Luminosity determination at LHCb during Run 3

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How to measure the instantaneous luminosity

- Instantaneous luminosity: $L_{inst} = \frac{\mu_c}{\sigma_c} \cdot N_{bb} f_{LHC}$
- μ_c is the visible number of interactions **(counter specific)** per bunch crossing
  - Can be obtained from logZero, average or PGF methods
  - It's a **relative luminosity measurement** → if μ_c doubles, the luminosity doubles (provided the counter is linear), but no info on the absolute scale
- σ_c is the cross section for a given process **(counter specific)**
  - Needs to be calibrated from van der Meer (vdM) or beam-gas imaging (BGI) → converts the relative measurement to an absolute measurement
  - Measured in dedicated fills, typically O(1) time per year, beam type and $\sqrt{s}$
- N_{bb}: number of bb crossings
- $f_{LHC} = 11245\ Hz$

logZero

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

average

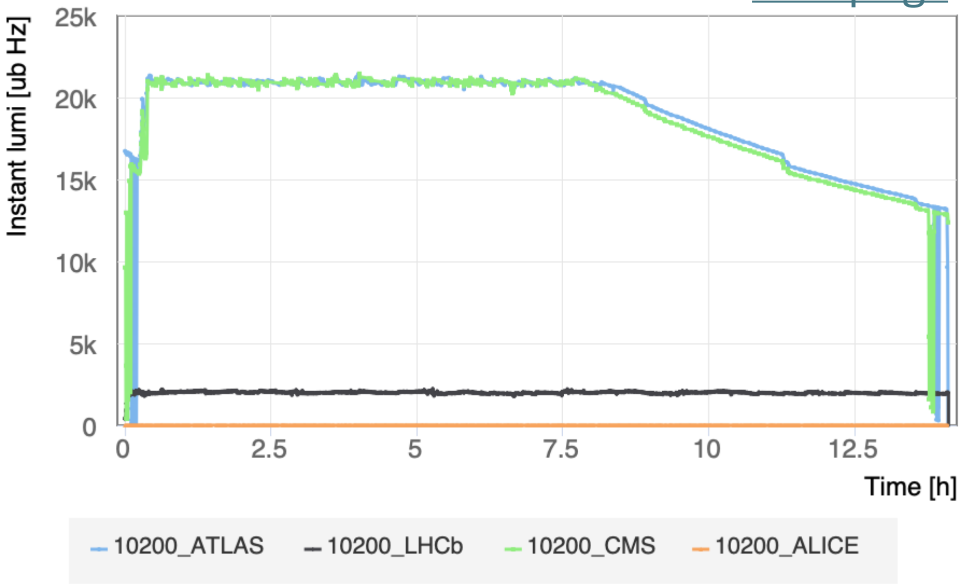
$$\mu_{\mathrm{vis}} = \frac{\sum_j^{\mathrm{evts}} N_j}{N_{\mathrm{evts}}}$$

Luminosity at LHCb

- Precise online luminosity determination is of **paramount importance for LHCb**
  - Real-time luminosity needed to ensure luminosity levelling in LHCb
  - Monitor beam conditions to ensure detectors safety
- Offline luminosity determination fundamental for physics analyses
  - It usually represents one of the main source of systematics (1.16% in Run 1) for absolute cross-section measurements

Instantaneous Fill Lumi

LPC page



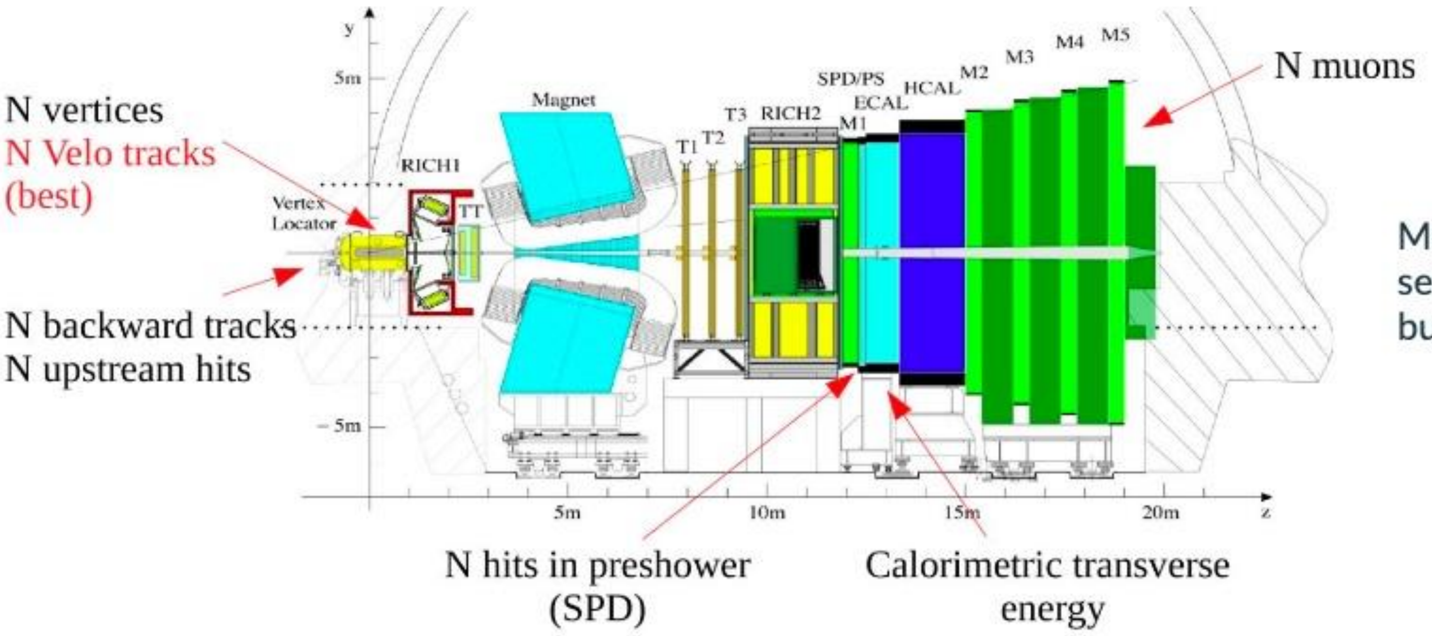
JHEP01(2016)155

$$\sigma_{W^+\to\mu^+\nu} = 1093.6 \pm 2.1 \pm 7.2 \pm 10.9 \pm 12.7 \text{ pb},$$
$$\sigma_{W^-\to\mu^-\bar{\nu}} = 818.4 \pm 1.9 \pm 5.0 \pm 7.0 \pm 9.5 \text{ pb},$$
$$\sigma_{Z\to\mu^+\mu^-} = 95.0 \pm 0.3 \pm 0.7 \pm 1.1 \pm 1.1 \text{ pb},$$

