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LHCb

Luminosity determination at LHCb during Run 3

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ICHEP 2024 | PRAGUE

Luminosity

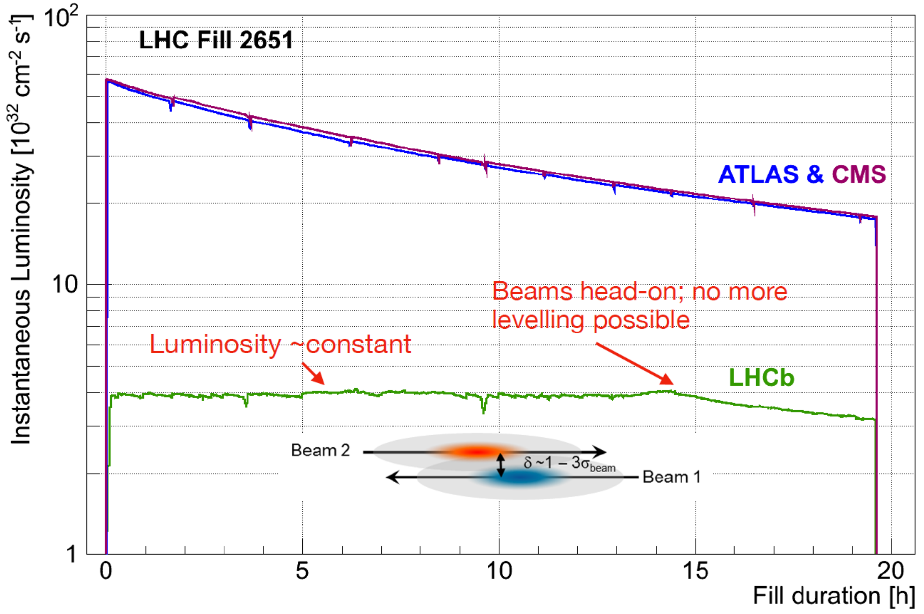
- The luminosity is a crucial parameter to
  - Ensure **efficient data-taking** → Luminosity levelling
  - Guarentee the **safety of the detector**
  - **Determine cross-sections** in physics's analyses
    - ~ 15 % of LHCb results

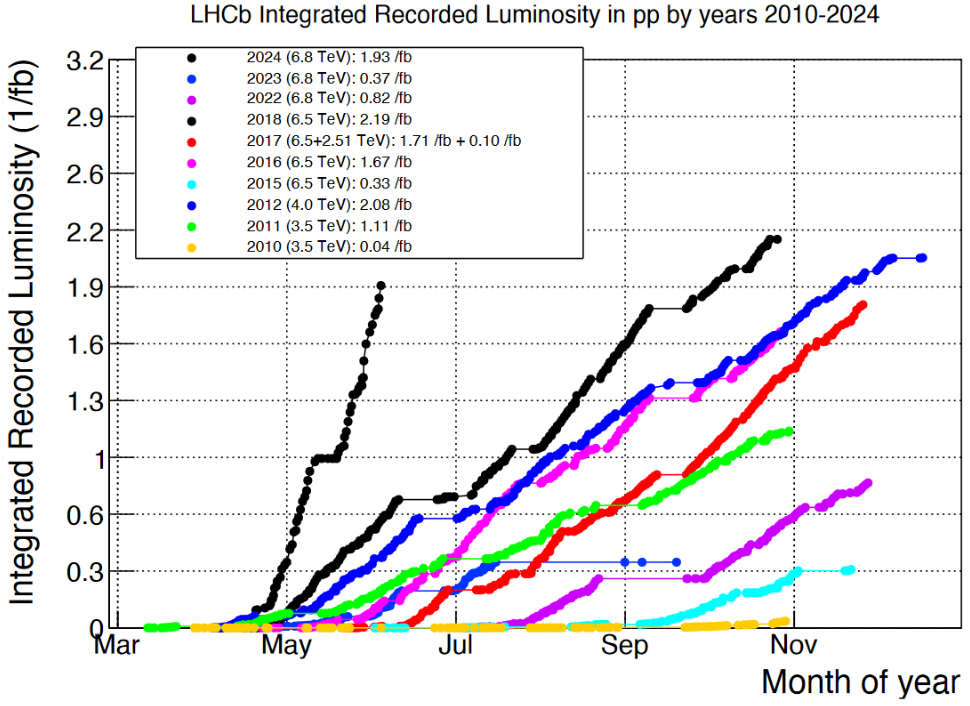
Run 3

$$L_{\text{inst}} = 2 - 4 \cdot 10^{32} \rightarrow 2 \cdot 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$$

Several detectors dedicated to luminosity operations:

- PLUME → Main Luminometer
- BCM (Beam Conditions Monitor)
- RMS (Radiation Monitoring System)
- Every other LHCb subdetector contributes with its own luminosity counters





Luminosity

$$\mathcal{L}_{\text{inst}} = \frac{\textbf{number of inelastic } pp \textbf{ collision /sec}}{\textbf{inelastic } pp \textbf{ cross-section}}$$

- In pratice need to consider the detector acceptance and efficiency, and the instantaneous luminosity over bunches is defined as

$$\mathcal{L}_{inst} = \frac{f_{LHC} \cdot \mu_{vis} \cdot n_{bb}}{\sigma_{vis}}$$

  - $f_{LHC} = 11245\ Hz$
  - μ_{vis} = number of visible interaction per event
  - σ_{vis} = visible cross-section
  - n_{bb} = number of colliding bunches in LHCb

Luminosity

- σ_{vis} and μ_{vis} depend on the acceptance and efficiency of the chosen counter (counter specific)
  - μ_{vis} is a ***relative luminosity measurement*** and it estimates the number of visible interactions / event. Can be determined using different methods

    - **Average**

$$\mu_{\text{vis}} = \frac{\sum_j^{\text{evts}} N_j}{N_{\text{evts}}}$$

    - **Log0**

$$\mu_{\text{vis}} = -\log\left(\frac{N_{\text{empty}}}{N_{\text{evts}}}\right)$$

    - PGF → make use of probability generating functions

$$\mu_{\text{vis}} = \log\left(\frac{\sum_j^{\text{evts}} z^{N_j}}{N_{\text{evts}}}\right), 0 < z < 1$$

  - σ_{vis} is an ***absolute luminosity measurement*** and it allows to obtain a luminosity value from the μ_{vis}. It's determined in LHCb using **Van der Meer** scan or **Beam Gas Imaging** method.

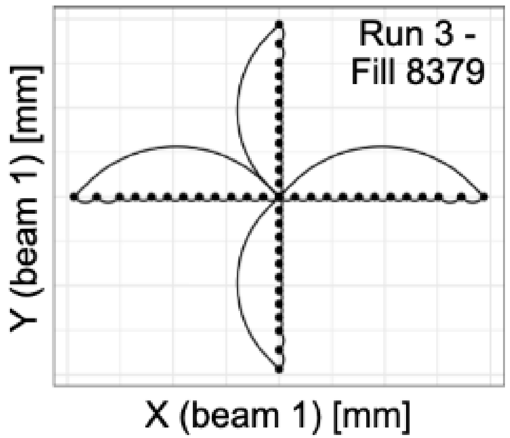
Precision at 1.47 % in Run 1 JINST 9 P12005
Main systematics sources: detectors effects, beam drifts, beam-beam effects, non-factorization

Absolute calibration: vdM

- Van der Meer principle: **scan beams** across one another to integrate out bunch profiles
  - Bunch populations from LHC instruments
- **Devoted fills in LHC** to move beams across transverse plane and measure the rates of collisions per step as a function of beam separation

