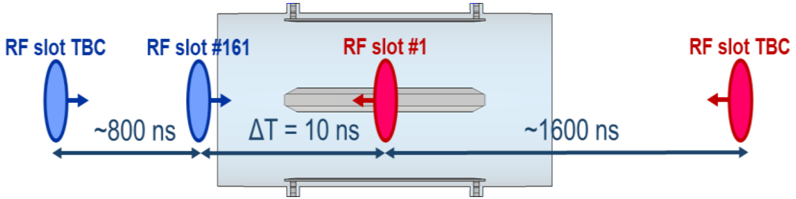
- New system being developed to replace DOROS
  - Necessary to meet specifications
  - Measure individual bunches (mask colliding/non-colliding)
  - Data processing to separate B1 - B2 signals
  - Current R&D process to prove required performance

Prototype Development



Single plane block diagram

4 channels @ 4 GSamples/s + SOC processing

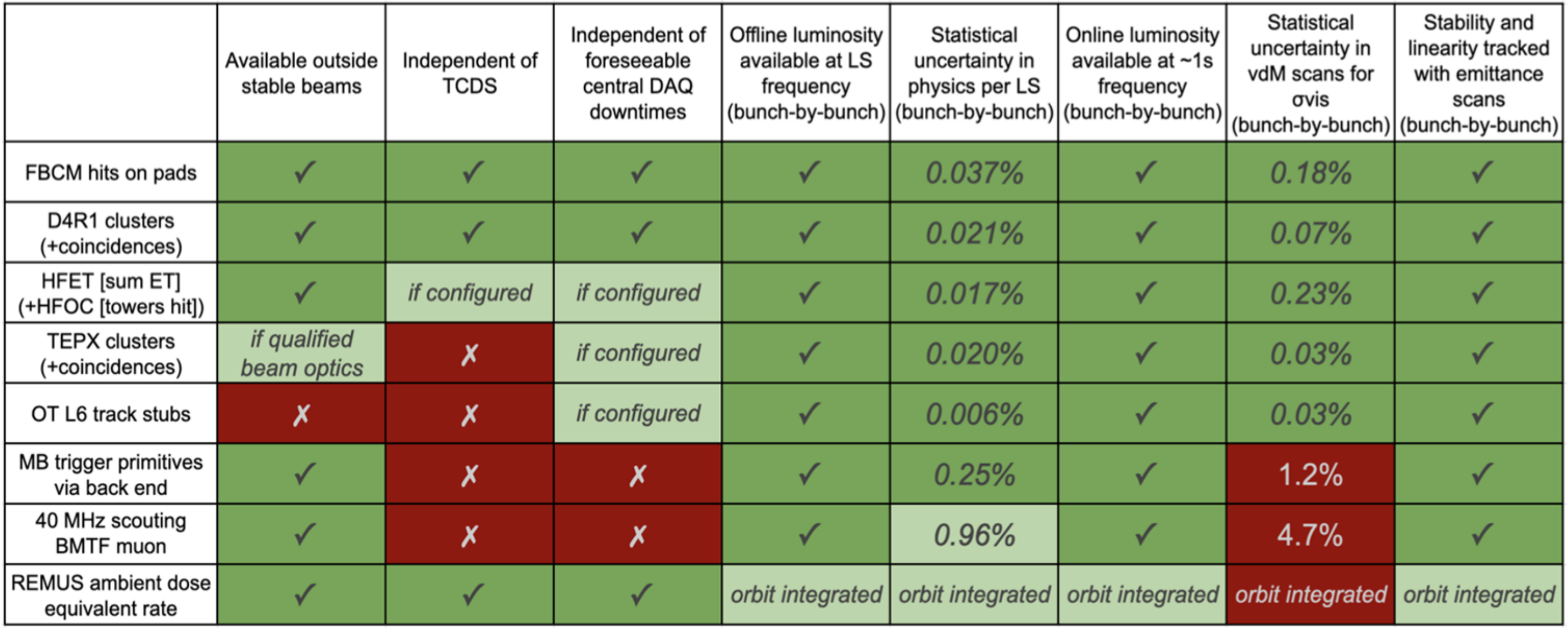


(RF cogging + orbit bumps)

D. R. Bett, I. Degl'Innocenti, M. Krupa

HL-LHC BPM System Development Status *JACoW IBIC 2022 (2022) 408-412*

Summary of Phase-II Luminometer Capabilities



	Available outside stable beams	Independent of TCDS	Independent of foreseeable central DAQ downtimes	Offline luminosity available at LS frequency (bunch-by-bunch)	Statistical uncertainty in physics per LS (bunch-by-bunch)	Online luminosity available at ~1s frequency (bunch-by-bunch)	Statistical uncertainty in vdM scans for σvis (bunch-by-bunch)	Stability and linearity tracked with emittance scans (bunch-by-bunch)
FBCM hits on pads	✓	✓	✓	✓	*0.037%*	✓	*0.18%*	✓
D4R1 clusters (+coincidences)	✓	✓	✓	✓	*0.021%*	✓	*0.07%*	✓
HFET [sum ET] (+HFOC [towers hit])	✓	*if configured*	*if configured*	✓	*0.017%*	✓	*0.23%*	✓
TEPX clusters (+coincidences)	*if qualified beam optics*	✗	*if configured*	✓	*0.020%*	✓	*0.03%*	✓
OT L6 track stubs	✗	✗	*if configured*	✓	*0.006%*	✓	*0.03%*	✓
MB trigger primitives via back end	✓	✗	✗	✓	*0.25%*	✓	1.2%	✓
40 MHz scouting BMTF muon	✓	✗	✗	✓	*0.96%*	✓	4.7%	✓
REMUS ambient dose equivalent rate	✓	✓	✓	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*

Summary table from BRIL TDR

- Data rates between the CMS subsystem and the BRILDAQ depend on the number of histograms per detector and memory required to store the object counts per lumi word.

- OT and FBCM use the largest bandwidth (~20 Mbps), but within control network limitations.