Uncertainty due to luminosity

[JINST 7 P01010, JINST 9 P12005]

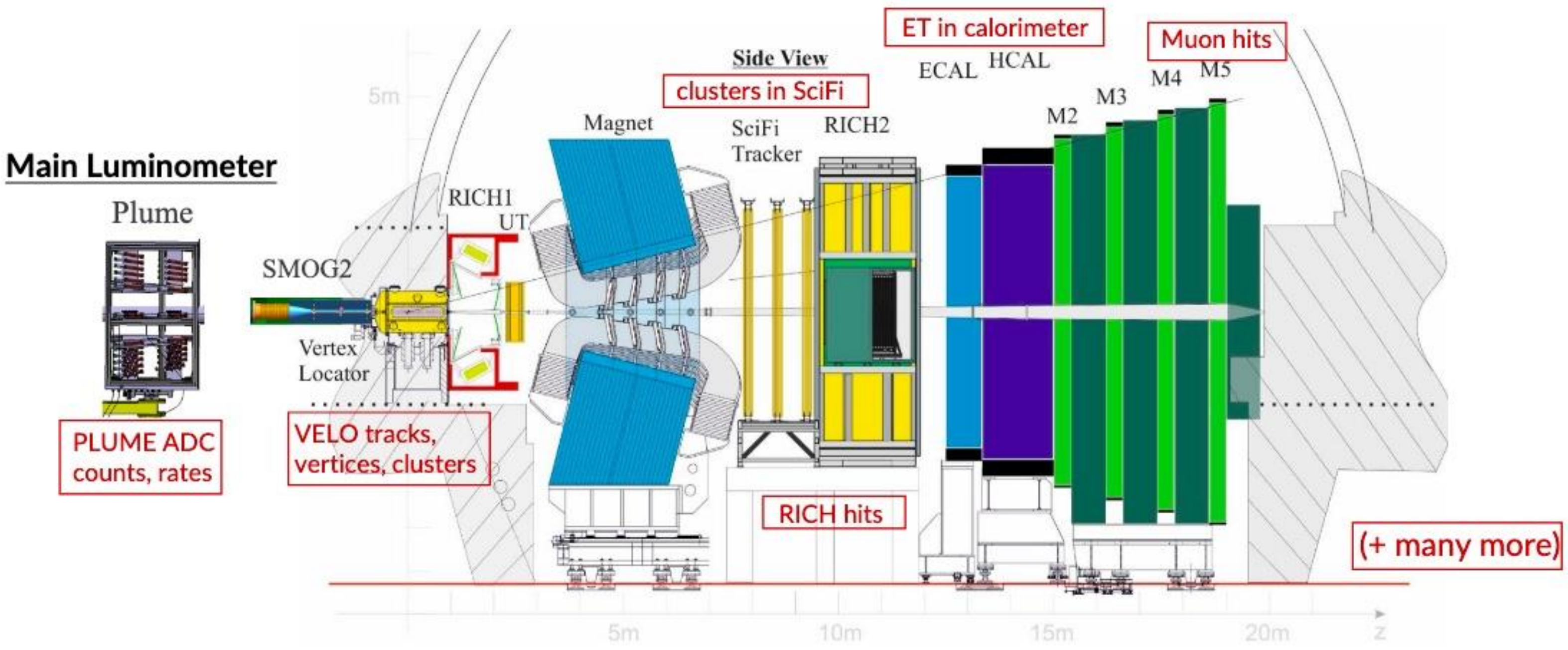
LHCb luminometers in Run 1 and 2



Many luminometers from several sub-detectors, but no dedicated system

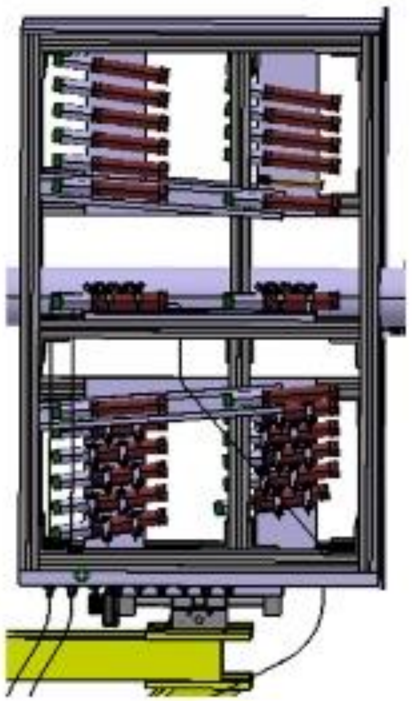
- Online luminosity: based on transverse energy measured by calorimeter L0 trigger boards
- Offline luminosity: mainly based on Vertex Locator (VELO reconstructed) quantities (tracks: smaller dependence on the luminous region z-position/width, vertices: low beam-gas background) and on the beam-gas imaging (BGI) method
- Luminosity precision: 1.16% (Run 1), main systematic uncertainties: overlap integral non-factorizability, beam orbit drifts, beam-beam interaction