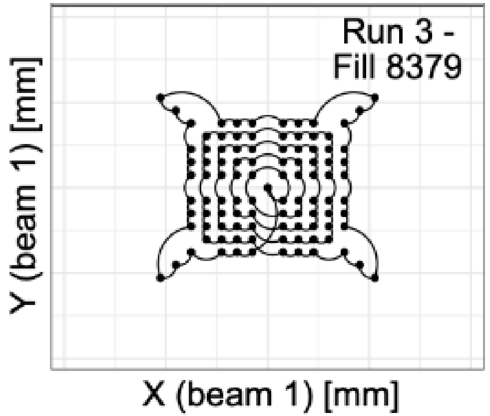
1D scan
Formula assumes factorizability → transverse betatron oscillations expected to be well decoupled in X and Y

$$\sigma_{\mathrm{vis}} = \frac{\int \mu_{\mathrm{vis}}(\Delta_x, \Delta_{y_0})\mathrm{d}\Delta_x \int \mu_{\mathrm{vis}}(\Delta_{x_0}, \Delta_y)\mathrm{d}\Delta_y}{N_1 N_2\, \mu_{\mathrm{vis}}(\Delta_{x_0}, \Delta_{y_0})}$$



2D scan
Non-factorization effects visible up to 2%

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



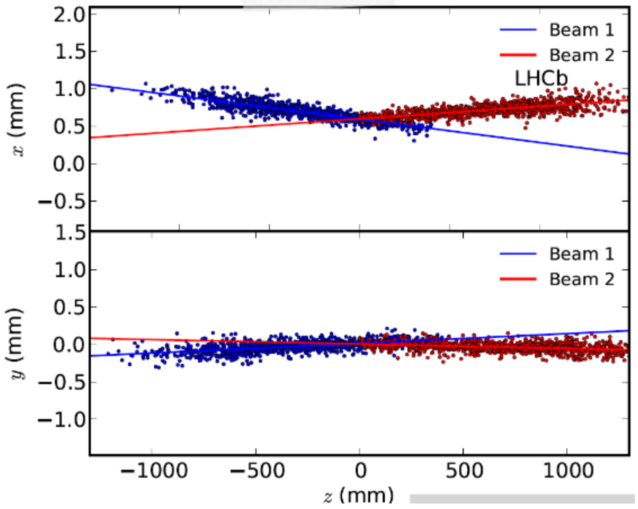
- $\mu_{vis}(\Delta x, \Delta y)$: average number of interactions per crossing as function of the separation in x and y
- Δ_{x0} , Δ_{y0} : beam separation
- $N_{1,2}$: bunch intensities

Absolute calibration: Beam-Gas imaging

JINST 9 (2014) P12005

Only in LHCb with help of SMOG (System for Measuring Overlap with Gas)

- Reconstruction of interaction vertices between beam and gas in beam pipe
- Allows the measurements of colliding bunches positions, shapes and beams crossing angles



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

Overlap integral assuming Gaussian bunches:

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

Dominant systematics: measurement spread, vertex resolution

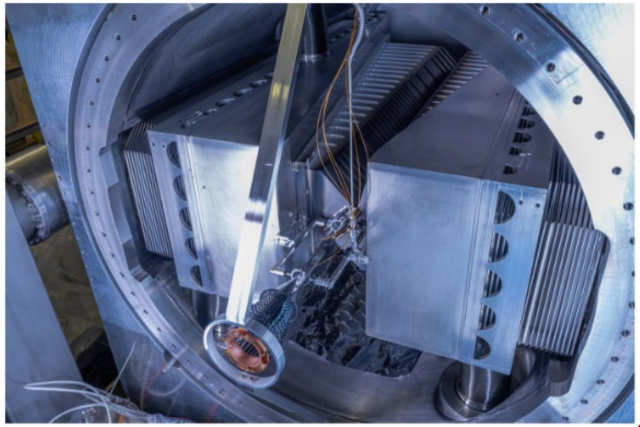
SMOG2 in Run3

Upgraded SMOG system with storage cell placed upstream nominal IP at z = [-500,-300] mm

- Gas density increased
- Separated luminous region from pp
- Gas targets

$H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$

Dedicated talk



Luminosity Counters

The Luminosity in LHCb is required to be measured with good accuracy both online (at least 10%) and offline (ideally < 2%)

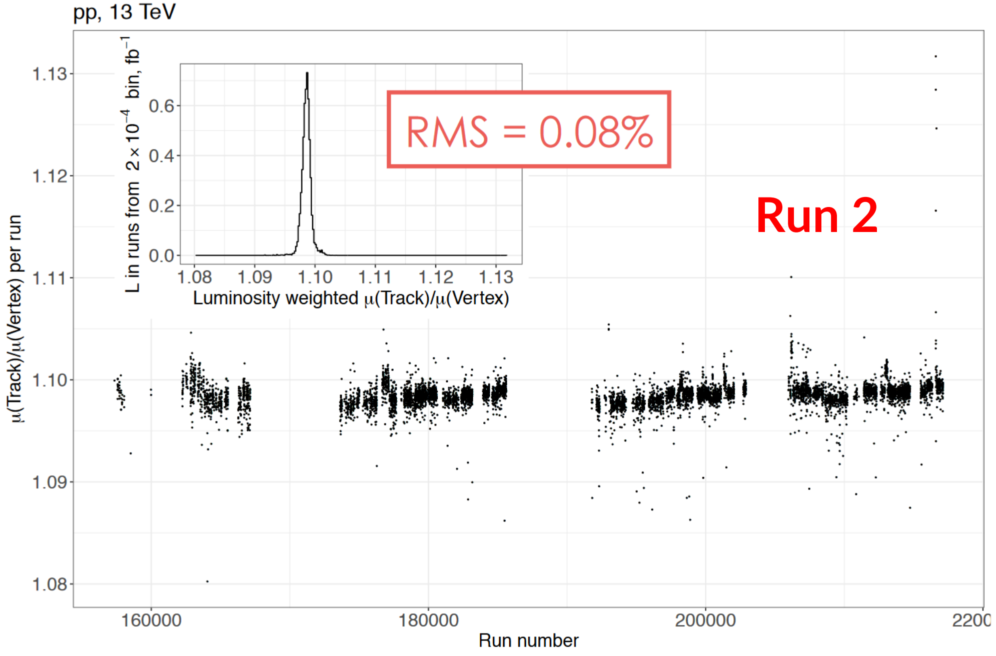
The subdetectors can provide **useful variables as counters** : **ratios** of different counters are useful for **stability checks**, **corrections** and to keep **systematics** under control

- Counters via Experiment Control System → cross-checks, backups and online monitoring in addition to PLUME
- High-level reconstructed variables → intended for offline analysis and online monitoring

Characteristics of a good Luminosity Counter:

- ✓ **linearity** vs luminosity
- ✓ **time stability**
- ✓ well known dependence on pile-up, spillover, bunch spacing…