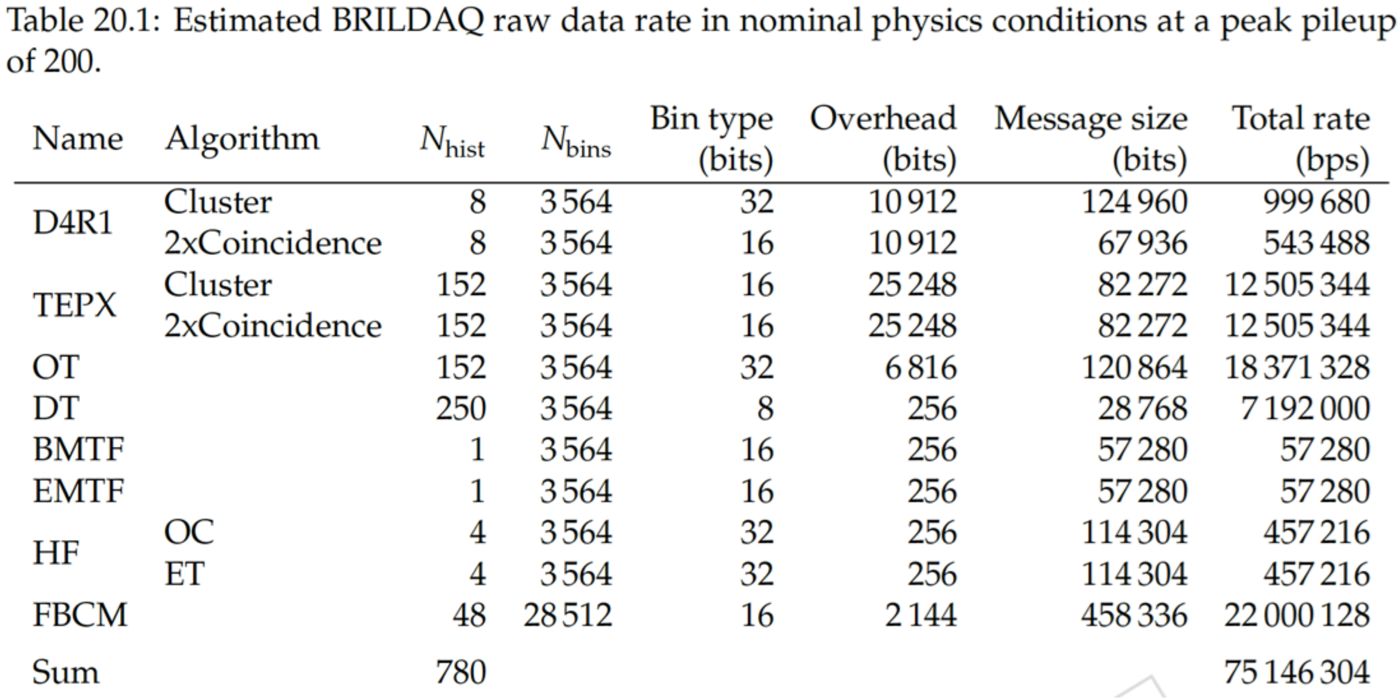


Table 20.1: Estimated BRILDAQ raw data rate in nominal physics conditions at a peak pileup of 200.

Name	Algorithm	N_{hist}	N_{bins}	Bin type (bits)	Overhead (bits)	Message size (bits)	Total rate (bps)
D4R1	Cluster	8	3 564	32	10 912	124 960	999 680
	2xCoincidence	8	3 564	16	10 912	67 936	543 488
TEPX	Cluster	152	3 564	16	25 248	82 272	12 505 344
	2xCoincidence	152	3 564	16	25 248	82 272	12 505 344
OT		152	3 564	32	6 816	120 864	18 371 328
DT		250	3 564	8	256	28 768	7 192 000
BMTF		1	3 564	16	256	57 280	57 280
EMTF		1	3 564	16	256	57 280	57 280
HF	OC	4	3 564	32	256	114 304	457 216
	ET	4	3 564	32	256	114 304	457 216
FBCM		48	28 512	16	2 144	458 336	22 000 128
Sum		780					75 146 304

vdM scan using LHCb BGI data for visualization

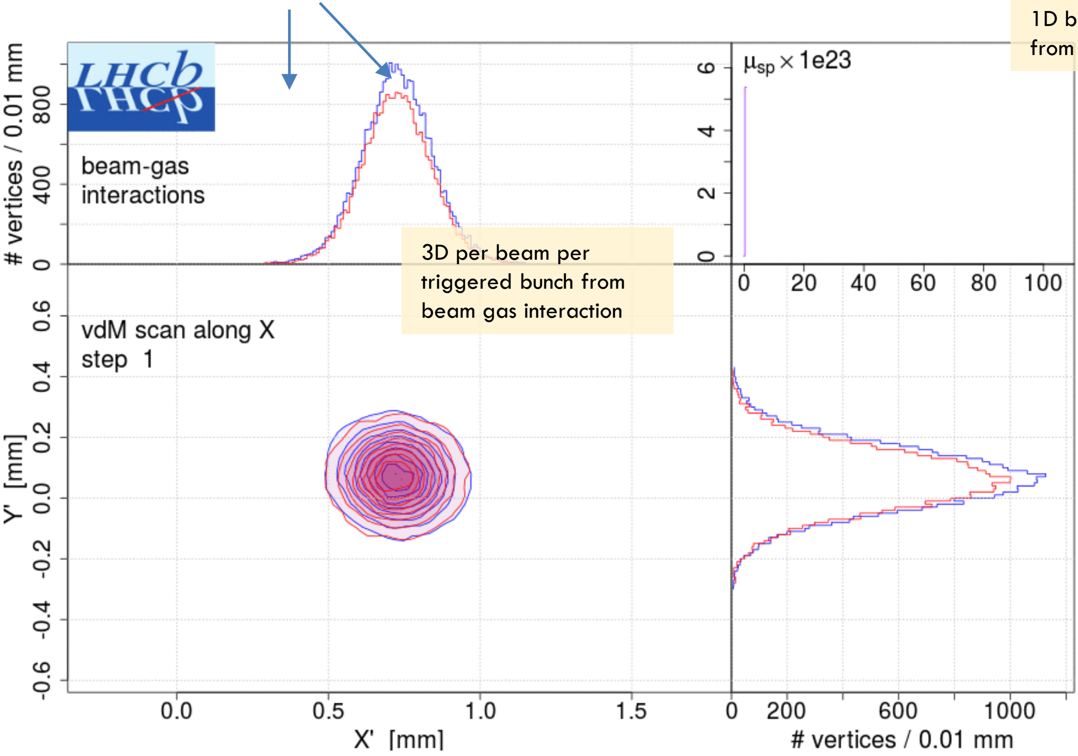
Measuring the beam overlap integral requires vertex detector, luminometer rates, LHC beam instrumentation and knowledge of beam physics (beam-beam interactions)