LHCb luminometers in Run 3

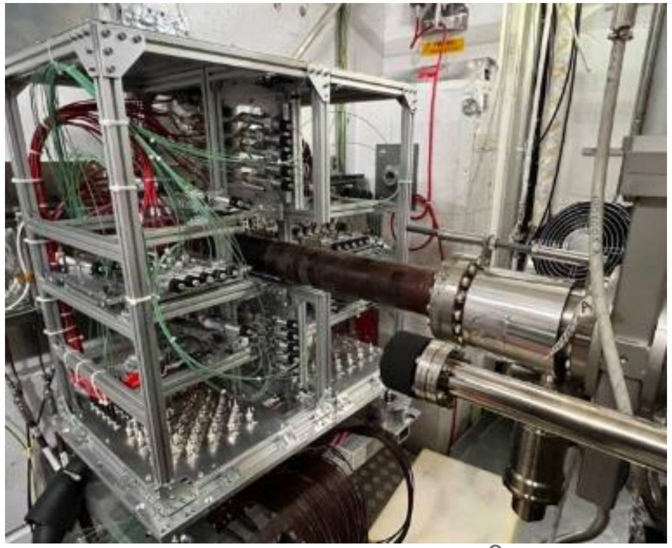


- Deployment of a dedicated luminometer: PLUME
- Significant efforts to study linearity and propose new luminosity counters from all subdetectors
- Potentially ~ 350 different counters for cross-check and systematics studies, many of them able to provide online luminosity too

Probe for LUminosity MEasurement (PLUME)

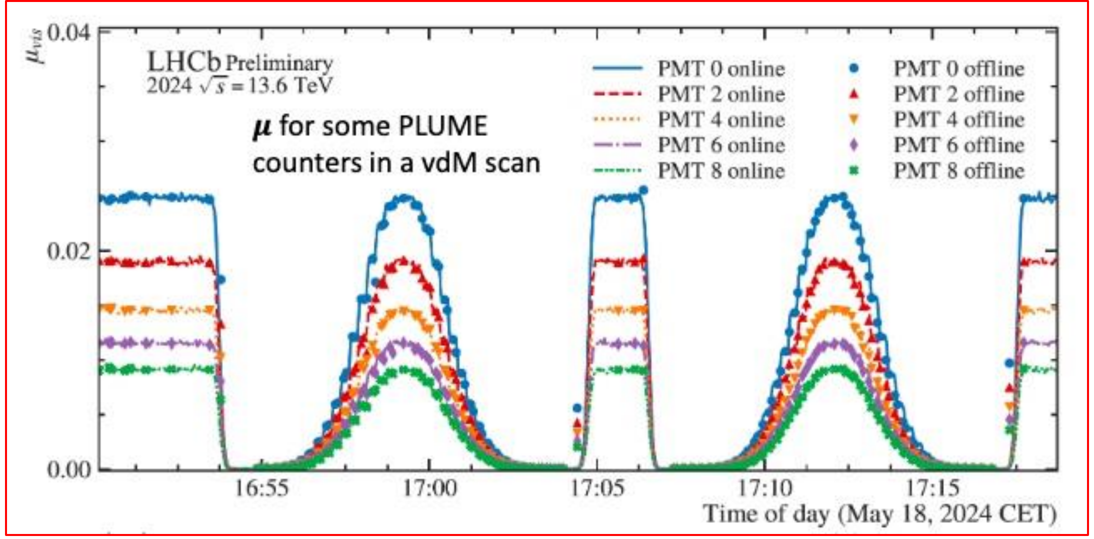


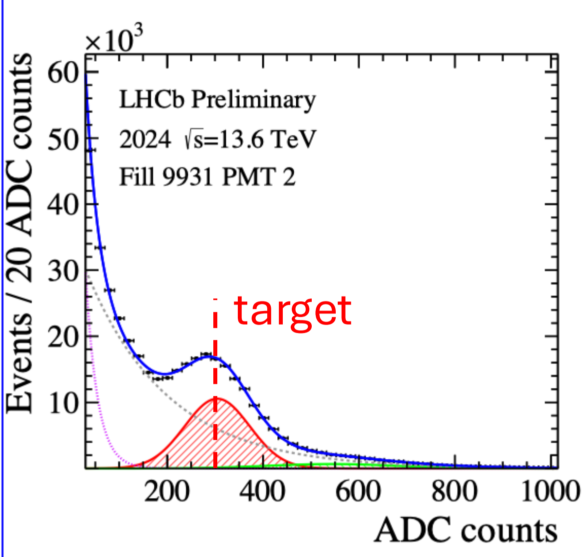
- Dedicated luminosity counter of LHCb
  - Hodoscope of 22 x 2PMTs R760 from Hamamatsu with quartz tablet glued on the entrance window
  - Detection of Cherenkov light produced by particles going through the quartz
- Mounted around the beampipe and upstream of the VELO
- Online counters implemented directly in the LHCb readout board firmware for each PMT and bunch crossing
- Data collected also by the High-Level Trigger (HLT) and stored on disk for precise luminosity determination
- Measure luminosity by counting the number of over threshold events (logZero) or with the average of ADC counts in each PMT → 44 independent measurements, then combined