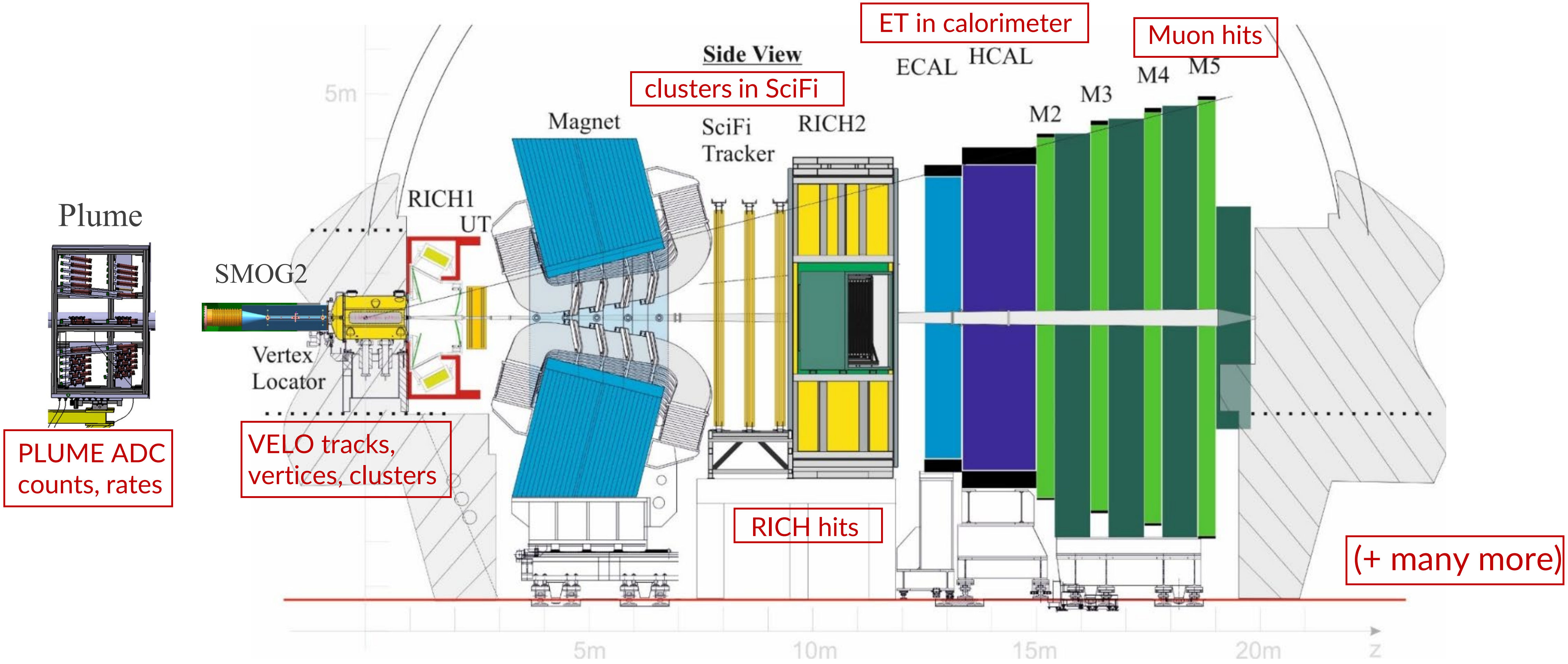
- In RUN 1-2 the most stable luminosity counters VELO (Vertex Locator) PVs and tracks in pp collisions



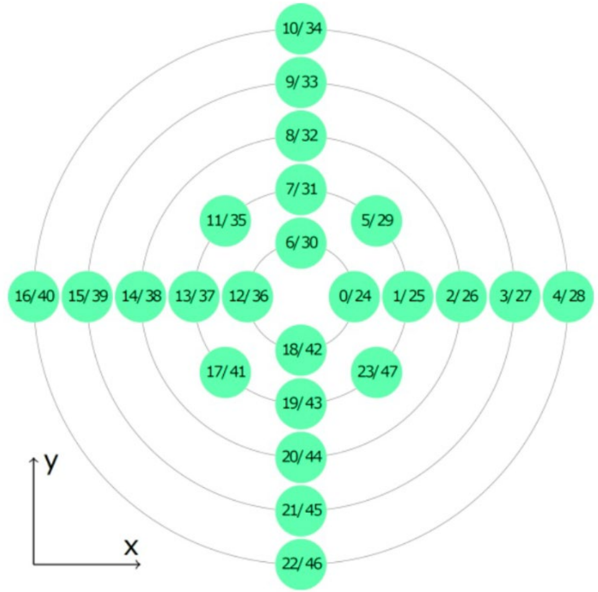
LHCb in Run 3

LHCb Run 3 Operation and Performance

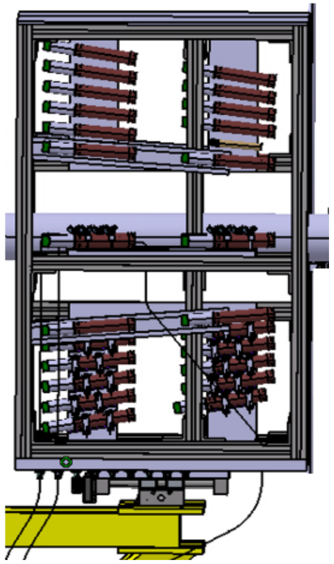
In Run 3, significant efforts to study linearity and propose new lumi counters from all subdetectors



PLUME
Probe for LUminosity MEasurement

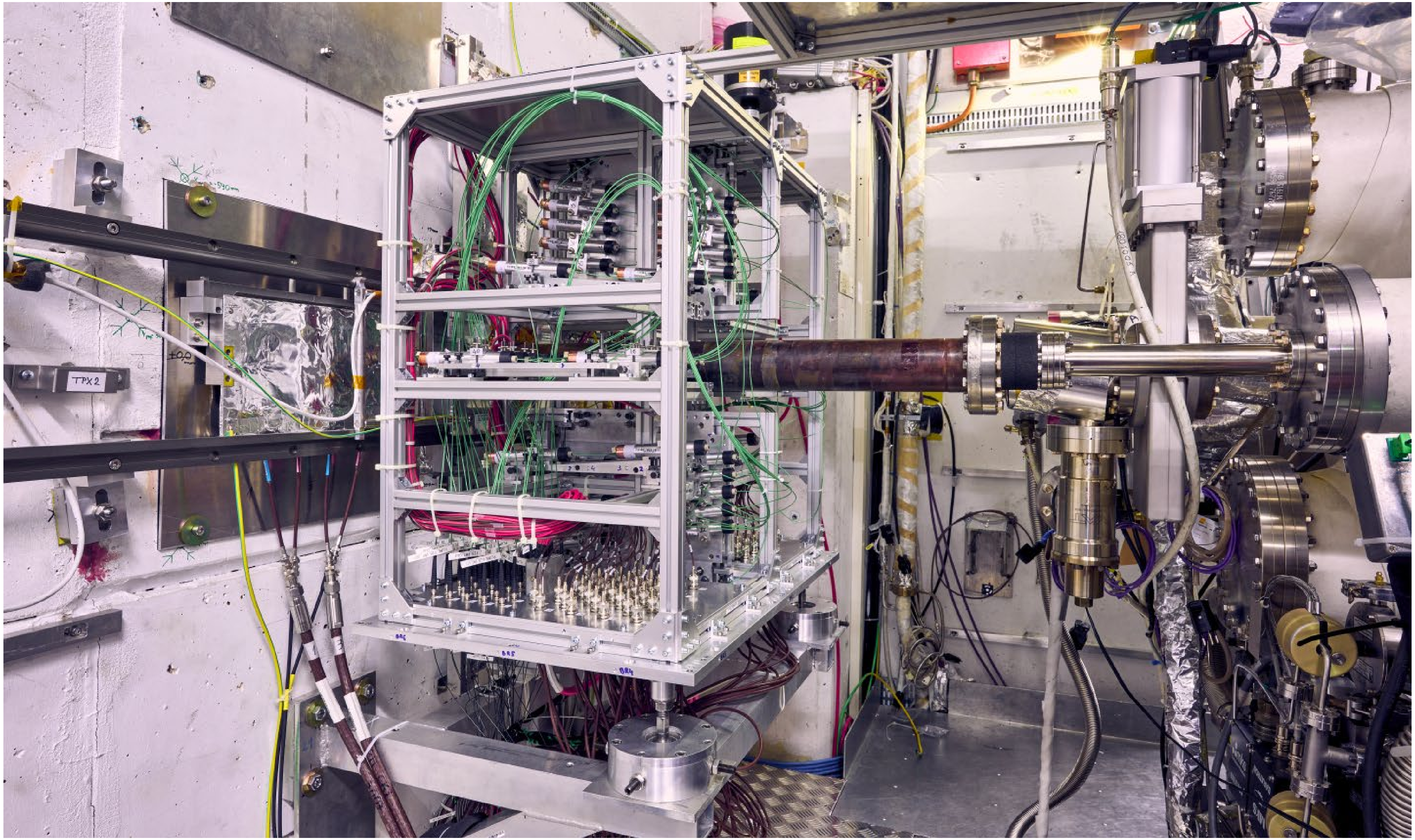


- **Dedicated** luminosity counter of LHCb
  - Hodoscope of $\mathbf{2 \times 24}$ **PMTs with quartz** tablet glued on the entrance window
  - Detection of **Cherenkov light** produced by particles going though the quartz
  - Mounted around the beampipe and **upstream** of the VELO