Precision knowledge of scan steps, X/Y
- Absolute "length" scale using vertex detector

Know residual non-linearity & hysteresis of LHC corrector magnets

Measure any residual orbit drifts – LHC beam instrumentation

Correct for displacement of beam due deflection caused by electromagnetic force between bunches



3D per beam per triggered bunch from beam gas interaction

1D beam overlap projection per plane from **rates of luminometer**

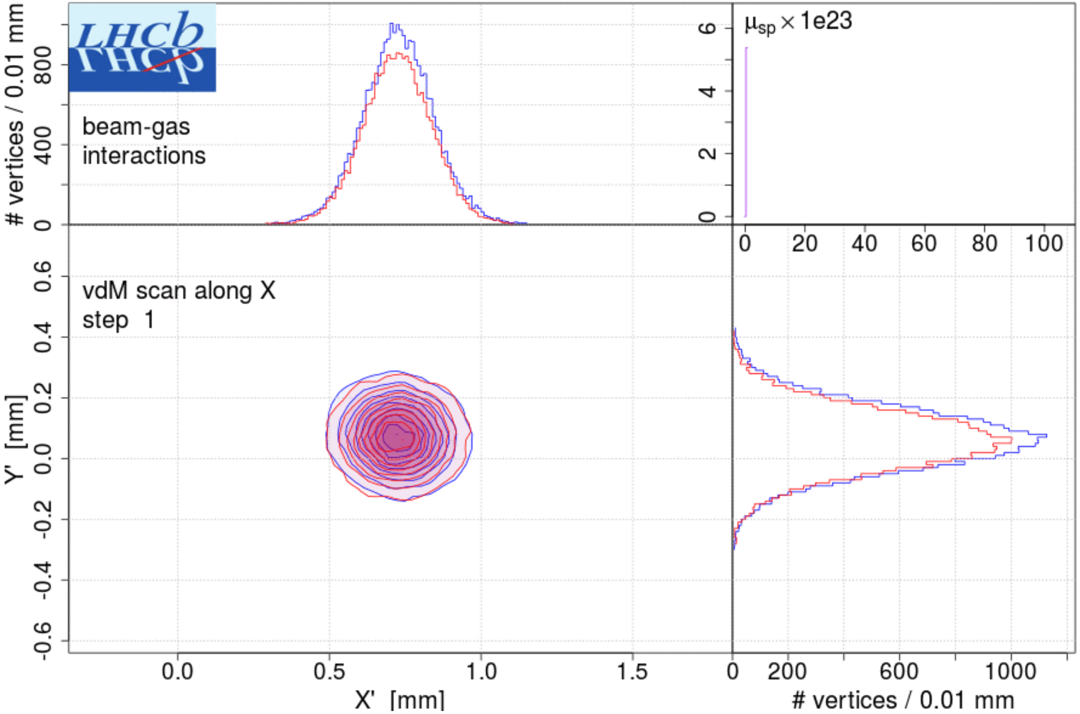
Factorization of X/Y assumed – must be probed with 3D or 2D or offset scans

Require linear luminometer of <u> steps in vdM scan and Extrapolation to higher <u>

Correct rate/ beam shape due to optical distortion (focusing/defocusing) of two beams that change the beam width during collision (equivalent to tune shift)

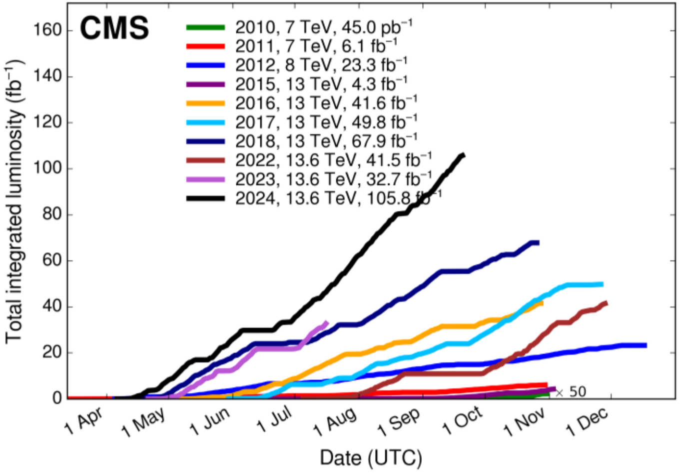
BGI animation Courtesy Vladislav Balagura, Lumi Days 2019 @ CERN

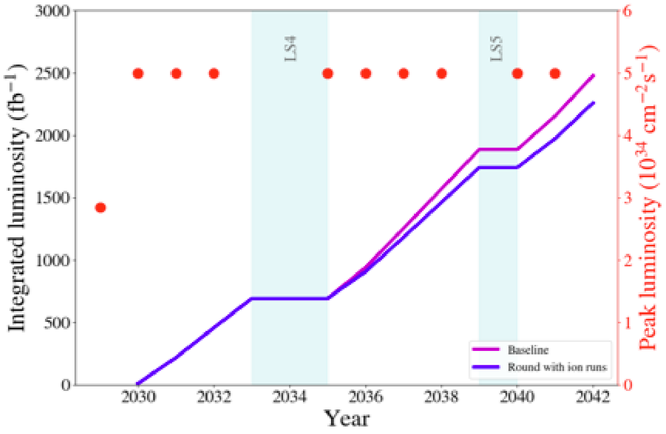
vdM scan using LHCb BGI data for visualization



Courtesy Vladislav Balagura, Lumi Days 2019 @ CERN

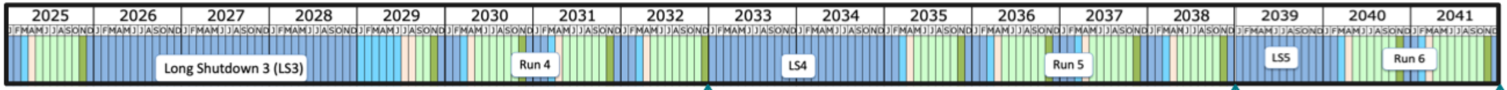
LHC & HL-LHC Integrated Luminosity -





See N. Mounet et al, 199th HL-LHC TCC and S. Kostoglou, 288th WP2 meeting

Longer term LHC schedule Jun 2024 (current baseline a change of schedule could add ±1 year shift)