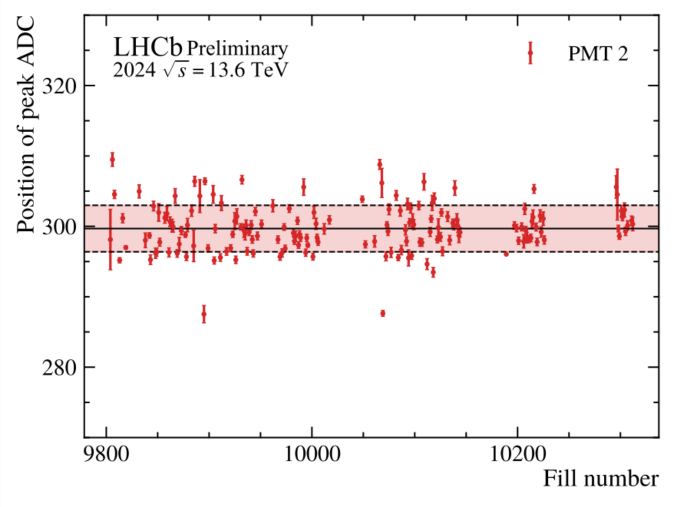


PLUME during 2024 operation

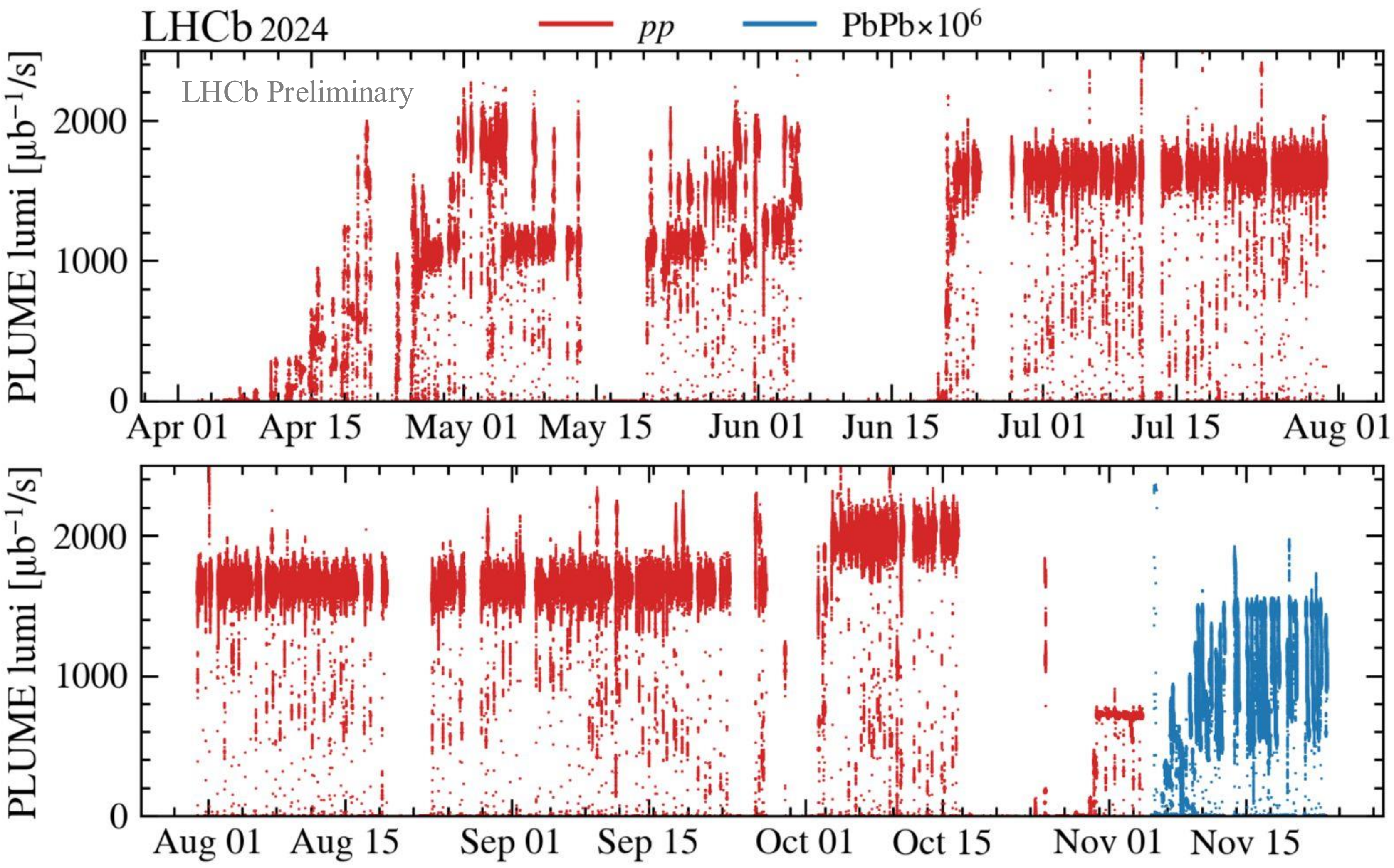
- Fast calibration (~ 2 days after the vdM) with online counters, validated with offline data from HLT shortly after
- Gain adjustment routine exploiting ADC histograms from LHCb monitoring system
  - Fits to the ADC distributions
  - Check average of peak due to particles impinging quasi-perpendicularly on the PMTs and keep it at 300 ADC counts
  - Gain stability kept around 1% throughout the year







2024 in a nutshell

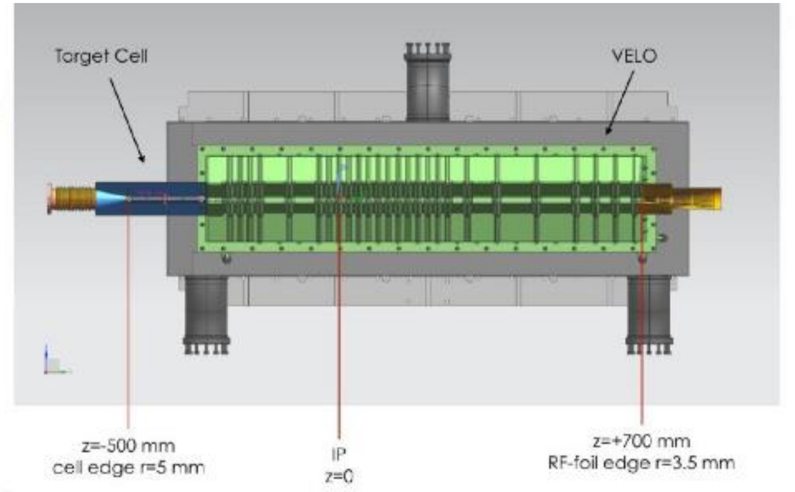


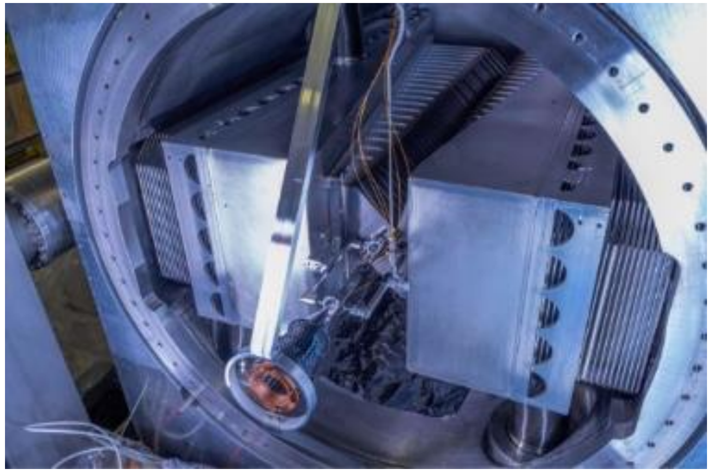
Challenges during data-taking

- During data taking in LHCb, the injection of the gas in the SMOG2 cell has become a 'standard' procedure
  - Parallel pp and p-gas data taking operation
- Due to this, we usually deal with a beam-empty (or empty-beam for PLUME) 'background' which is non-negligible
- Background subtraction formula takes into account also beam populations in different beam crossing types