- Luminosity counters adopted by PLUME:
  - the sum of ADC counts for a single channel
  - number of events over a threshold for a single channel
- Instantaneous luminosity proxies computed for each bunch-crossing ID directly in firmware

PLUME



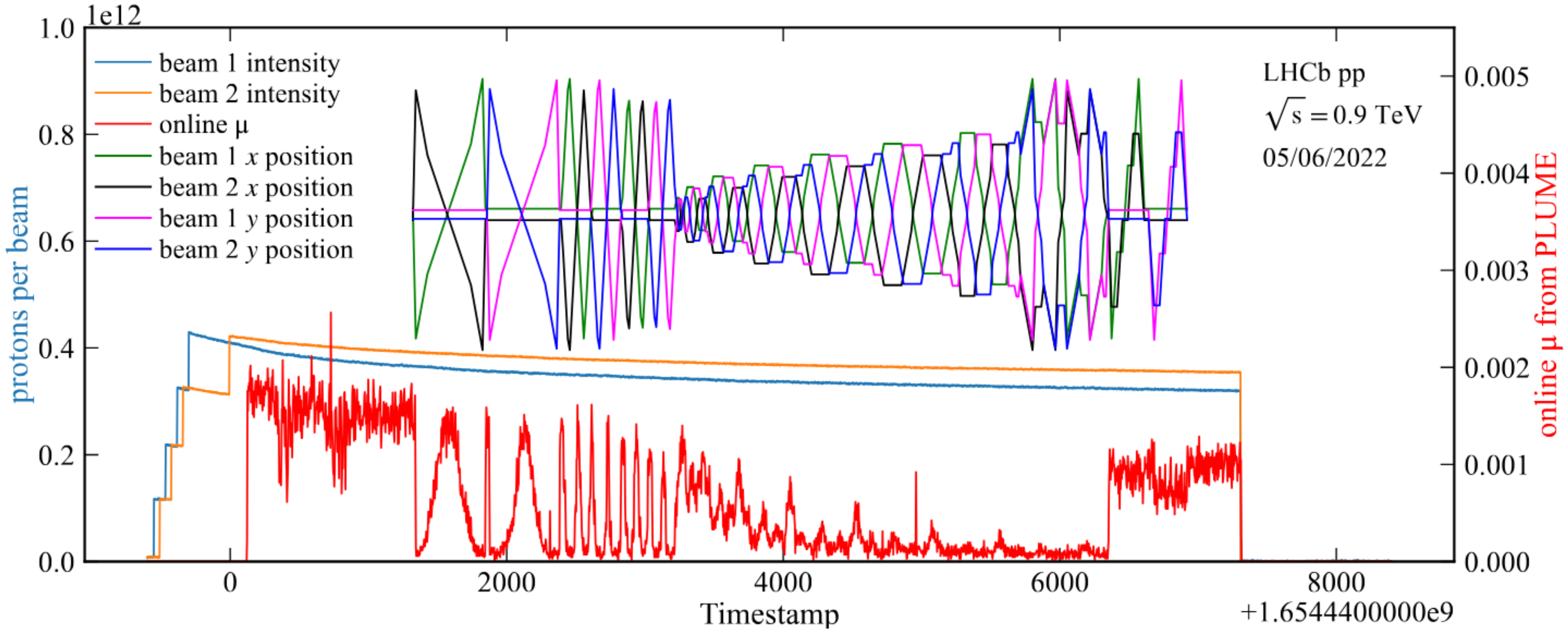
Absolute calibration: vdM

Commissioned in Run 3 also **Emittance Scans** (mini-vdM)

- Same optics of data-taking
- Higher luminosity and narrower beams
- Check linearity of counters to physics conditions
- Check time-stability of counters

Dedicated configuration:

- β^* = 24 m (2 m in standard data-taking)
  - “wider” beam, lower average number of visible interactions → $\sigma \sim \sqrt{\beta^*}$
- larger crossing angle needed to suppress satellite charge contributions