> 450/fb from LHC

+ 600/fb from HL-LHC

+ 1100/fb from HL-LHC

+ 800/fb from HL-LHC

> 450/fb

~ 1000/fb

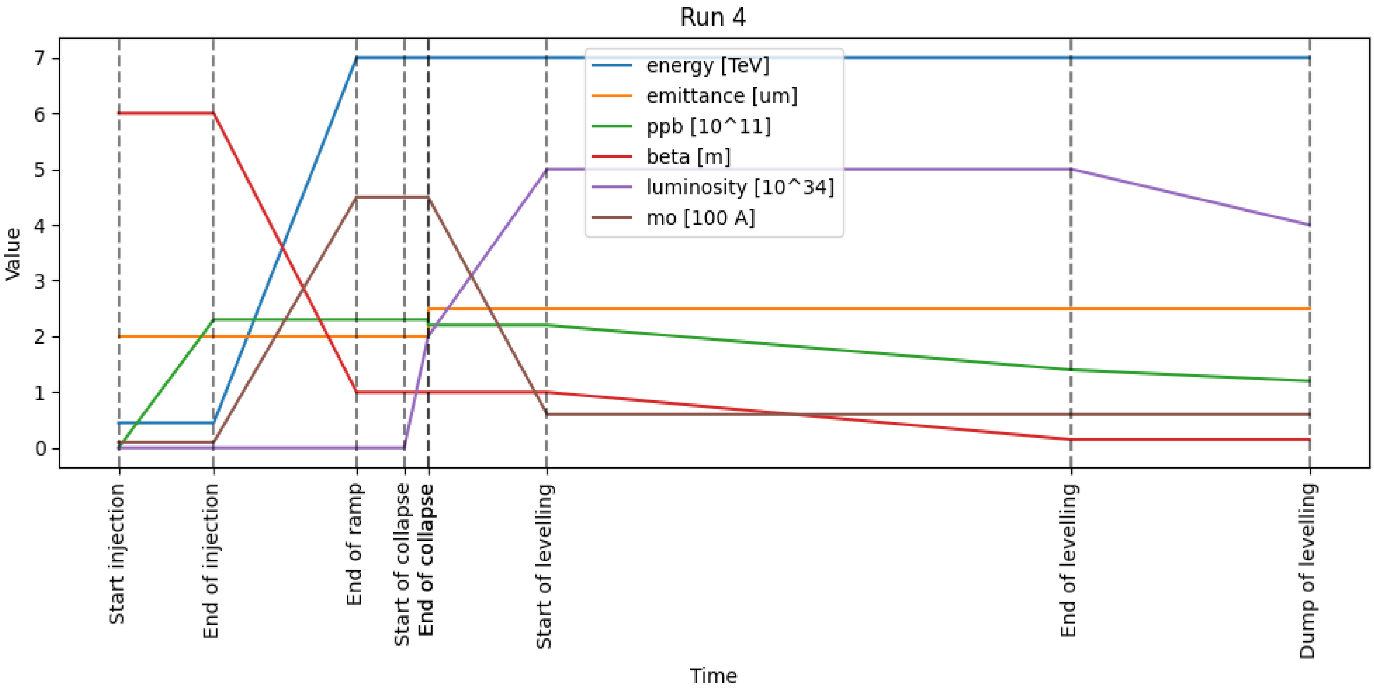
~2200/fb

~3000/fb

$\sqrt{2}$

$\sqrt{2}$

Run 4 cycle



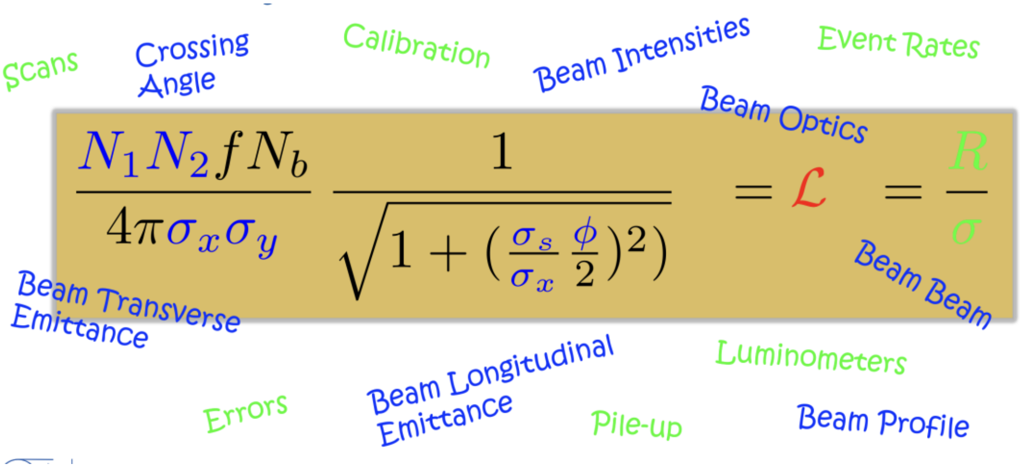
Example cycle evolution (not to scale).

Lumi Days 2019 Workshop

Discussions of state of the art of knowledge of luminosity calibration and monitoring