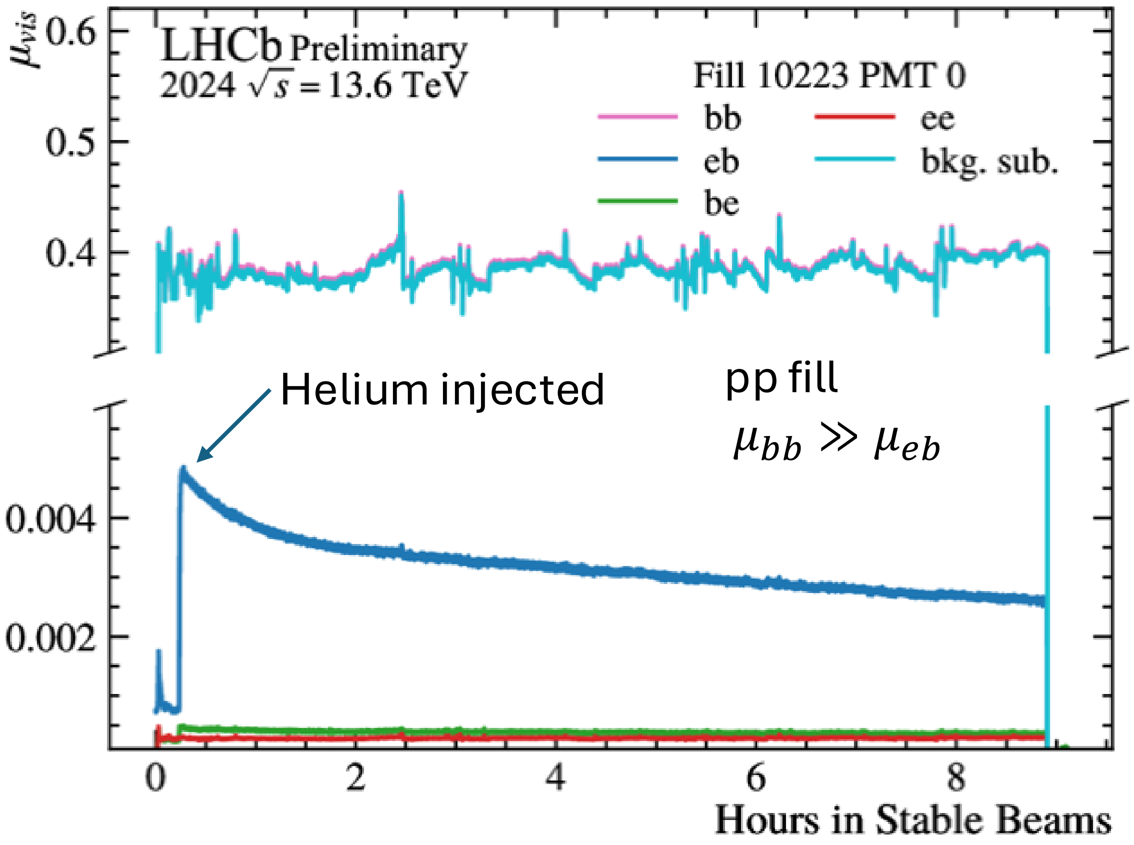
$$\mu_{bkg.sub.} = \mu_{bb} - \frac{\langle N_{bb}^{beam1} \rangle}{\langle N_{be}^{beam1} \rangle}\mu_{be} - \frac{\langle N_{bb}^{beam2} \rangle}{\langle N_{eb}^{beam2} \rangle}\mu_{eb} + \mu_{ee}$$

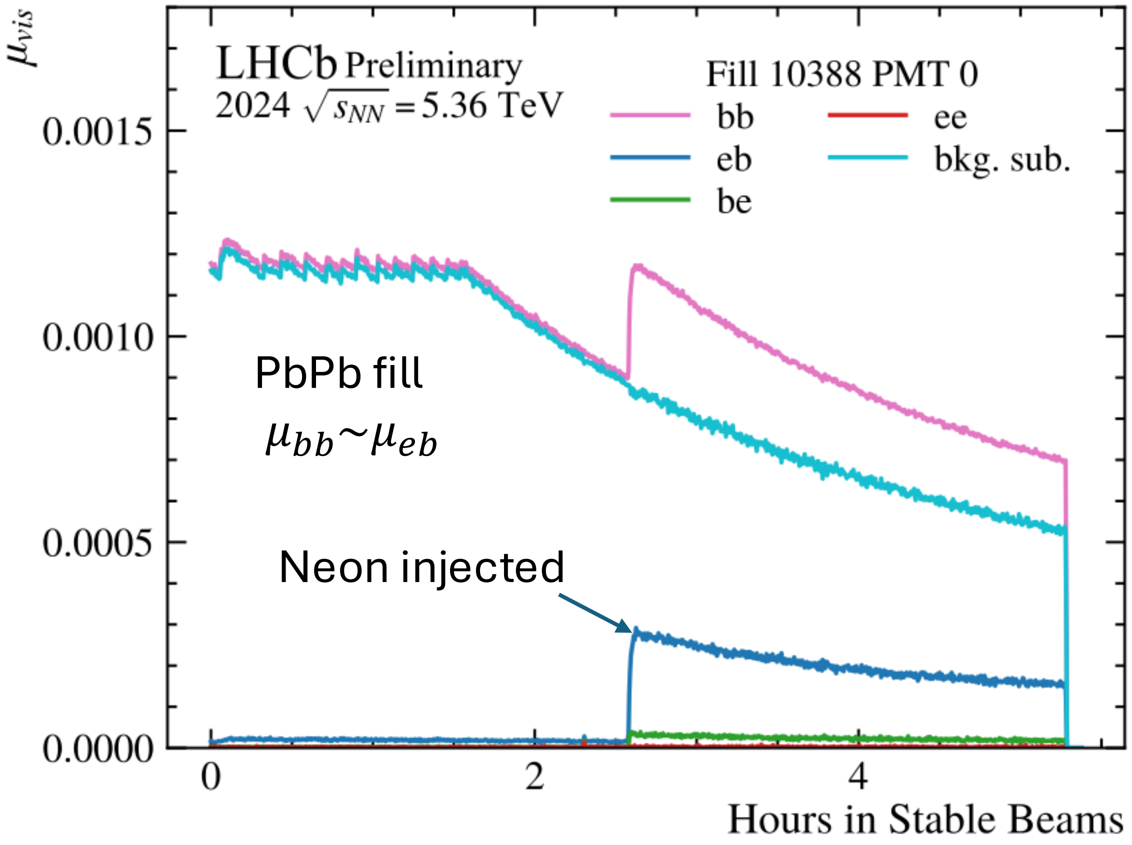
- Weighting the background subtraction with the bunch population has a significant effect when $\mu_{bb} \sim \mu_{be} (\mu_{eb})$ during ion runs





