Luminosity at LHCb in Run 3

Lepton-Photon 2023, Melbourne

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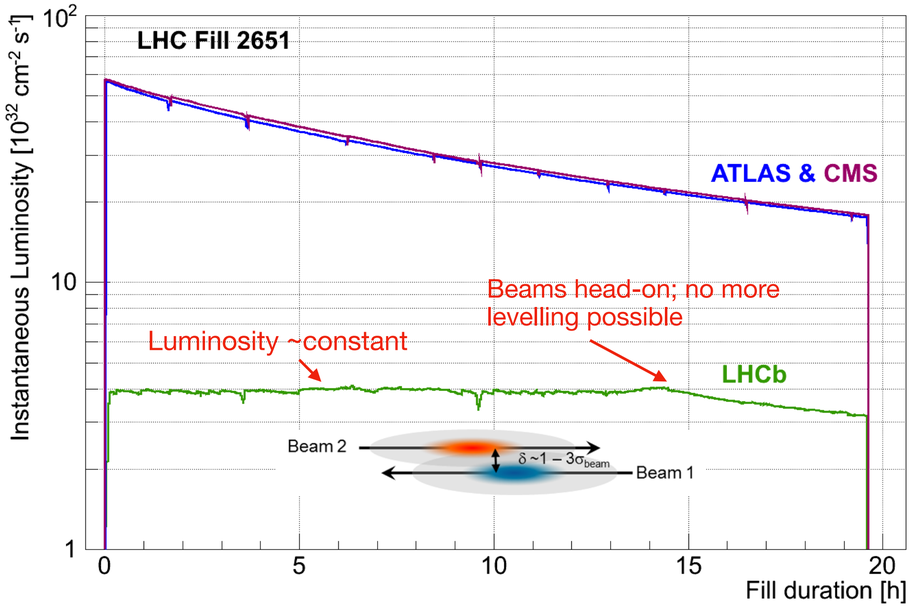
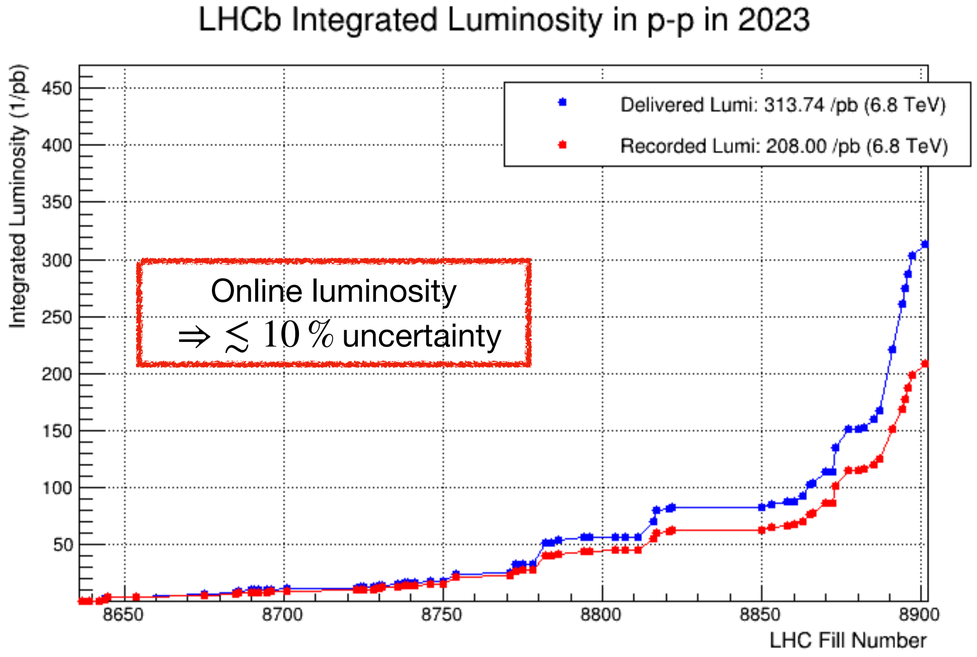
Basic luminosity definitions

- **Luminosity relates the cross section, σ_c, of some process, c, to its production rate, R_c:**

$$\mathscr{L}_{\text{int.}} = \frac{1}{\sigma_c}\int R_c(t)dt$$

- Crucial input to cross section measurements - $\sim 15\,\%$ of LHCb results (e.g. [JHEP 06 (2023) 22], [JHEP 07 (2022) 26])
- At LHCb, online luminosity used for levelling throughout each fill
  - Beams offset at start of fill then gradually brought together





Relative luminosity measurements

- Measure rates proportional to $\mathscr{L}$ without absolute calibration
- Provide online luminosity during data taking
  - Runs 1 and 2: calo E_T
  - Run 3: PLUME (backup hierarchy W.I.P.)
- Provide counter rates for offline calibrations and propagation to ‘physics’ luminosity
- LogZero method historically used at LHCb:
  - $\mu_c = -\log(P(0)) = -\log(n_{\text{empty}}/n_{\text{total}})$, assuming Poisson statistics $\left(P(0) = \frac{\mu_c^0 \exp(-\mu_c)}{0!}\right)$
  - For Run 3, $\mu \times 5 \implies$ potentially shift to Linear or PGF (generalisation of Linear/LogZero) method