https://indico.cern.ch/event/813285/timetable/

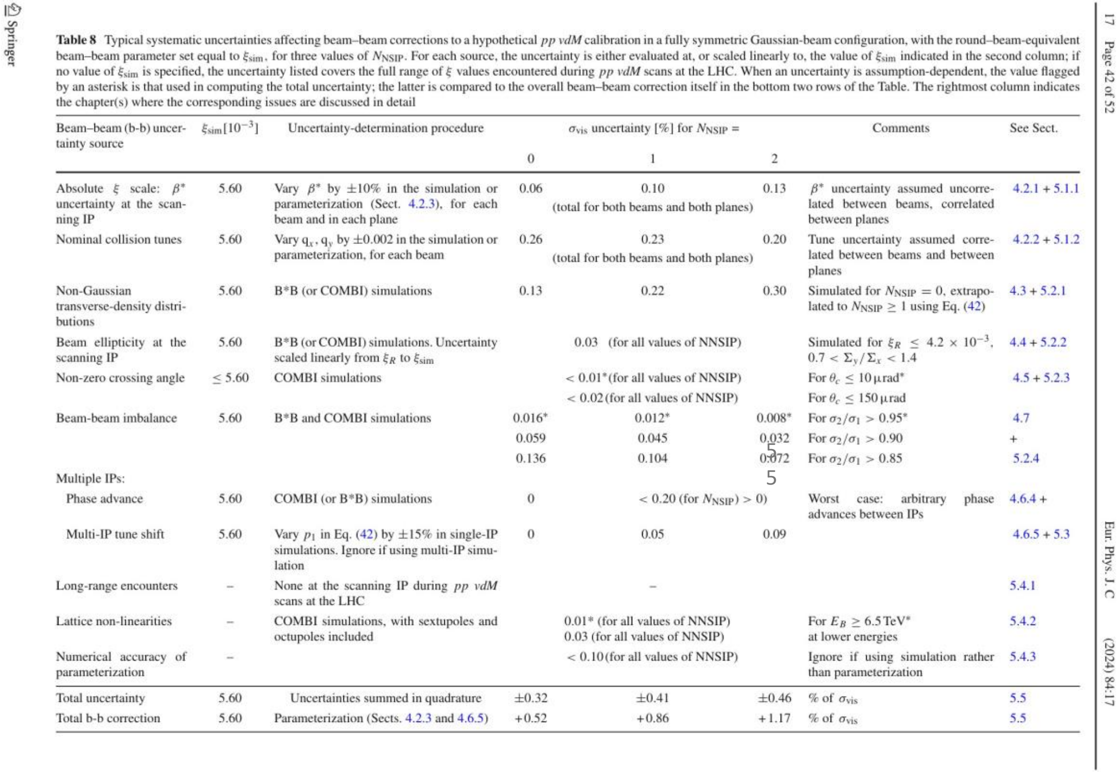
Coming together of the Accelerator and LHC Experiments communities



$$\frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}\frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2)}} = \mathcal{L} = \frac{R}{\sigma}$$

https://cds.cern.ch/record/2677409?ln=en

From beam-beam paper:
Backup – exhaustive list of systematic effects



Springer

17 Page 42 of 52 Eur. Phys. J. C (2024) 84:17

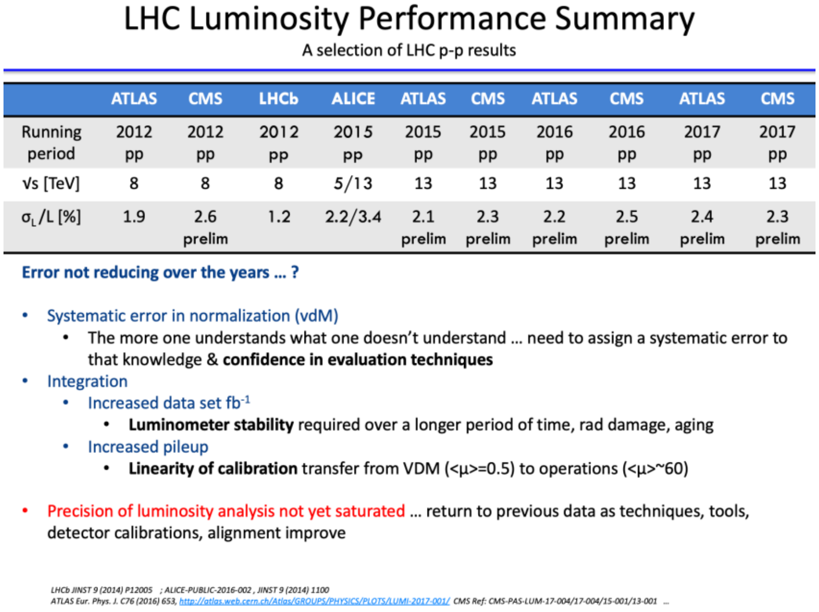
Table 8 Typical systematic uncertainties affecting beam–beam corrections to a hypothetical *pp vdM* calibration in a fully symmetric Gaussian-beam configuration, with the round–beam-equivalent beam–beam parameter set equal to $\xi_{\rm sim}$, for three values of $N_{\rm NSIP}$. For each source, the uncertainty is either evaluated at, or scaled linearly to, the value of $\xi_{\rm sim}$ indicated in the second column; if no value of $\xi_{\rm sim}$ is specified, the uncertainty listed covers the full range of ξ values encountered during *pp vdM* scans at the LHC. When an uncertainty is assumption-dependent, the value flagged by an asterisk is that used in computing the total uncertainty; the latter is compared to the overall beam–beam correction itself in the bottom two rows of the Table. The rightmost column indicates the chapter(s) where the corresponding issues are discussed in detail

Beam–beam (b-b) uncertainty source	$\xi_{\rm sim}[10^{-3}]$	Uncertainty-determination procedure	$\sigma_{\rm vis}$ uncertainty [%] for $N_{\rm NSIP}$ =			Comments	See Sect.
			0	1	2		
Absolute ξ scale: β^* uncertainty at the scanning IP	5.60	Vary β^* by ±10% in the simulation or parameterization (Sect. 4.2.3), for each beam and in each plane	0.06	0.10 (total for both beams and both planes)	0.13	β^* uncertainty assumed uncorrelated between beams, correlated between planes	4.2.1 + 5.1.1
Nominal collision tunes	5.60	Vary q_x, q_y by ±0.002 in the simulation or parameterization, for each beam	0.26	0.23 (total for both beams and both planes)	0.20	Tune uncertainty assumed correlated between beams and between planes	4.2.2 + 5.1.2
Non-Gaussian transverse-density distributions	5.60	B*B (or COMBI) simulations	0.13	0.22	0.30	Simulated for $N_{\rm NSIP} = 0$, extrapolated to $N_{\rm NSIP} \geq 1$ using Eq. (42)	4.3 + 5.2.1
Beam ellipticity at the scanning IP	5.60	B*B (or COMBI) simulations. Uncertainty scaled linearly from ξ_R to $\xi_{\rm sim}$		0.03 (for all values of NNSIP)		Simulated for $\xi_R \leq 4.2 \times 10^{-3}$, $0.7 < \Sigma_y/\Sigma_x < 1.4$	4.4 + 5.2.2
Non-zero crossing angle	≤ 5.60	COMBI simulations		< 0.01* (for all values of NNSIP) < 0.02 (for all values of NNSIP)		For $\theta_c \leq 10\,\mu$rad* For $\theta_c \leq 150\,\mu$rad	4.5 + 5.2.3
Beam-beam imbalance	5.60	B*B and COMBI simulations	0.016* 0.059 0.136	0.012* 0.045 0.104	0.008* 0.032 0.072	For $\sigma_2/\sigma_1 > 0.95$* For $\sigma_2/\sigma_1 > 0.90$ For $\sigma_2/\sigma_1 > 0.85$	4.7 + 5.2.4
Multiple IPs:							
Phase advance	5.60	COMBI (or B*B) simulations	0	< 0.20 (for $N_{\rm NSIP}$) > 0)		Worst case: arbitrary phase advances between IPs	4.6.4 +
Multi-IP tune shift	5.60	Vary p_1 in Eq. (42) by ±15% in single-IP simulations. Ignore if using multi-IP simulation	0	0.05	0.09		4.6.5 + 5.3
Long-range encounters	–	None at the scanning IP during *pp vdM* scans at the LHC		–			5.4.1
Lattice non-linearities	–	COMBI simulations, with sextupoles and octupoles included		0.01* (for all values of NNSIP) 0.03 (for all values of NNSIP)		For $E_B \geq 6.5$ TeV* at lower energies	5.4.2
Numerical accuracy of parameterization	–			< 0.10 (for all values of NNSIP)		Ignore if using simulation rather than parameterization	5.4.3
Total uncertainty	5.60	Uncertainties summed in quadrature	±0.32	±0.41	±0.46	% of $\sigma_{\rm vis}$	5.5
Total b-b correction	5.60	Parameterization (Sects. 4.2.3 and 4.6.5)	+0.52	+0.86	+1.17	% of $\sigma_{\rm vis}$	5.5