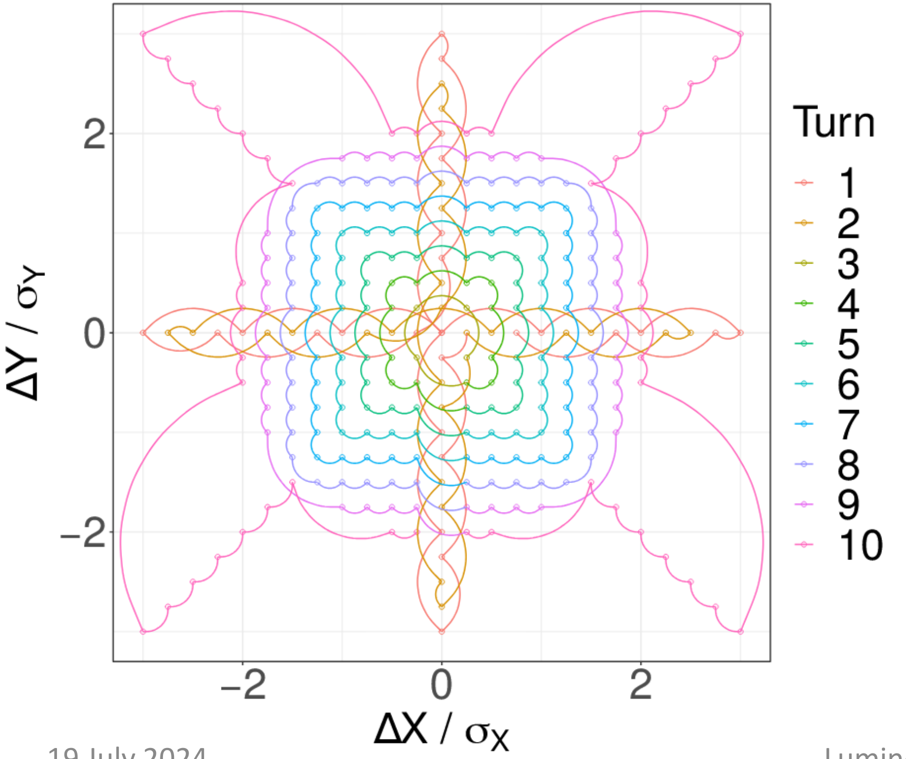


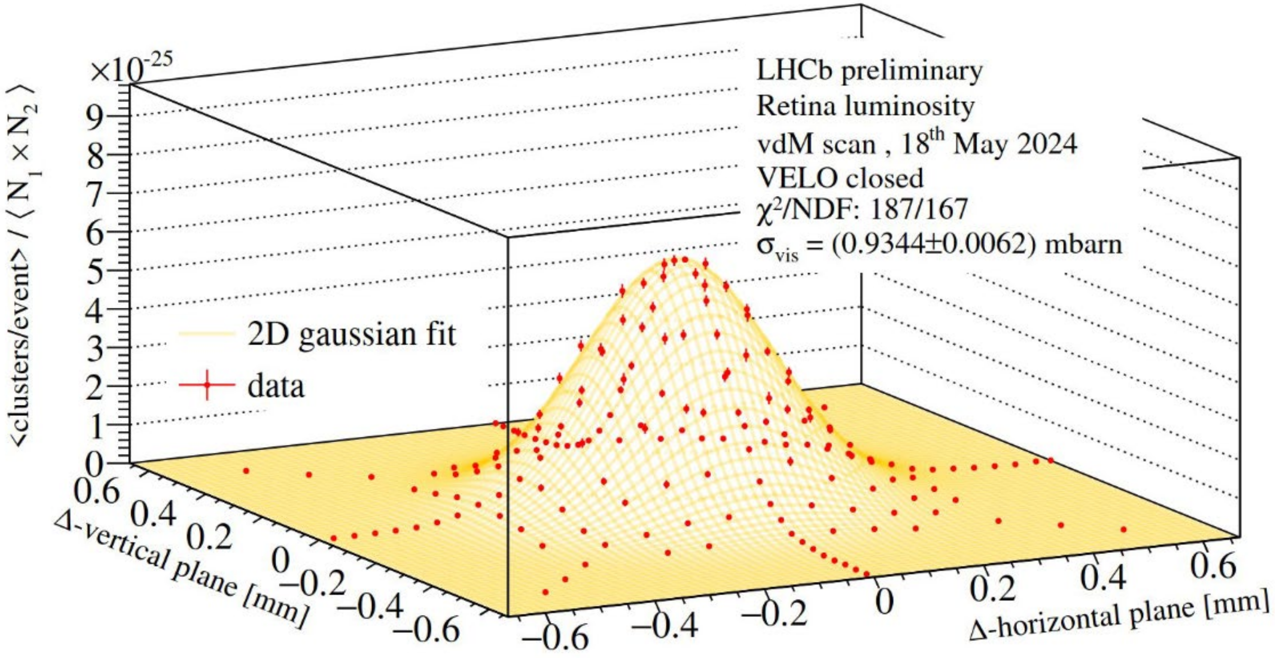
Absolute calibration: vdM

- **Usually,** vdM scans are performed once per year and per energy in dedicated LHC fills
- **2D scans** pioneered at LHCb in Run 2
  - Allows to fully **control bunch shape non-factorizability**

$$\sigma_c = \int \frac{\mu_c(\Delta x, \Delta y)}{N_1 N_2} d\Delta x d\Delta y$$

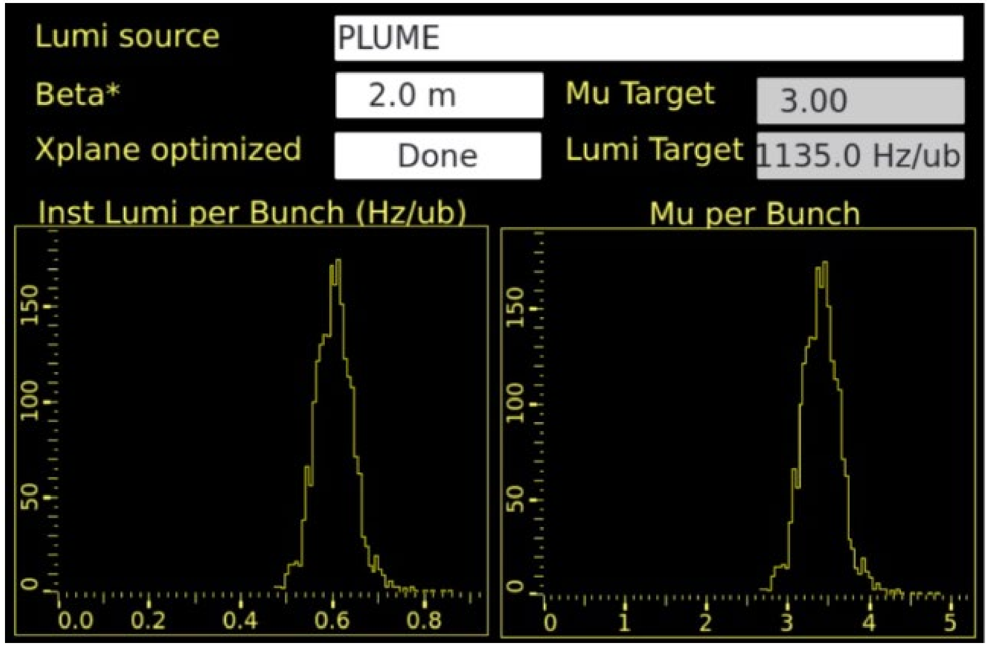
Most recent counters calibration achieved with **vdM on May 24**

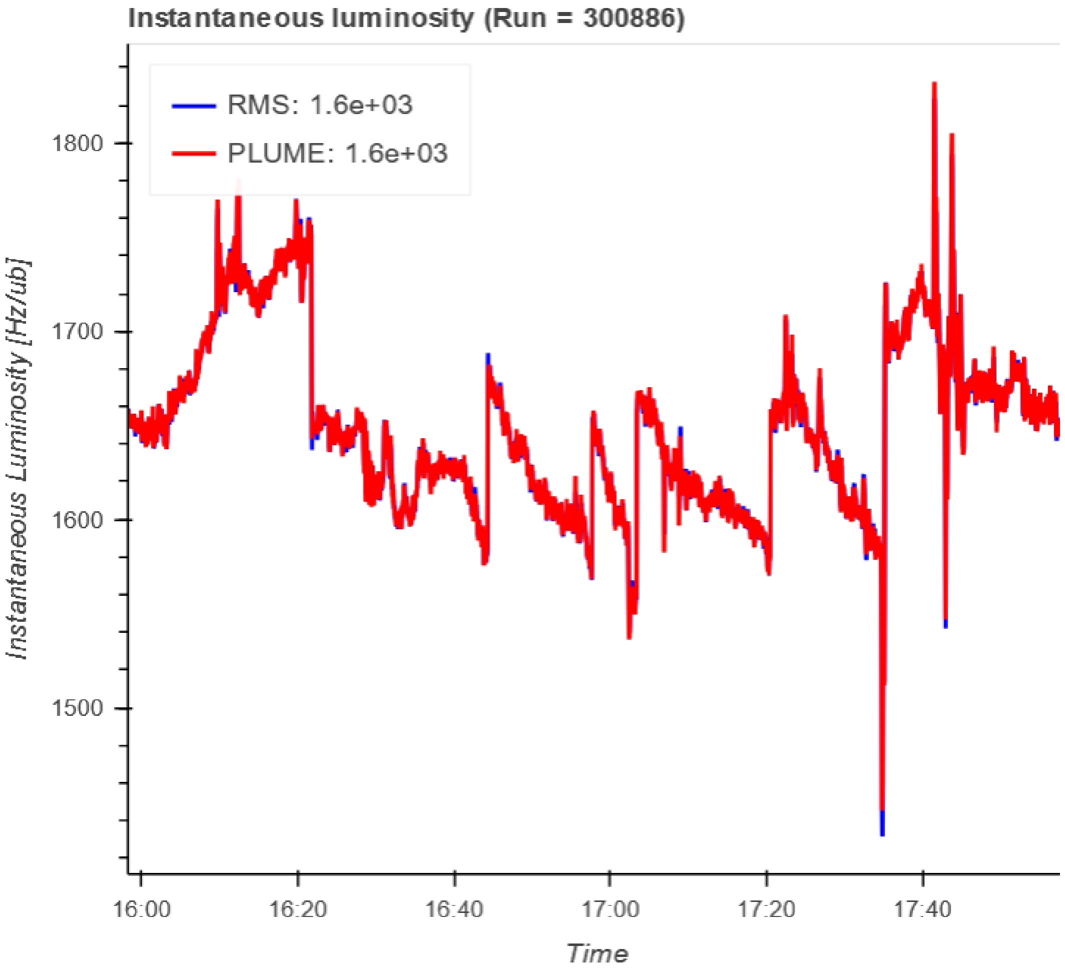




Real-time luminosity counters

- **PLUME** online luminosity **always provide, independently on the DAQ state**
  - **Luminosity per bunch crossing** for each PMT
- Luminosity values provided to the LHC every 2.4 seconds
- Radiation Monitoring System (**RMS**) is calibrated on PLUME and it acts as a **backup**