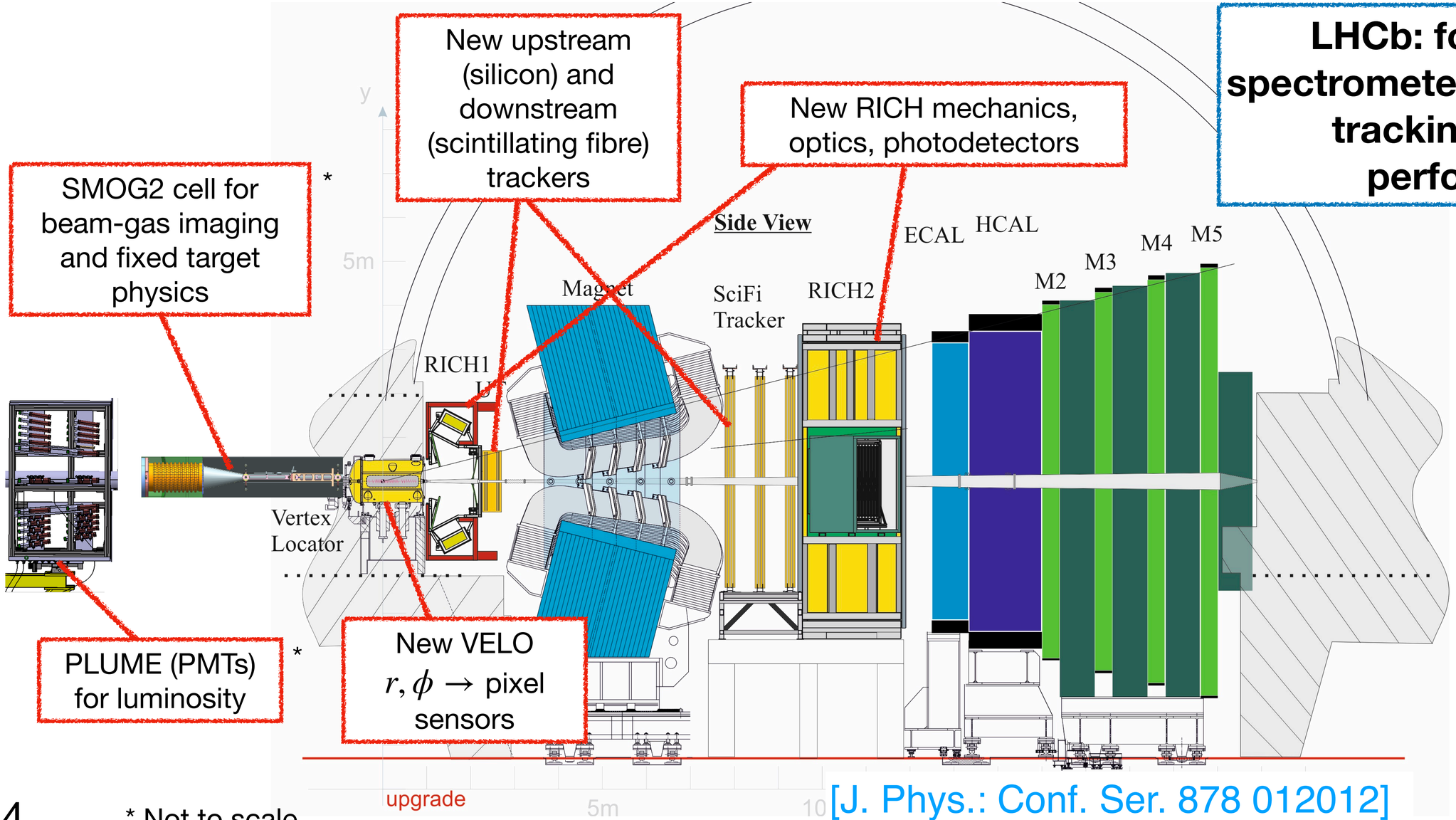
The LHCb upgrade for Run 3

LHCb: forward arm spectrometer, with excellent tracking and PID performance

New upstream (silicon) and downstream (scintillating fibre) trackers

New RICH mechanics, optics, photodetectors

SMOG2 cell for beam-gas imaging and fixed target physics *



+ New frontend electronics and DAQ for all sub-detectors

+ Fully software trigger at 40 MHz on GPUs + CPUs

PLUME (PMTs) for luminosity *

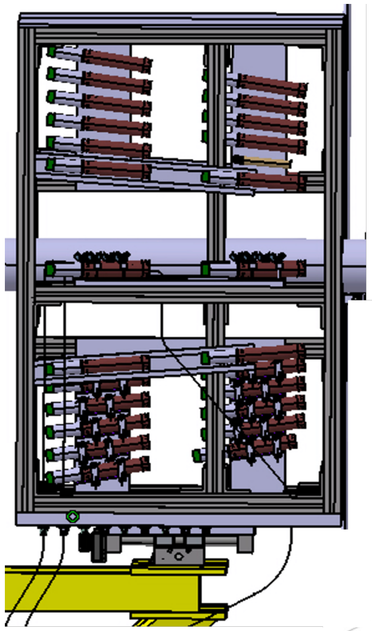
New VELO $r, \phi \rightarrow$ pixel sensors

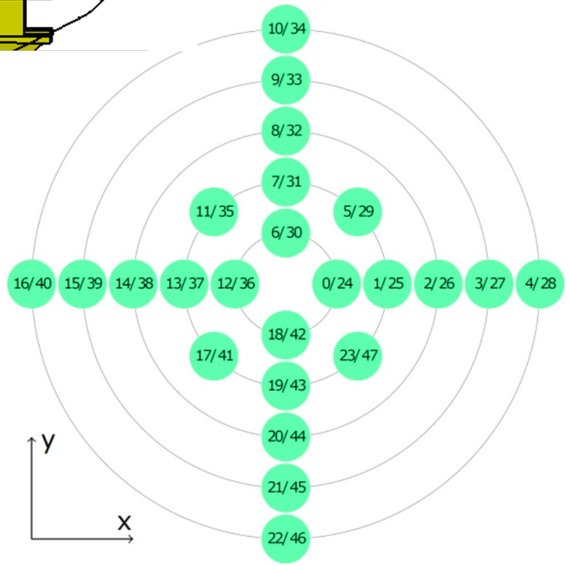
[J. Phys.: Conf. Ser. 878 012012]

* Not to scale

PLUME [CERN-LHCC-2021-002]