Luminosity determination at HL-LHC: a first discussion

Anne Dabrowski (CERN)
On behalf of the LHC Experiments

Workshop on the physics of HL-LHC, and perspectives
at HE-LHC, 18-20 Jun 2018, CERN, Geneva



LHC Luminosity Performance Summary

A selection of LHC p-p results

	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Running period	2012 pp	2012 pp	2012 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp	2017 pp	2017 pp
√s [TeV]	8	8	8	5/13	13	13	13	13	13	13
σ_L/L [%]	1.9	2.6 prelim	1.2	2.2/3.4	2.1 prelim	2.3 prelim	2.2 prelim	2.5 prelim	2.4 prelim	2.3 prelim

Error not reducing over the years … ?

- Systematic error in normalization (vdM)
  - The more one understands what one doesn't understand … need to assign a systematic error to that knowledge & **confidence in evaluation techniques**
- Integration
  - Increased data set fb^{-1}
    - **Luminometer stability** required over a longer period of time, rad damage, aging
  - Increased pileup
    - **Linearity of calibration** transfer from VDM (<μ>=0.5) to operations (<μ>~60)
- Precision of luminosity analysis not yet saturated … return to previous data as techniques, tools, detector calibrations, alignment improve

LHCb JINST 9 (2014) P12005 ; ALICE-PUBLIC-2016-002 , JINST 9 (2014) 1100
ATLAS Eur. Phys. J. C76 (2016) 653, http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/ CMS Ref: CMS-PAS-LUM-17-004/17-004/15-001/13-001 …

LLCMWG strategy for work on systematics common to all experiments refined during Lumi day 2019 workshop

Intensive work since 2018 on vdM calibration systematics and luminosity monitoring (LLCMWG)

Beam-beam corrections
Non factorisation (e.g., 2D scans, beam imaging, beam gas)
Orbit drift, magnetic non-linearity, LHC beam instrumentation
Monitoring of luminometer efficiency and linearity
mu and emittance scans
Z-counting rate measurements

LHC Luminosity Performance Summary

A selection of LHC p-p results until 2017 updated since 2018

	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Running period	2012 pp	2012 pp	2012 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp	2017 pp	2017 pp
√s [TeV]	8	8	8	5/13	13	13	13	13	13	13
σ_L /L [%] (2018)	1.9	2.6 prelim	**1.2**	2.2/3.4	**2.1 prelim**	**2.3 prelim**	**2.2 prelim**	**2.5 prelim**	**2.4 prelim**	2.3 prelim
σ_L /L [%] (latest)	1.9	2.6 prelim	**1.2**	2.2/3.4	**1.13**	**1.6**	**0.89**	**1.2**	**1.13**	Paper in preparation

"Luminosity determination in pp **collisions at** s√=13 **TeV using the ATLAS detector at the LHC"**
Eur. Phys. J. C 83 (2023) 982

"Precision luminosity measurement in proton-proton collisions at s√= **13 TeV in 2015 and 2016 at CMS**
" Eur. Phys. J. C 81 (2021) 80

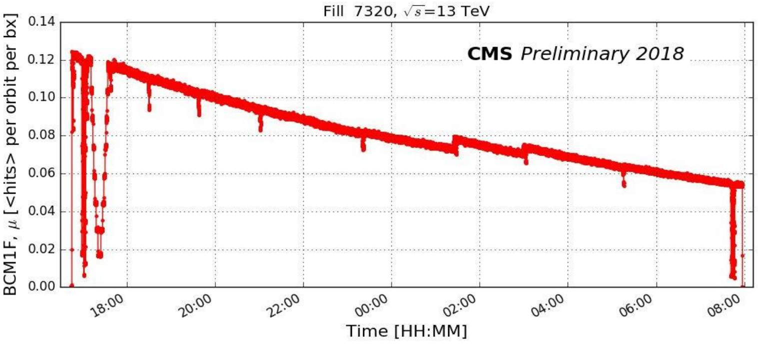
- ✓ Precision of luminosity analysis not yet saturated … return to previous data as techniques, tools, detector calibrations, alignment improve
- NB somewhat different recipes used to evaluate uncertainties between the collaborations

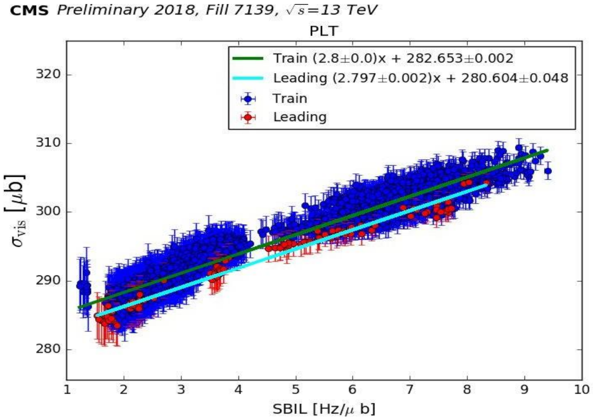
Precision luminosity calibration is an intensive, creative effort requiring cross-experiment-accelerator-groups collaboration