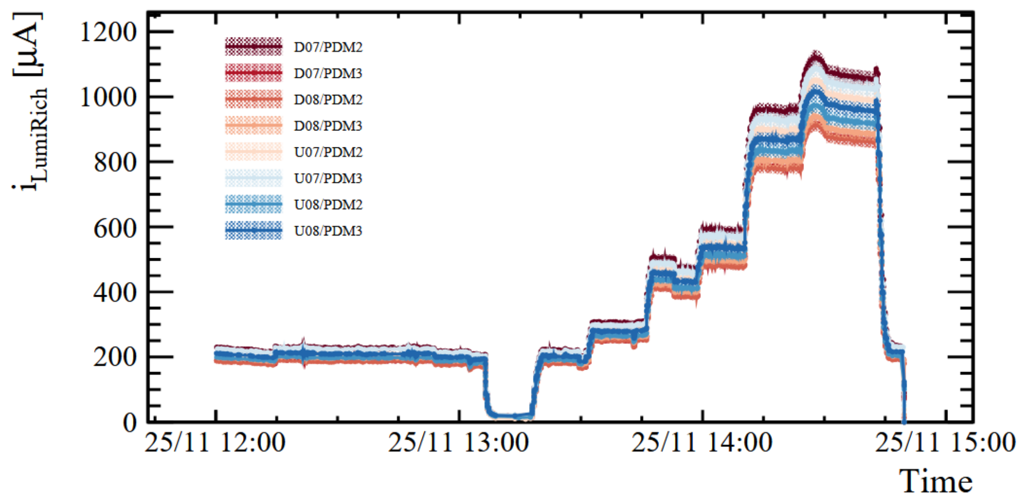




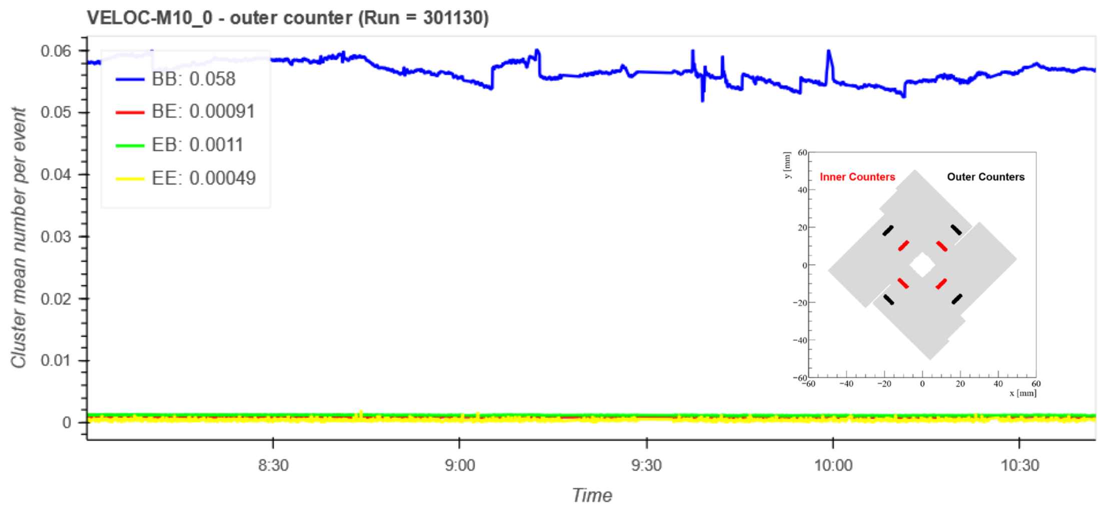
Real-time luminosity counters

Multiple proxies have been calibrated to provide online luminosity in addition to PLUME, some examples shown here

- VELO – Super Pixel Packet on ASIC, **number of Retina Clusters**
- SCIFI – number of clusters, HV currents
- RICH – **MaPMTs anode currents**
- MUON - MWPCs currents



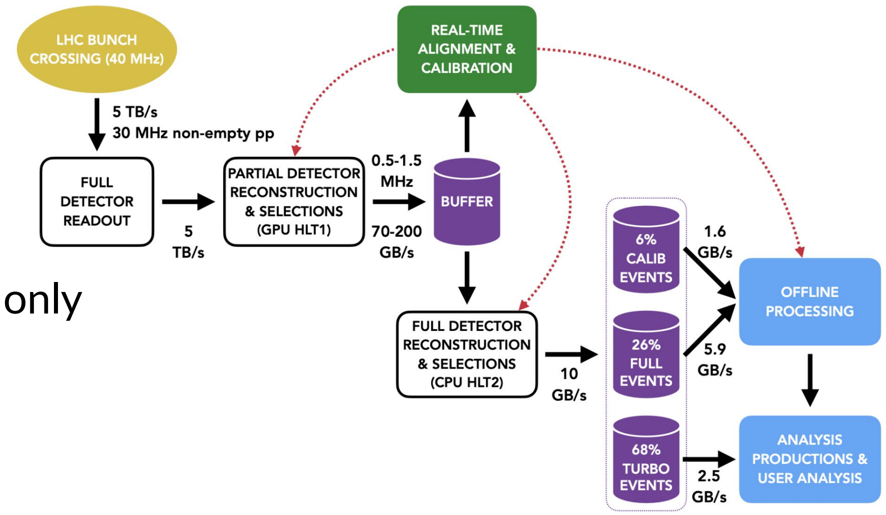
- Currents scale linearly with luminosity
- Integrated effect



VELO Retina ECS counters

- Implemented in firmware
- 8 counters on each of the 26 VELO stations
- Running average luminosity measured via both average and log0 method for inner and outer regions
- Cluster counts are divided by bunch-crossing type

Offline Luminosity



- Measure a rate R of interactions per bunch crossing in small lumi-events containing only luminometers
- The events are selected with a random trigger to get unbiased samples
- We collect luminosity counters for offline analysis into dedicated lines:

  - first-level reconstruction (online in Run 3)
    - Basic lumi line: fires by every lumi event, only “essential” counters → 30 kHz rate
    - Extra line to host a much larger collection of counters → 1 kHz rate

  - second-level reconstruction
    - Adds variables on top of the 30 kHz line

- Beam-beam, beam-empty, empty-beam and empty-empty bunch crossing are selected for detailed studies

Some counters per subdetectors:
- PLUME - ADC over threshold
- VELO - clusters, vertices and tracks
- ECAL - energy
- SCIFI - hits
- MUON - hits
- RICH - hits