Probe for LUminosity MEasurement





- New for Run 3 - dedicated luminosity sub-detector!
- **Design**:
  - Hodoscope of 22 PMT pairs (+2 for timing) around the upstream beam-pipe
  - Detect Cherenkov radiation produced by particles traversing quartz tablet
  - Readout with calorimeter electronics
  - Radiation hard ⇒ time-stability of counters
- **Purpose**:
  - Online luminosity for levelling ($\leq 10\,\%$ precision, 3s integration time)
  - Stable counter(s) for absolute calibrations ($\sim 1\,\%$ precision)
  - Fast (~ 100 ps) timing ⇒ monitor LHCb/LHC clock shift, beam 2 bunch structure measurements

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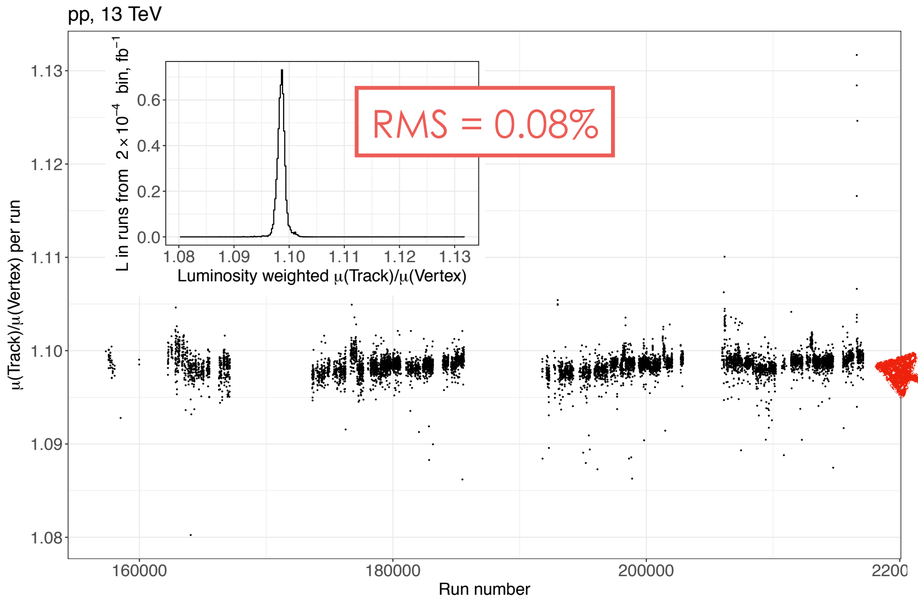
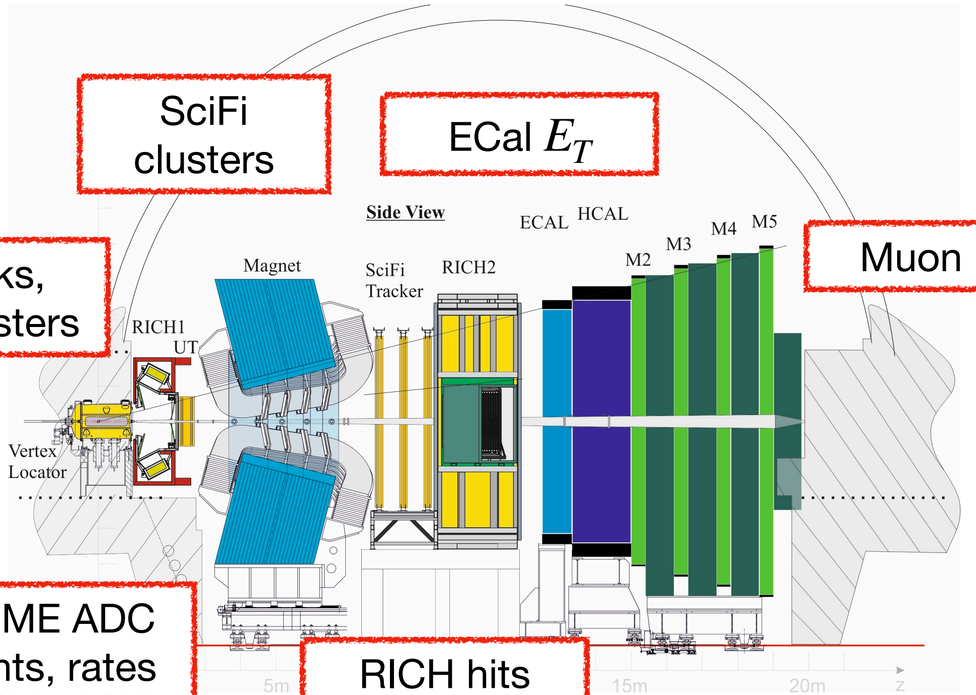
Luminosity counters

- **Every sub-detector can be a luminosity counters**
  - Stable ratios give confidence in time-stability and μ-linearity
- Requirements:
  - Linear scaling with $\mathscr{L}$
  - Stable in time
  - No dependence on LHC filling scheme etc
  - (Optionally) reasonable fraction of empty events for LogZero method



VELO track/vertex counter ratio for **entire** Run 2 - extremely stable!