PLUME background subtraction

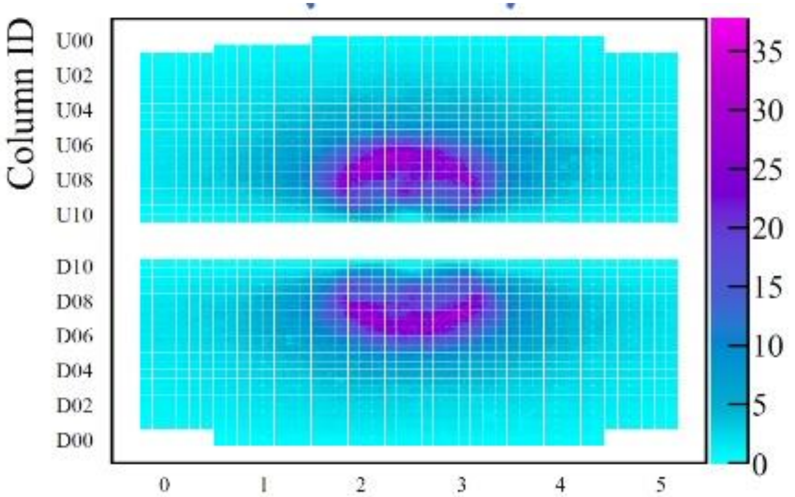




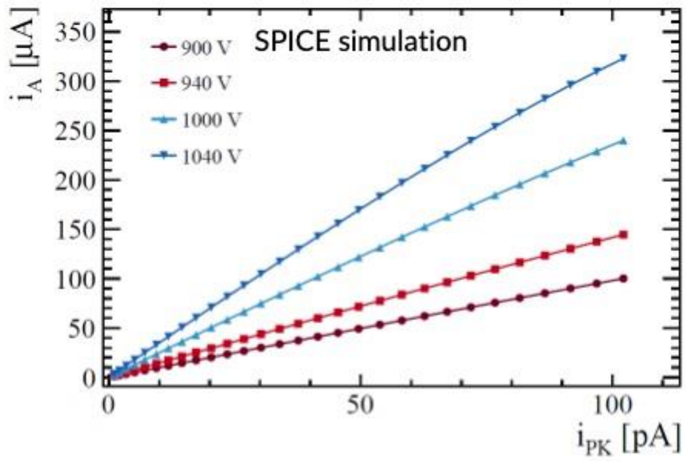
- Take home message: background subtraction is really important during ion runs
- Imperfections up to 7% in the subtraction observed for heaviest gases, work ongoing to understand them

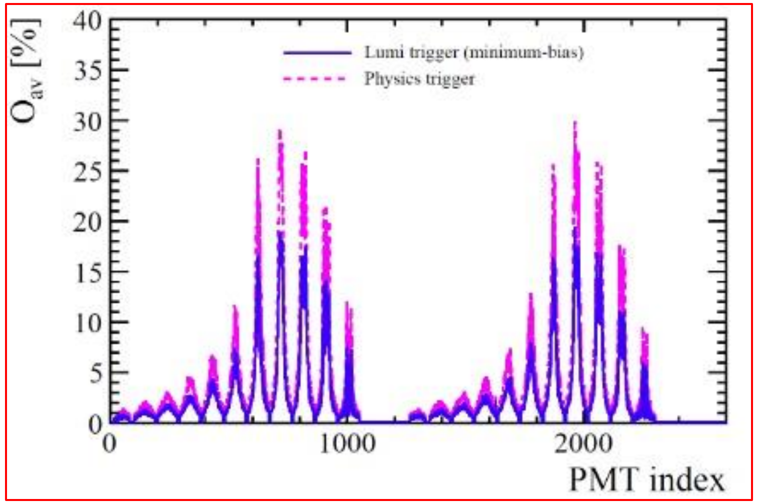
Luminosity with the Ring-Imaging Cherenkov (RICH) detectors

- RICH planes adopt MultiAnode Photomultipliers (MaPMTs)
- Occupancy up to 30% in the high-occupancy region or RICH 1
- Dedicated procedure implemented to maintain a constant gain
  - MaPMTs are operated by using a powering scheme involving the bias of the last of the twelve dynodes
  - Compensates the voltage drop induced by the anode current at high rates
  - Last dynodes in monitoring mode during RAMP and switched on at SQUEEZE



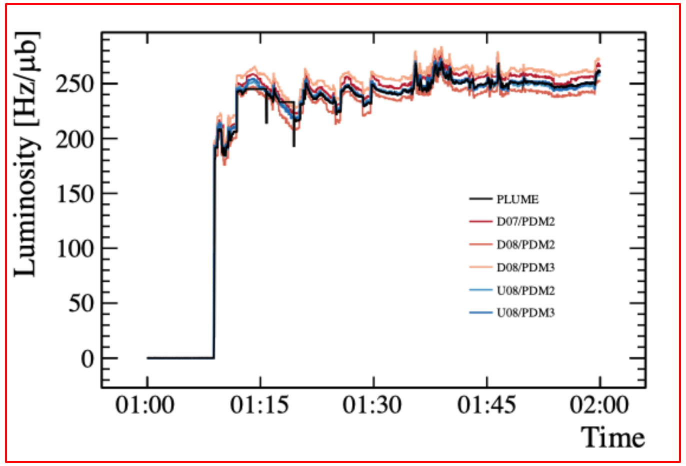
iPK ~ 80 pA at highest rate in RICH 1 with gain 1 Me