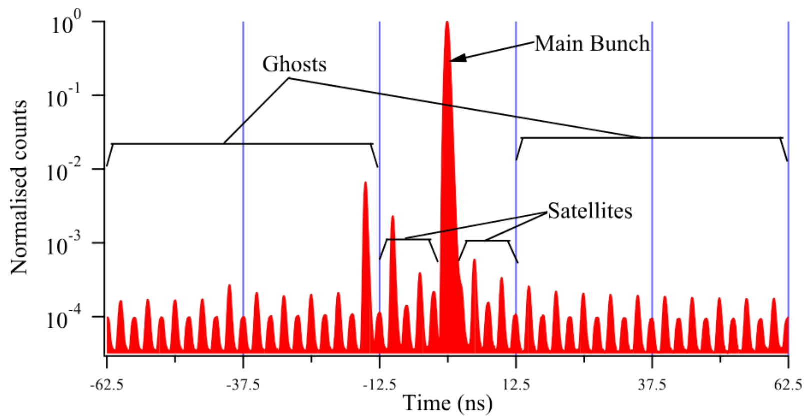
Ghost Charges

LHC ring dived in 3 564 slots space by 25 ns, made of 2.5 ns RF buckets

- Bunch populations ($N1$, $N2$) from LHC transformers are crucial for absolute luminosity for all LHC experiments
- **Satellite charge**: in filled bunch slot, outside filled RF bucket (2.5ns)
- **Ghost charge**: circulating in LHC, outside filled bunch slots (25ns)

The charges outside the filled buckets must be carefully analyzed and subtracted

CERN-ATS-Note-2012-029

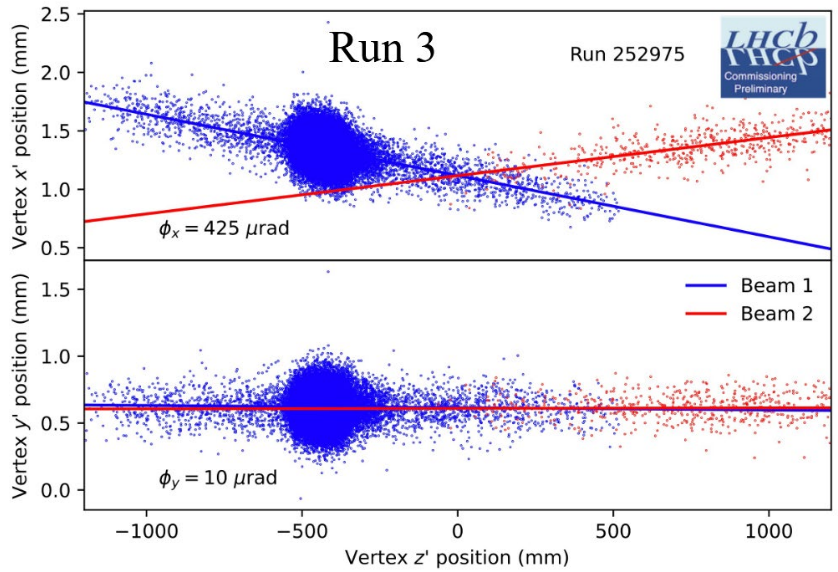


Beam Synchrotron Radiation Telescope (BSRL):
- measure synchrotron photons with 90 ps resolution
- can measure satellite and ghosts

The LHCb experiment can provide **complementary measurements** of the **ghost charge** fraction through beam-gas imaging (BGI) by measuring the rate of beam-gas interactions per-beam in nominally empty bunch slots:

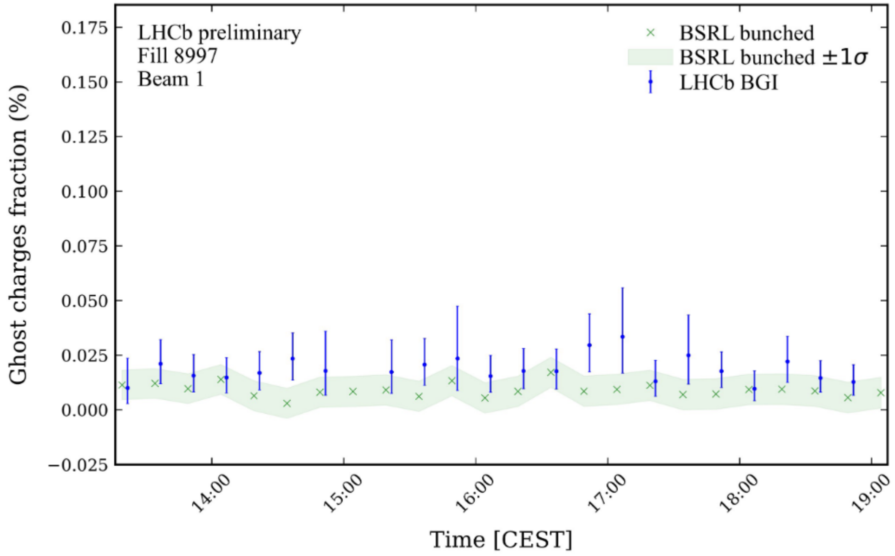
- **SMOG injected** to enhance interaction of ghost charges
- Number of beam-gas interactions of the bunch is **proportional to the charge** (of the bunch)

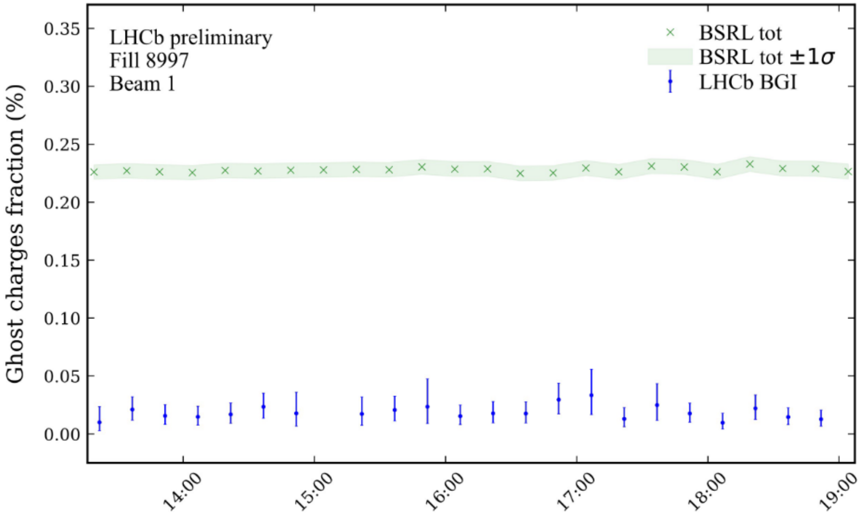
$$f^{1(2)}_{\text{ghost}} \approx \frac{I^{1(2)}_{\text{ghost}}}{I^{1(2)}_{\text{filled}}} = \frac{N^{1(2)}_{ee+eb(be)}}{N^{1(2)}_{be(eb)}} \frac{I^{1(2)}_{be(eb)}}{I^{1(2)}_{bb+be(eb)}} \frac{1}{\varepsilon^{1(2)}_{\text{trigger}}}$$