SciFi clusters

ECal E_T

VELO tracks, vertices, clusters

Muon hits

PLUME ADC counts, rates

RICH hits

(+ many more)

Absolute luminosity measurements

- Physics luminosity propagated from absolute calibration measurements:

Integrated luminosity per colliding bunch pair

Relative luminosity from LogZero (or Linear/PGF)

$$\mathscr{L}_{\text{int.}} = \frac{\mu_{\text{c}}}{\sigma_{\text{c}}} \times n_{\text{crossings}}$$

Absolute calibration: van der Meer (vdM) or beam-gas imaging (BGI)

Special conditions fill ~ once per year, per $\sqrt{s}$, per beam type (pp, pPb, etc)

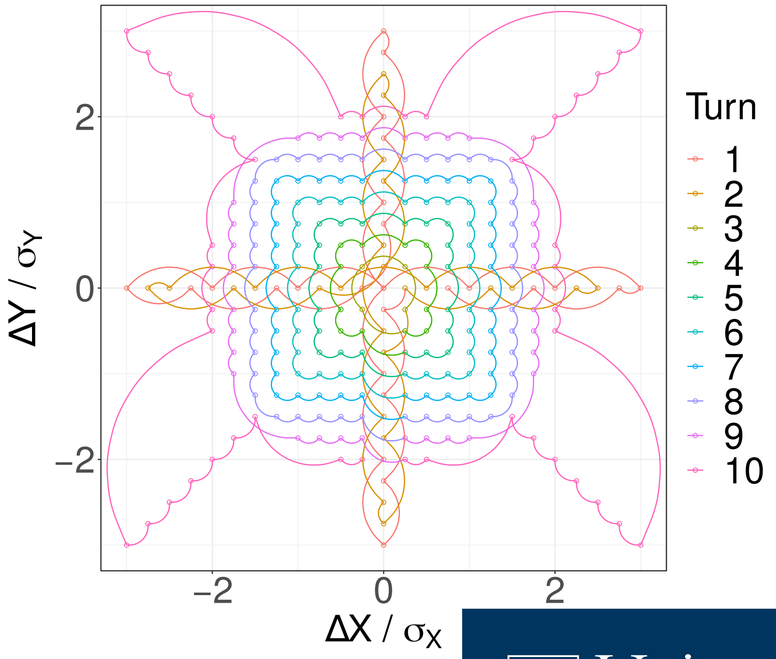
Absolute calibration: vdM

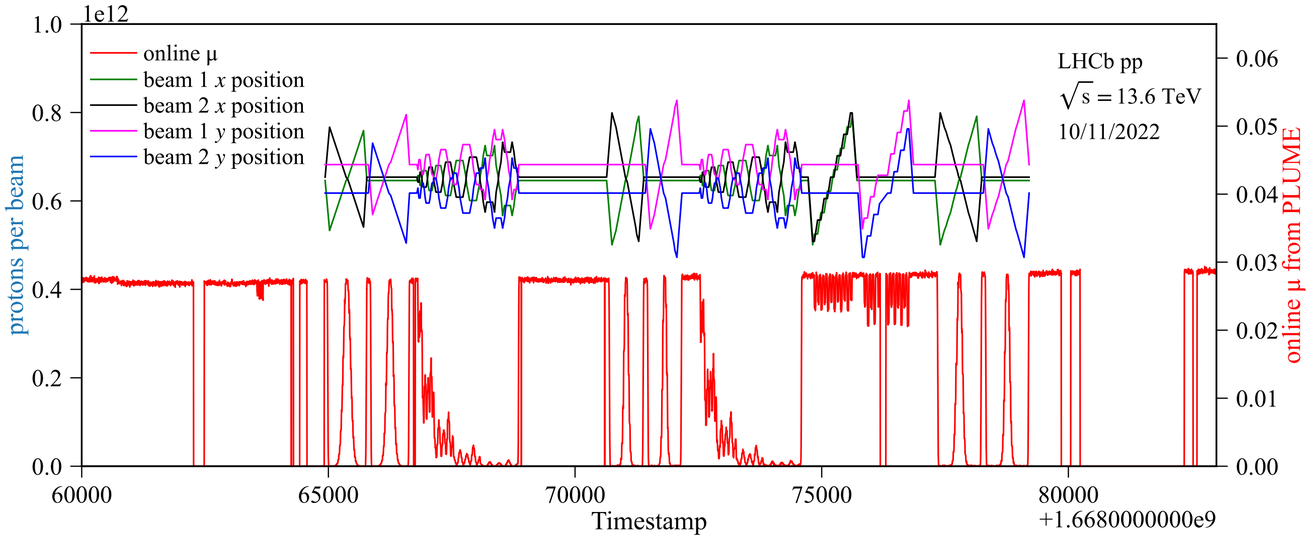
Original proposal (1D): [CERN-ISR-PO-68-31]
2D generalisation: [CERN-pp̄-Note-38]
2D implementation: [V. Balagura, LumiDays 2019]

- **van der Meer** principle: scan beams across one another to integrate out bunch profiles
  - Cross section given by integral of μ_c/N_1N_2 across the $(\Delta x, \Delta y)$-plane
  - Bunch populations from LHC instruments
- 2D scans pioneered at LHCb in Run 2
  - Allows to fully control bunch shape non-factorisablility, $\rho(x,y) \neq \rho(x)\rho(y)$
  - Expect to be more widely adopted in Run 3
- Dominant systematics: beam-beam effect, beam drifts, non-factorisability
- Precision: $1.47\ \%$ at LHCb in Run 1 [JINST 9 P12005]

$$\sigma_{\mathrm{c}} = \int \frac{\mu_{\mathrm{c}}(\Delta x, \Delta y)}{N_1 N_2} d\Delta x d\Delta y$$

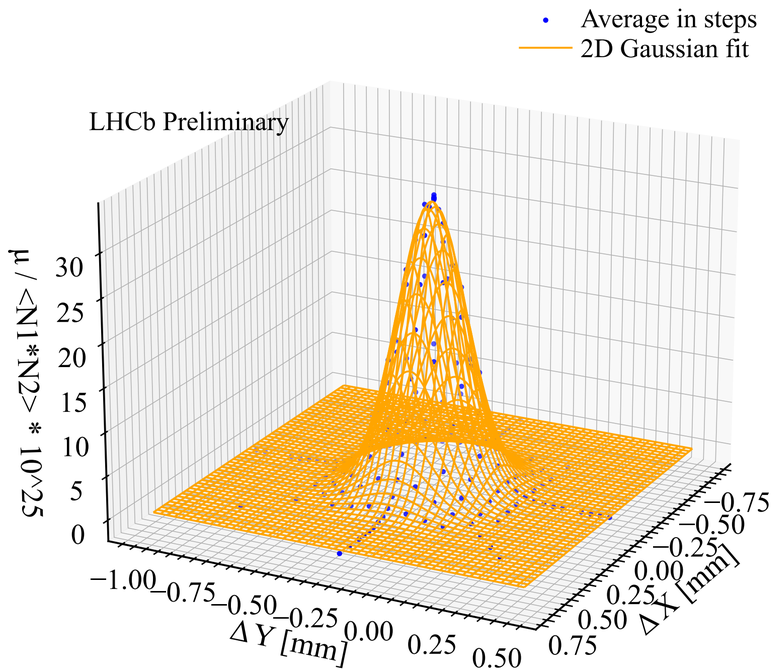
First absolute calibration with PLUME @ $\sqrt{s} = 0.9$ TeV
[LHCB-FIGURE-2022-012]