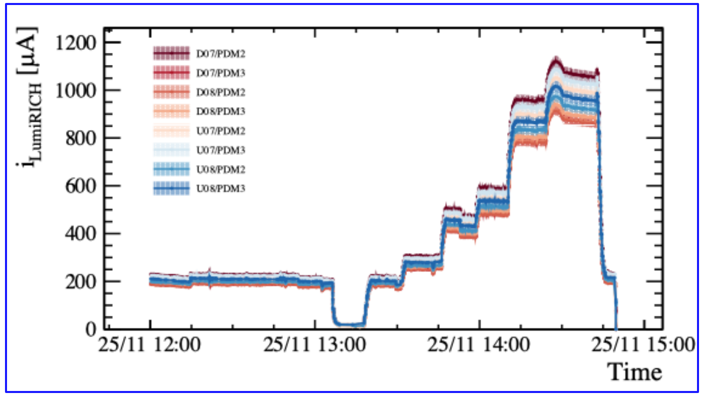


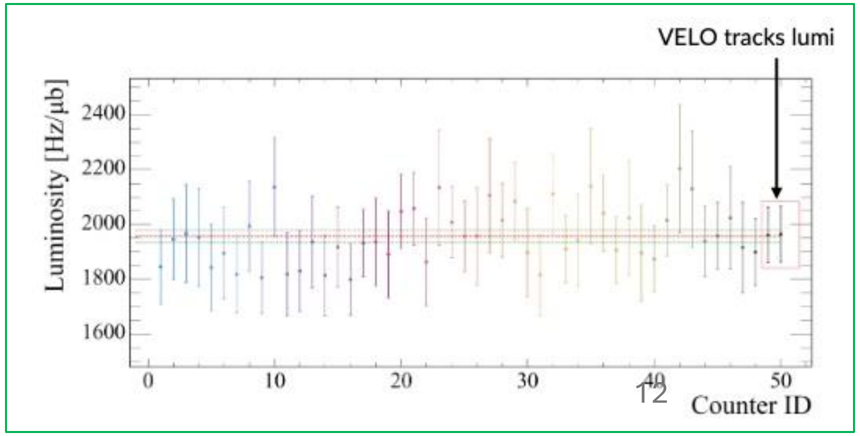


Luminosity with the Ring-Imaging Cherenkov (RICH) detectors

- Online luminosity: real-time monitoring of anode currents
  - Need at least 90 colliding bunches to see sizeable effect
  - Calibration with μ scans
  - Very useful as online monitoring for comparison with PLUME
- Offline counters: number of hits per module (grouping MaPMTs with similar gain)
  - Calibration with vdM scans
  - Expected saturation due to hits digitization
  - Luminosity with logZero compatible with VELO tracks from preliminary offline luminosity studies

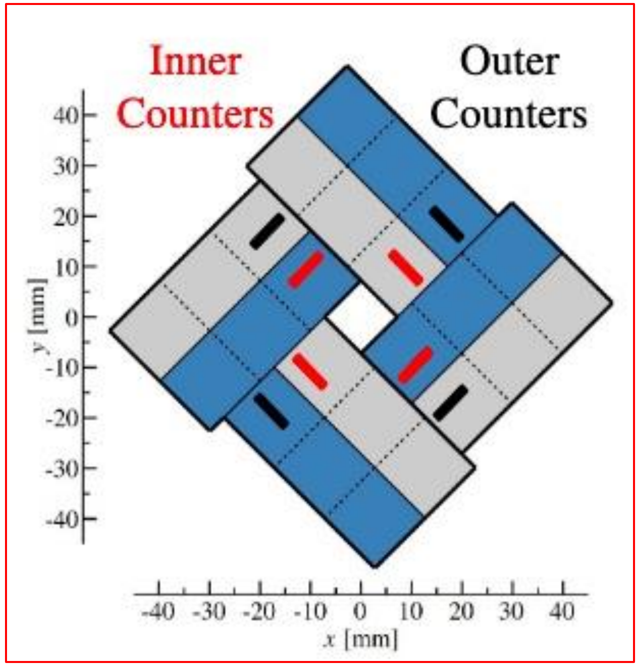






VELO-hit counting for luminosity measurement

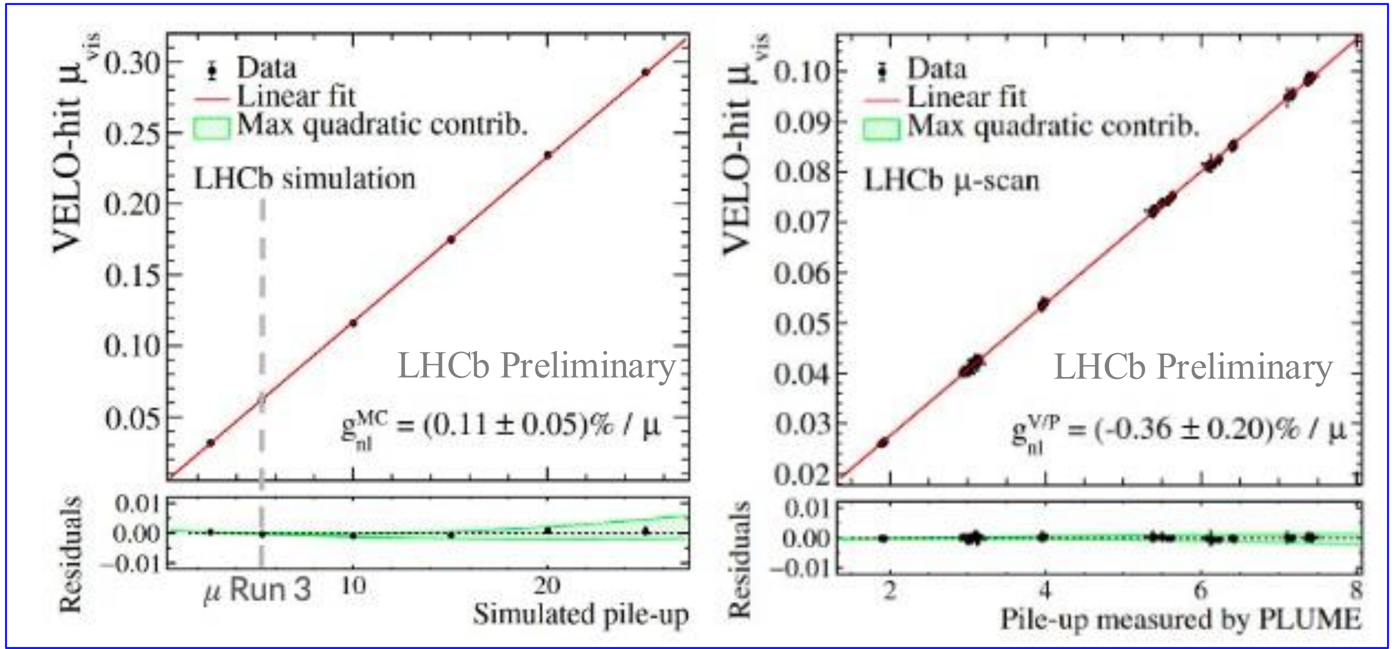
- Reconstructed hits on the VELO, available at the readout level, allows for real-time measurements using high-level primitive
- Hit counting is a powerful proxy to measure the luminosity (pixel cluster counting used in luminosity measurement from CMS [Eur. Phys. J. C 81, 800 (2021)]
  - Robust against radiation damage / HV changes that affect the number of active pixels per cluster
  - Potential non-linearity due to hit-merging at higher occupancies
- Luminosity counters implemented directly on VELO's readout FPGAs [CERN-THESIS-2022-231]
  - Fast readout (available online), high redundancy and great flexibility
  - Freedom in choice of the number/position/shape of accumulation regions over the VELO sensors ⇒ 8 counters per VELO station, 8×26=208 for the whole VELO