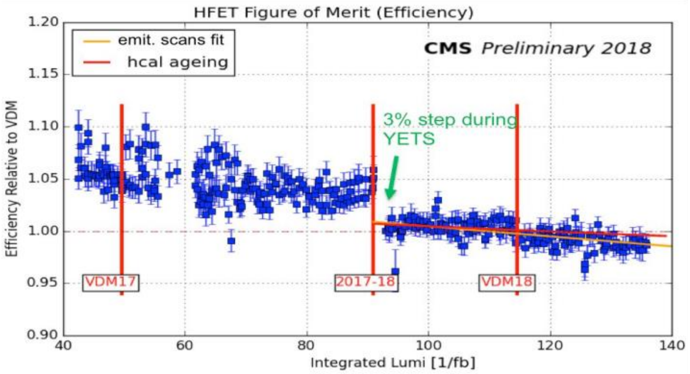
LHCb JINST 9 (2014) P12005 ; ALICE-PUBLIC-2016-002 , JINST 9 (2014) 1100
ATLAS Eur. Phys. J. C76 (2016) 653, http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/ CMS Ref: CMS-PAS-LUM-17-004/17-004/15-001/13-001 …

Emittance scans, efficiency & linearity

- Exploit high statistics per bunch online luminometers and LHC ability to do “mini” vdM scans (“emittance scans” in nominal consitions
- Emittance scans are treated like mini vdM calibrations
- From that the stability of the calibration is monitored
- Compared as function of time and SBIL to extract Linearity and efficiency corrections

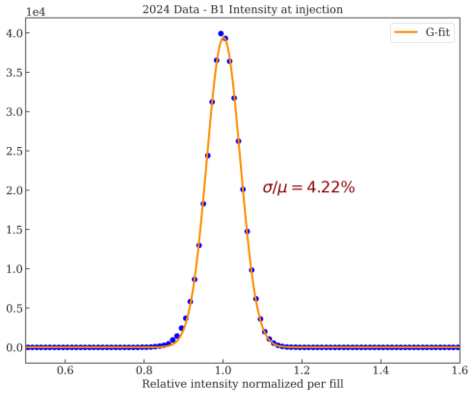




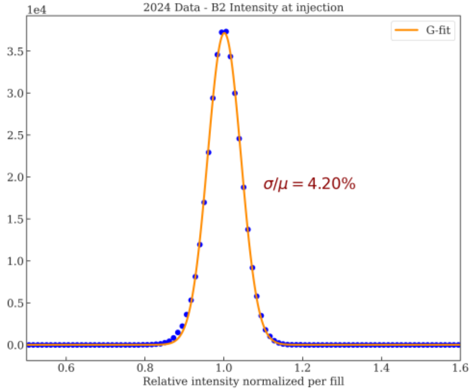


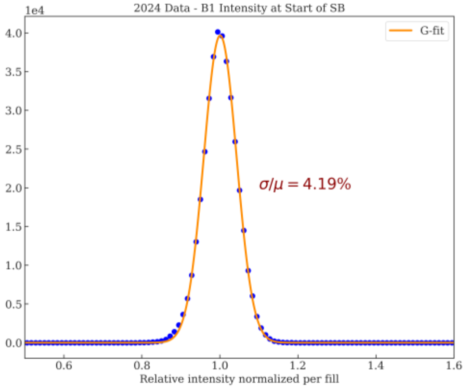
Beam Intensity Fluctuations in the cycle

Selected 204 fills in 2024 (>2h in SB, >1900bunches)

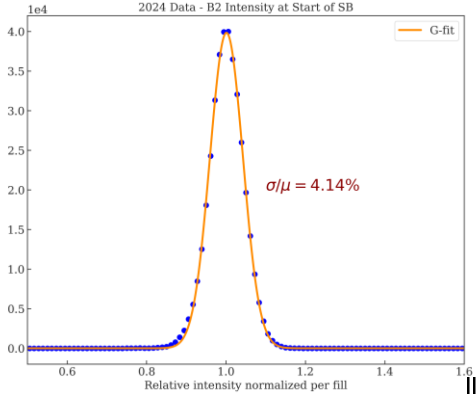


Injection





Start of SB

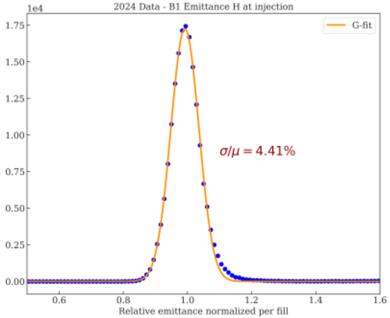


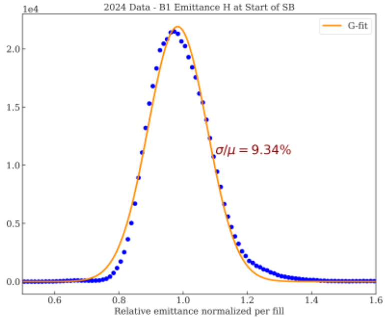
Ilias Efthymiopoulos BE/ABP

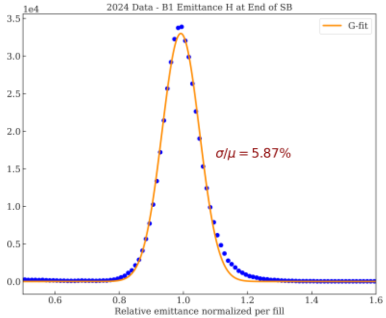
Bunch intensities normalized to the mean of each fill

Emittance Fluctuations in the cycle

Selected 204 fills in 2024 (>2h in SB, >1900bunches)