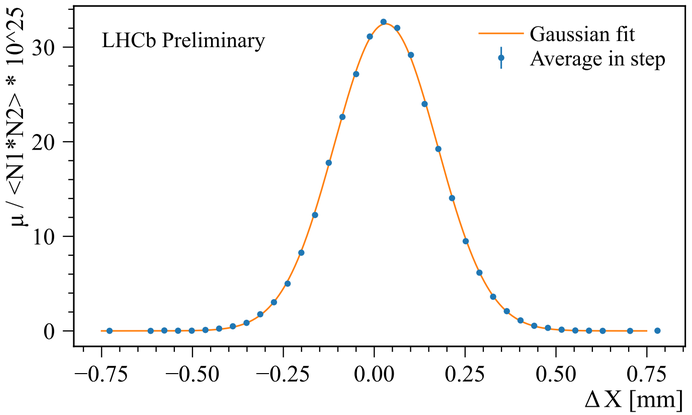


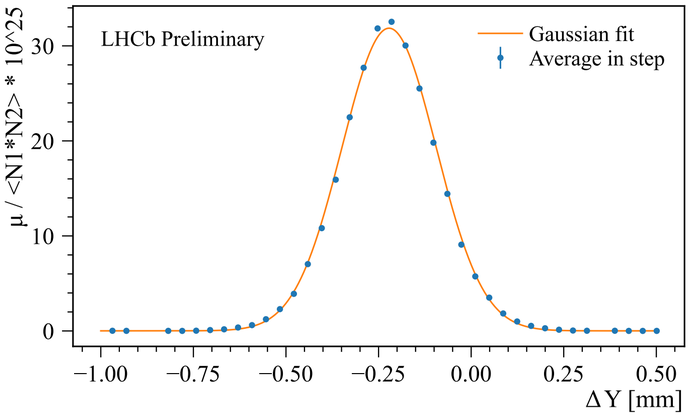


Run 3 preliminary vdM results

- **Absolute luminosity measurement at LHCb at 13.6 TeV!**
- Results from PLUME analysis of November 2022 vdM scans
  - Several counter options: PMT pair coincidences (shown), average ADC counts, single PMT rates
- Linearity of each counter with $\mathscr{L}$ under study - counters taken at full crossing rate (22×11.245 kHz)!
- Analysis of other counters ongoing
- Emittance scan (per-fill small vdM) machinery in place; commissioning ongoing







Absolute calibration: BGI

$$\left(\mathcal{O} = \int \rho_1(\vec{x}) \rho_2(\vec{x}) d\vec{x} \right)$$

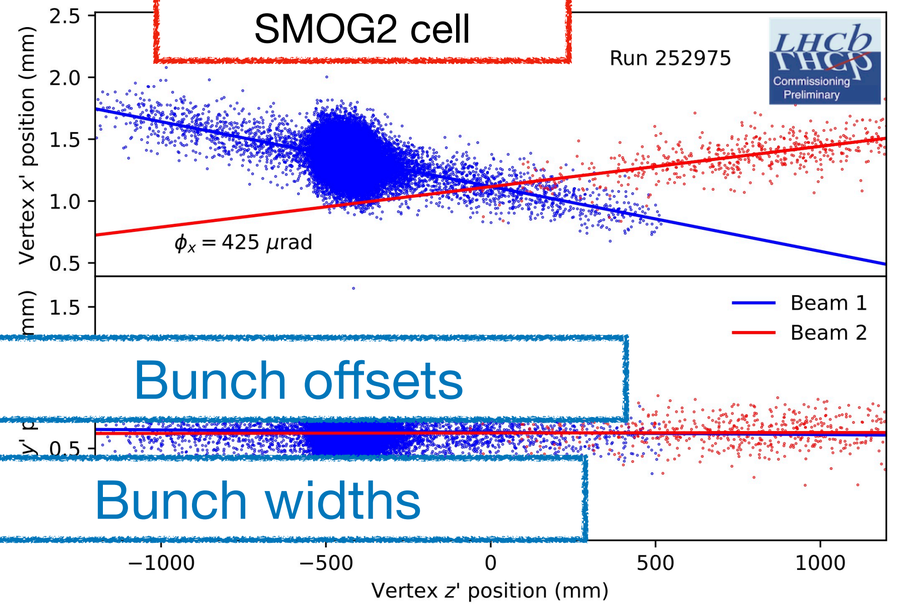
- Reconstruct beam profiles using beam-gas interactions
- Relating luminosity to beam parameters:

$$\mathscr{L} = n_{\text{crossings}} \times N_1 N_2 \mathcal{O} \implies \sigma_c = \frac{\mu_c}{N_1 N_2 \mathcal{O}}$$

- Overlap integral assuming Gaussian bunches:

$$\mathcal{O} = \frac{e^{-\Delta x^2/2\Sigma_x^2} e^{-\Delta y^2/2\Sigma_y^2}}{2\pi\Sigma_x\Sigma_y}$$