Ghost Charges in LHCb - Results

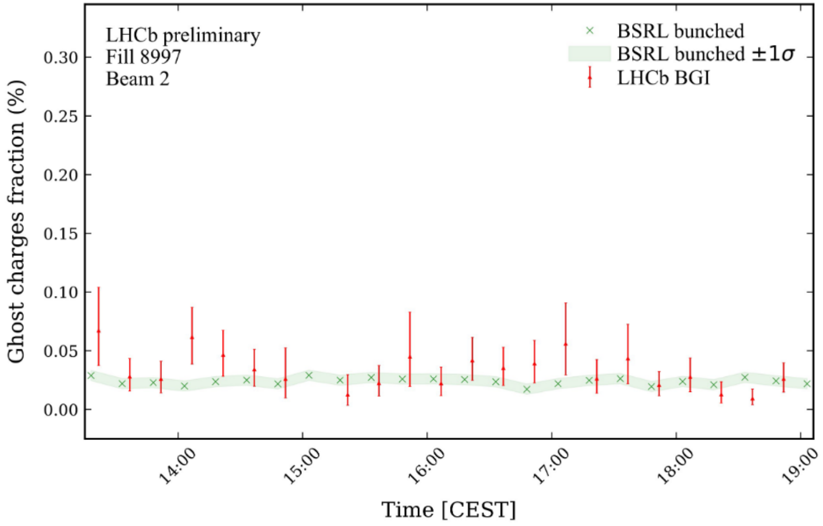
- **Result compatible with BSRL bunched measurement**
- Same order of magnitude as November 2022 measurement → LHCb-FIGURE-2023-003

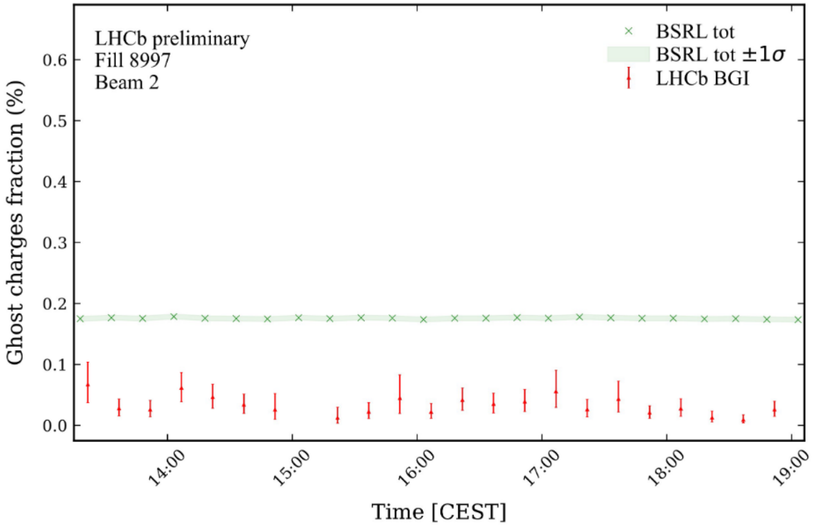




LHCB-FIGURE-2024-001

- Confirm **ghost fraction to be negligible for vdM calibrations** and well below percent level





Conclusions

- LHCb: almost **entirely new detector for Run 3** → large availability of good counters to measure luminosity
- All relevant **counters** are **calibrated in Run 3 using vdM scan** (1D and 2D)
- **PLUME fully operative and continuously providing average and per-bunch crossing luminosity** to LHC as main LHCb luminometer

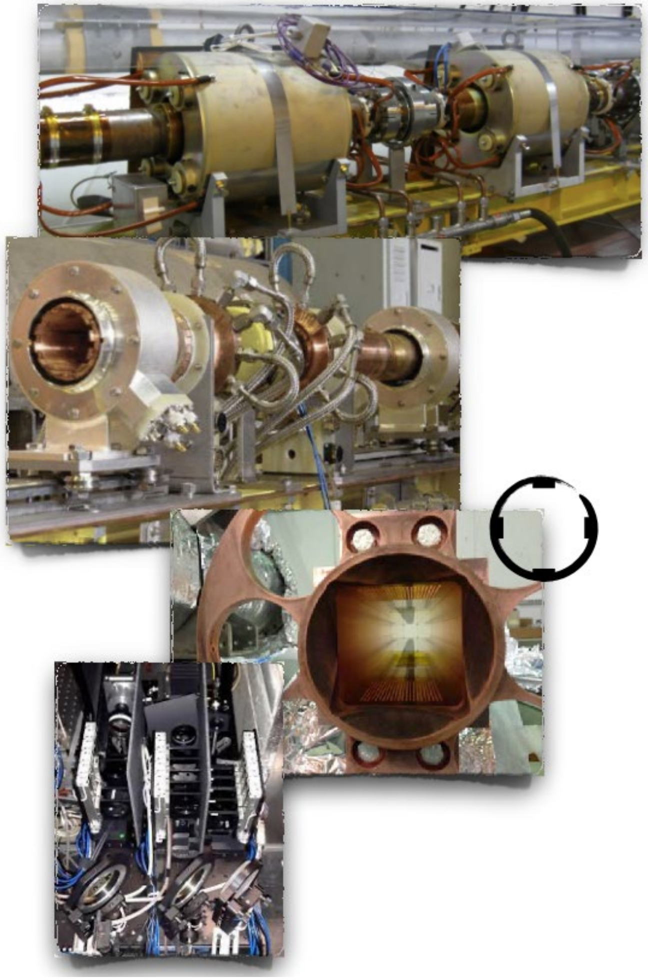
- **Ghost charge fraction measurement using BGI** in agreement with previous measurement

- Reliable and efficient infrastructure for LHCb Run 3 luminosity.
- Expected soon:
  - Offline analysis with new luminometers for 2024
  - Absolute calibration with BGI method

Spares

LHC instruments

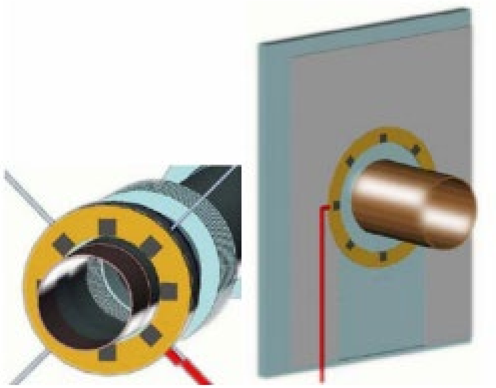
- DCCT (Direct-Current Current Transformer):
  - Measures the total number of charges per beam
- FBCT (Fast Beam Current Transformer):
  - Measures the relative bunches intensities
- BSRL (Beam Synchrotron Radiation - Longitudinal):
  - Measures longitudinal distribution of charges with high dynamic range to quantify the population in nominally empty buckets
- DOROS (Diode ORbit Oscillation System):
  - Beam Position Monitor (improved readout) around interaction points

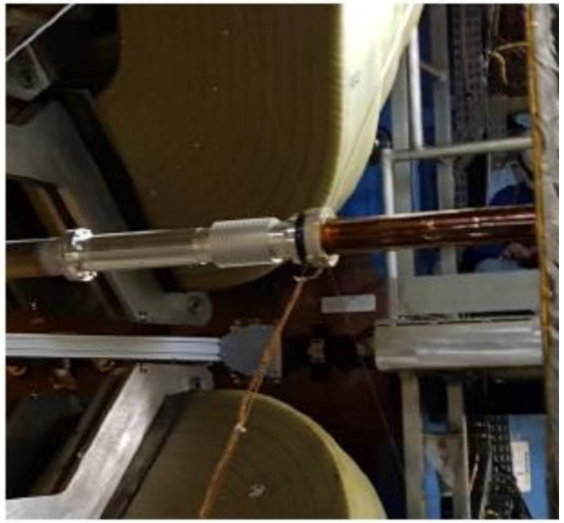


Beam Conditions Monitor – BCM

BCM-U

- Made of 8 diamond sensors and measures the particle flux
- Crucial role for LHCb safety since it’s used to dump the beam





BCM-D

Radiation Monitoring System - RMS

Four pairs of sensor (MDF technology) around the beam pipe
Measures rate of MIPs, readout every 1s

- Relative luminosity measurement $R_{RMS} \propto \mathcal{L}_{inst}$
- Beam and Background monitoring
- Relative IP location
- Operating stably in Run 3