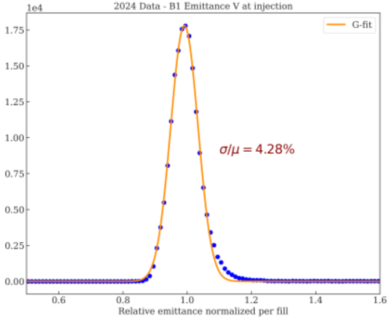


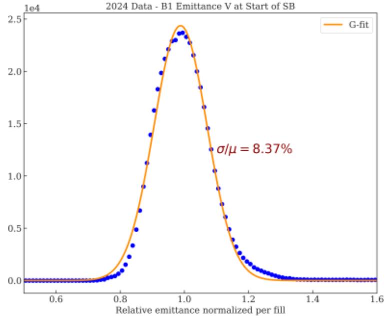


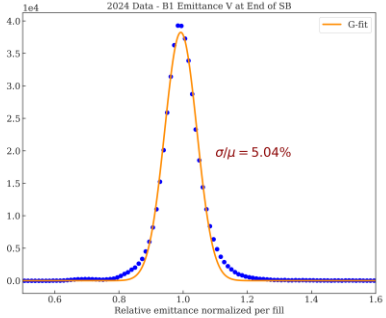
Injection

Start of SB

End of SB



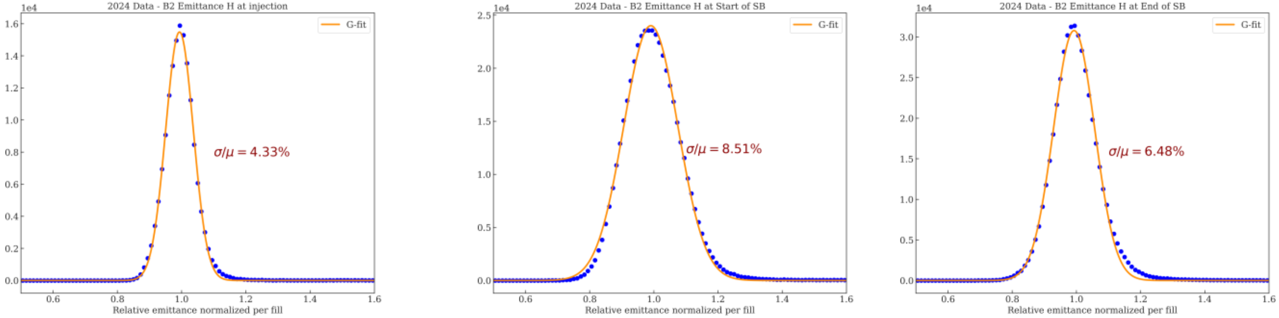




Bunch emittances normalized to the mean of each fill

Emittance Fluctuations in the cycle

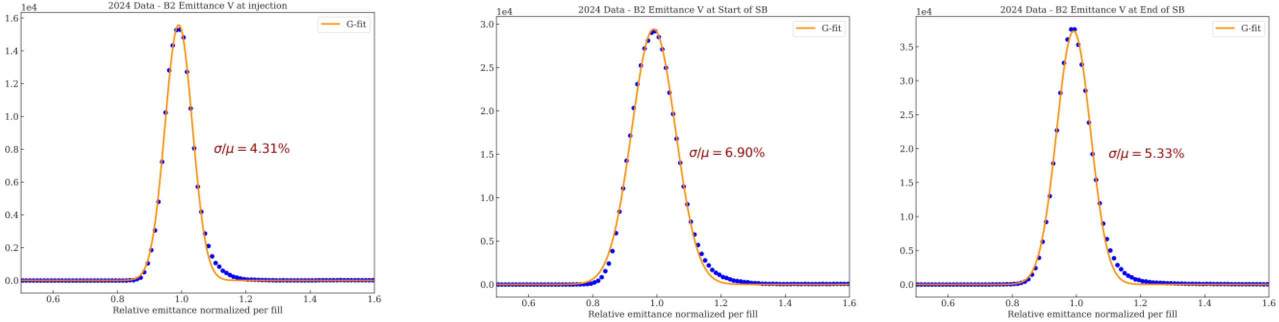
Selected 204 fills in 2024 (>2h in SB, >1900bunches)



Injection

Start of SB

End of SB



Bunch emittances normalized to the mean of each fill

Ilias Efthymiopoulos BE/ABP

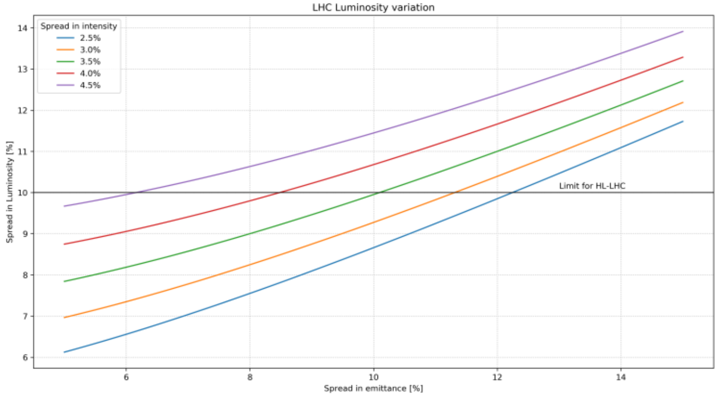
Luminosity fluctuation in Run 2

Reminder:

$$\begin{aligned}\mathcal{L} &= \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}\\ &= \frac{N_1 N_2 f N_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{1x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}}\\ &= \frac{N_1 N_2 f N_b}{2\pi\sqrt{\beta^*_{1,2\,x}\beta^*_{1,2\,y}}\sqrt{\epsilon_{1x}+\epsilon_{1x}}\sqrt{\epsilon_{1y}+\epsilon_{2y}}}\end{aligned}$$

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sqrt{\beta^*_x\beta^*_y}\sqrt{\epsilon_x}\sqrt{\epsilon_y}}$$

$$\boxed{\frac{\delta\mathcal{L}}{\mathcal{L}} = \sqrt{4\left(\frac{\delta N}{N}\right)^2 + \frac{1}{4}\left(\frac{\delta\epsilon_x}{\epsilon_x}\right)^2 + \frac{1}{4}\left(\frac{\delta\epsilon_y}{\epsilon_y}\right)^2}}$$



- Luminosity fluctuations dominated by intensity
- In the selected fills:
  - **4.37% in intensity** (average B1, B2)
  - **9.77% in emittance** (average over beams and planes)

Luminosity variation to **~11%**

Goal for HL-LHC : 10%

- can be met with:
  - 3% relative spread in intensity, and
  - 11% spread in emittance (average over beams and planes)