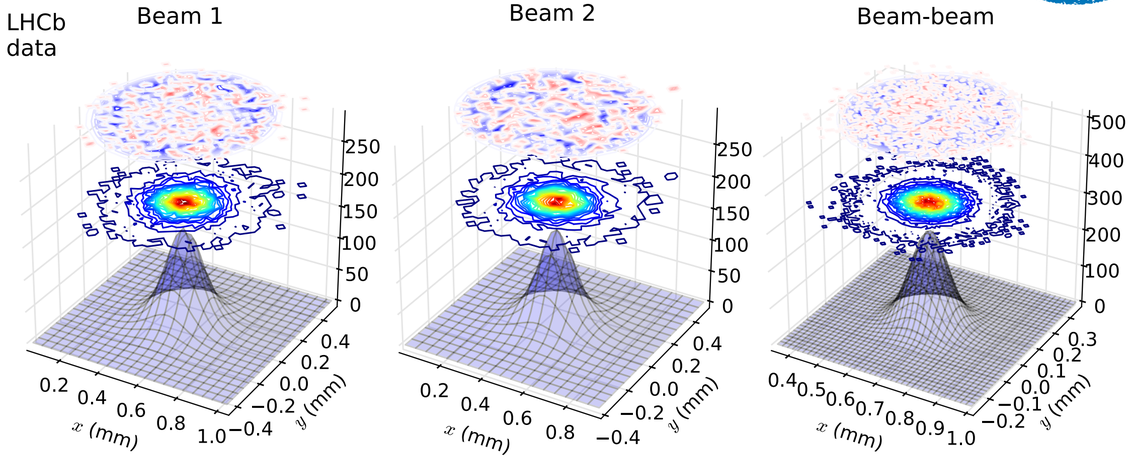
New from Run 3 with SMOG2 cell



Bunch offsets

Bunch widths

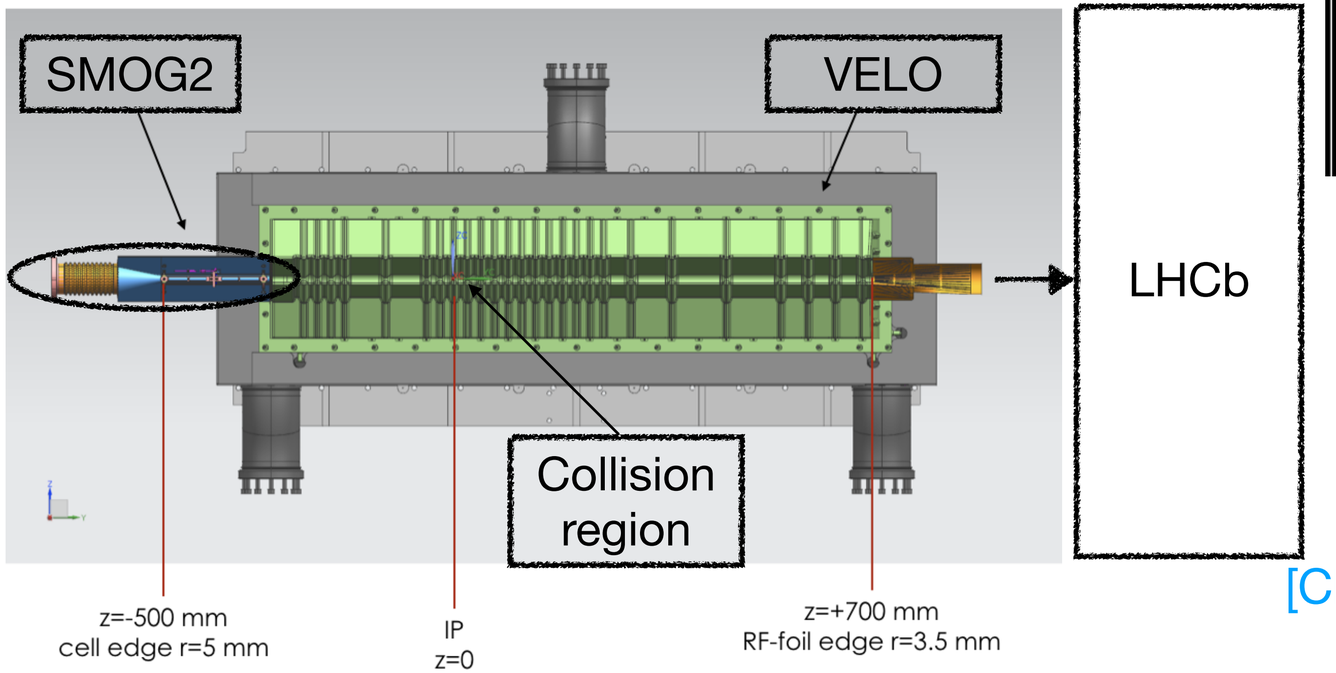
[JINST 9 P12005]

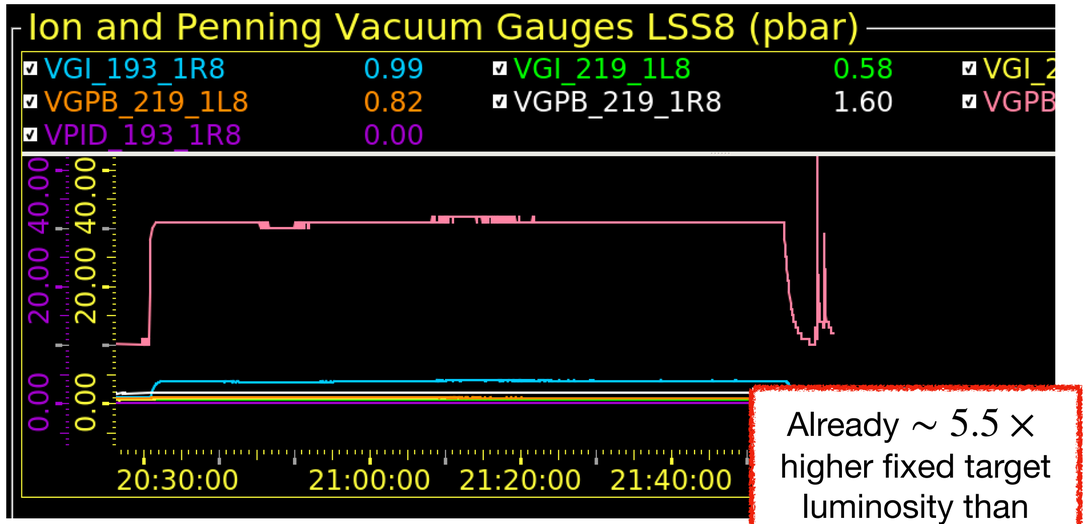


- 2D fits allow for modelling non-factorisability ($\mathcal{O}(\%)$ effect)
- New regime with SMOG2: beam 1 statistics ≈ beam-beam statistics
- Dominant systematics: measurement spread, vertex resolution

SMOG2 storage cell

- System for Measuring Overlap with Gas (SMOG) developed for luminosity in Run 2
  - Demonstrated possibilities for fixed target physics at LHCb
- New for Run 3: **SMOG2** gas storage cell
  - Two halves ⇒ open and close with VELO
  - Possible to inject H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe
- Gas areal density increased by order of magnitude from SMOG
  - e.g. $\sim 5.6 \times 10^{11} \rightarrow 6.0 \times 10^{12}$ atoms / cm^2 for He





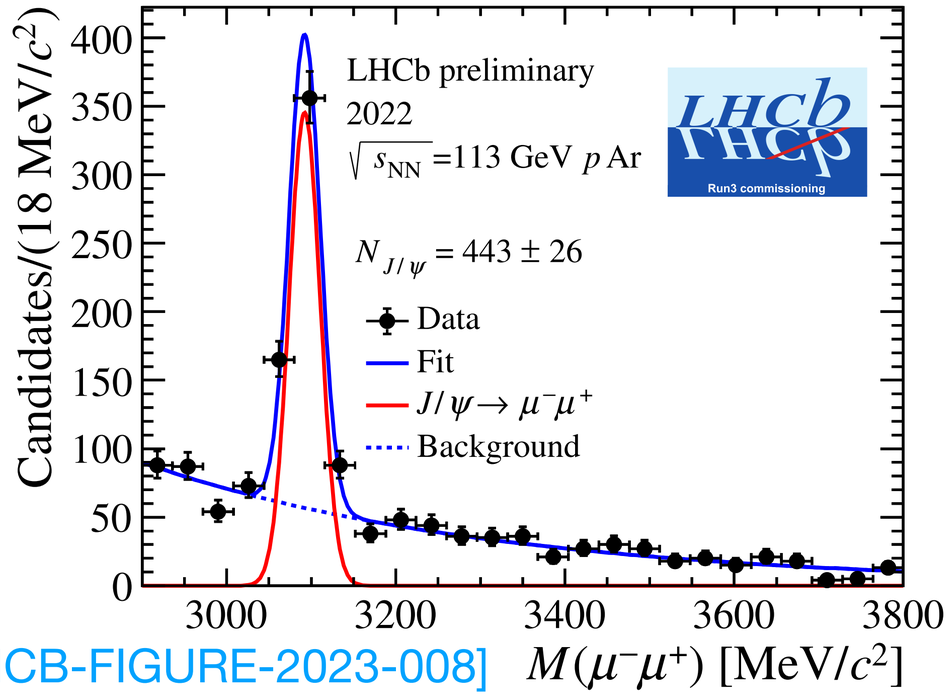
Already $\sim 5.5\times$ higher fixed target luminosity than SMOG

First successful injection (Ar) in closed cell on 1/11/23!

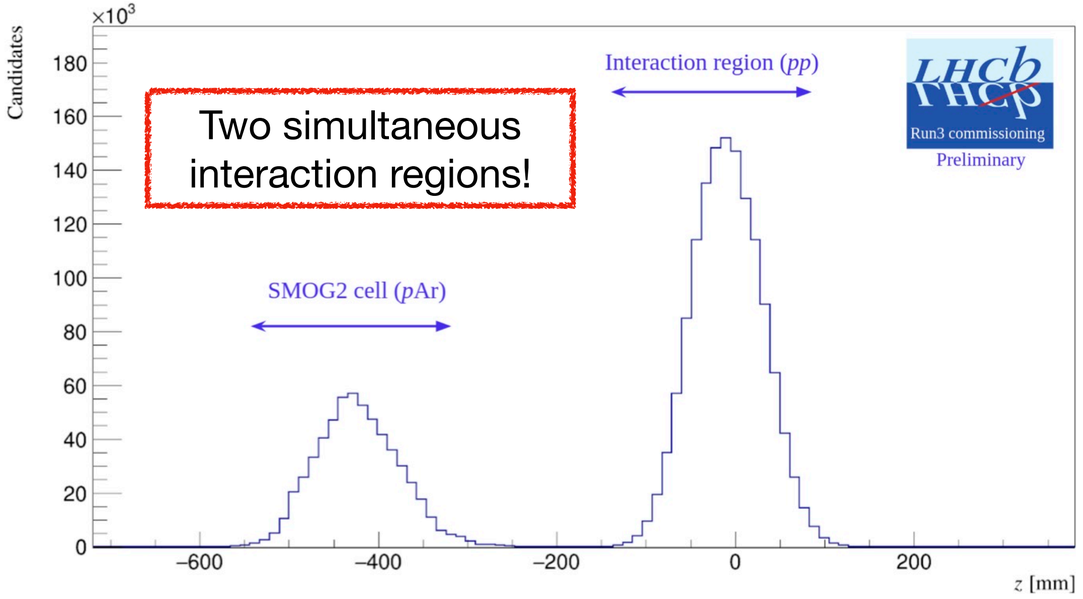
[CERN-LHCC-2019-005]

SMOG2 commissioning

- LHCb operating as both colliding and fixed target experiment
- Successful commissioning programme with Ar, H_2, and He injections
- Successful injections for November 2022 vdM ghost charge measurements (next slide)



[LHCB-FIGURE-2023-008]

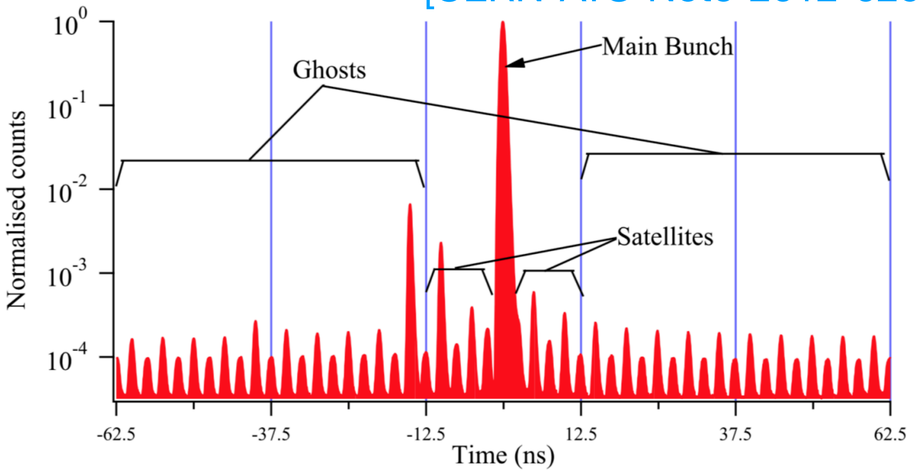


[LHCB-FIGURE-2023-001]

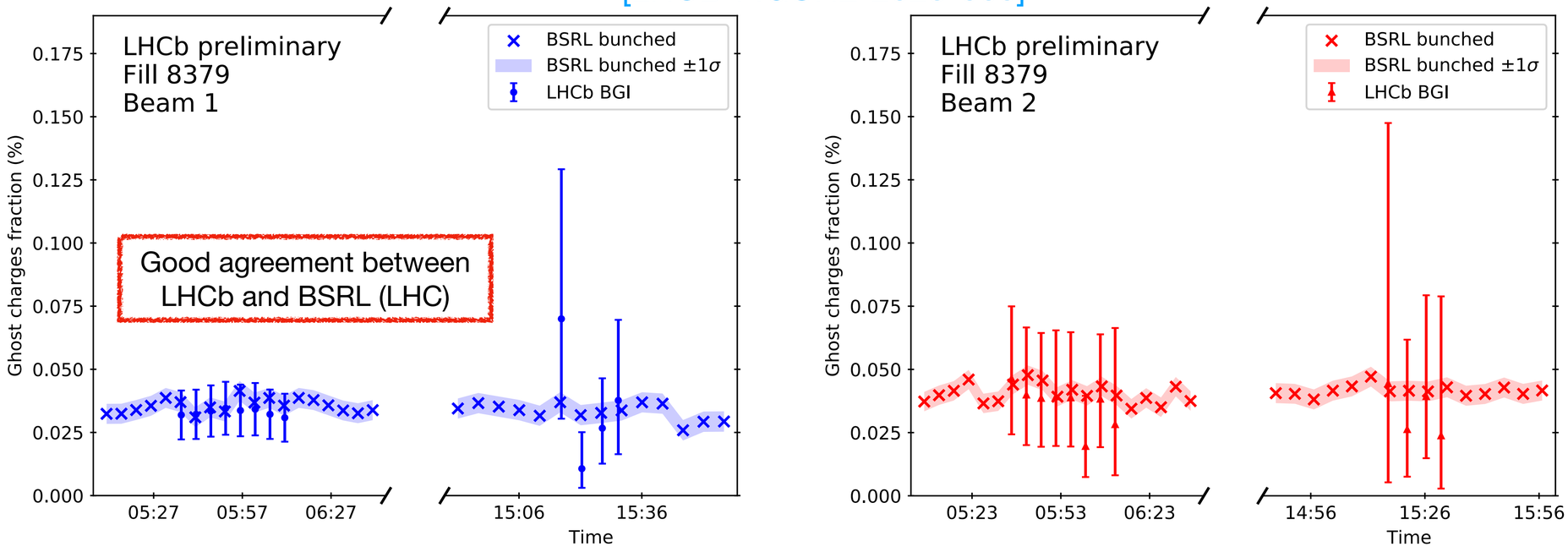
November 2022 ghost charge measurements

- Bunch populations (N_1, N_2) from LHC transformers crucial for absolute $\mathscr{L}$ for all LHC experiments
- Ghost charge: circulating in LHC, outside filled bunch slots (25ns)
  - Measure at LHCb using beam-gas interactions in non-colliding crossings
- Satellite charge: in filled bunch slot, outside filled RF bucket (2.5ns)
  - 100 ps timing with PLUME ⇒ possible at LHCb for beam 2 in the future

[CERN-ATS-Note-2012-029]



[LHCB-FIGURE-2023-003]



Summary

- LHCb: almost entirely new detector for Run 3
  - New 40 MHz fully software trigger
  - PLUME (dedicated luminosity detector) and SMOG2 (gas storage cell) successfully commissioned
- First vdM calibrations at 13.6 TeV
  - Full suite of counters implemented, further analysis ongoing
- New for Run 3: Emittance scans to test linearity to higher physics μ
- Luminosity providing some early Run 3 LHCb results:
  - First absolute calibration with PLUME
  - November 2022 ghost charge measurements

Backup material

Emittance scans

- New at LHCb for Run 3: emittance scans **every fill**
  - Already common at other LHC experiments
  - Check linearity of counters to physics conditions (~ 5 - $10 \times$ higher μ)
  - Check time-stability of counters
  - Machinery in place; commissioning still ongoing
- Scan one axis with other offset, then switch and repeat
  - Too high luminosity at head-on