VELO-hit counting for luminosity measurement

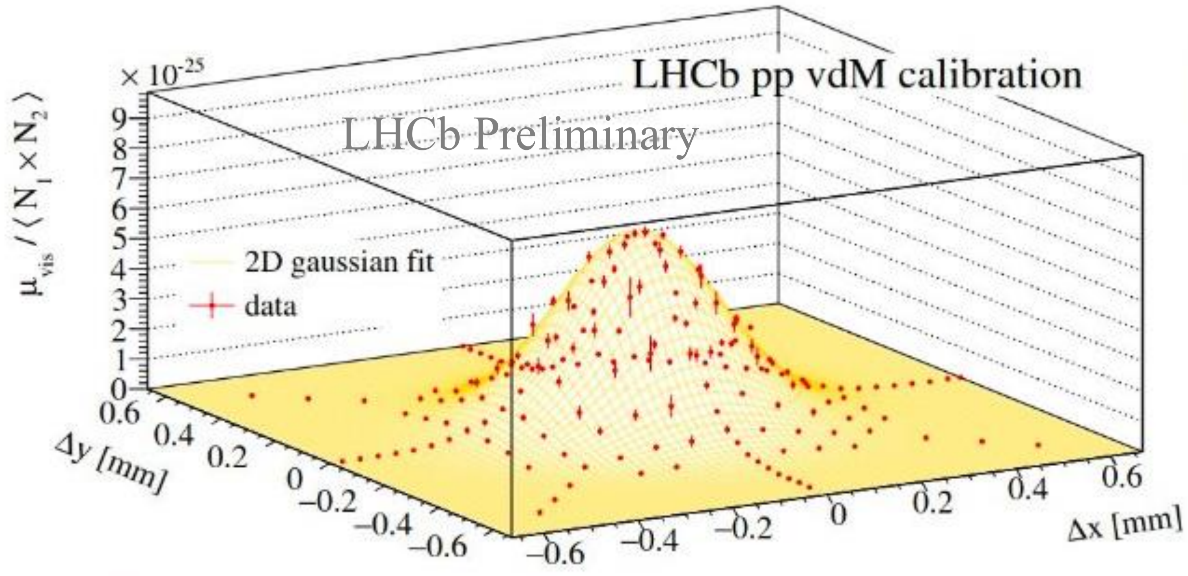
- Firmware counters divided per:
  - Bunch-crossing type, integrated in time using a running-mean, with both average and logZero methods
  - Per-bunch-crossing: logZero method
- Linearity of the VELO-hit counters verified on MC and in dedicated μ-scans in PHYSICS conditions

VELO μ vs simulated or PLUME μ for one outer counter at z~0

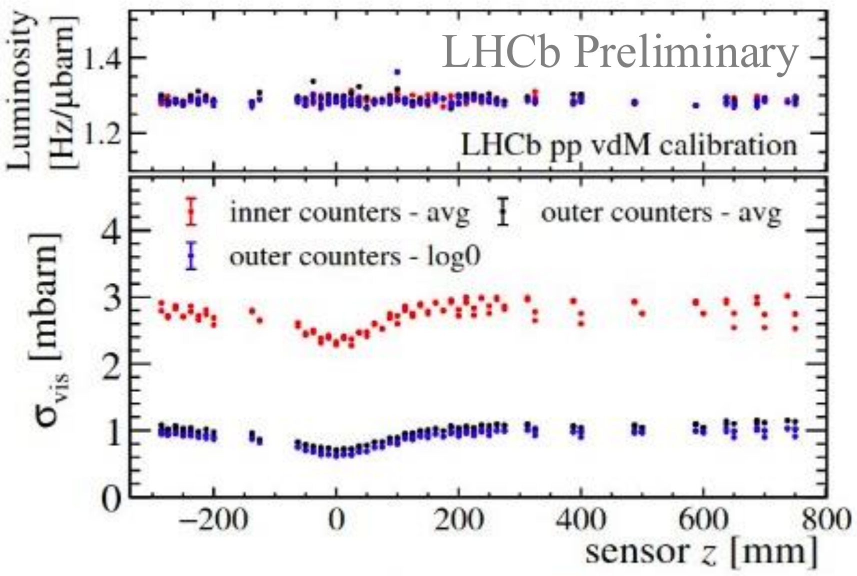


VELO-hit counting: calibration

- Calibration performed during vdM scans



vdM fit for one outer counter at z~0



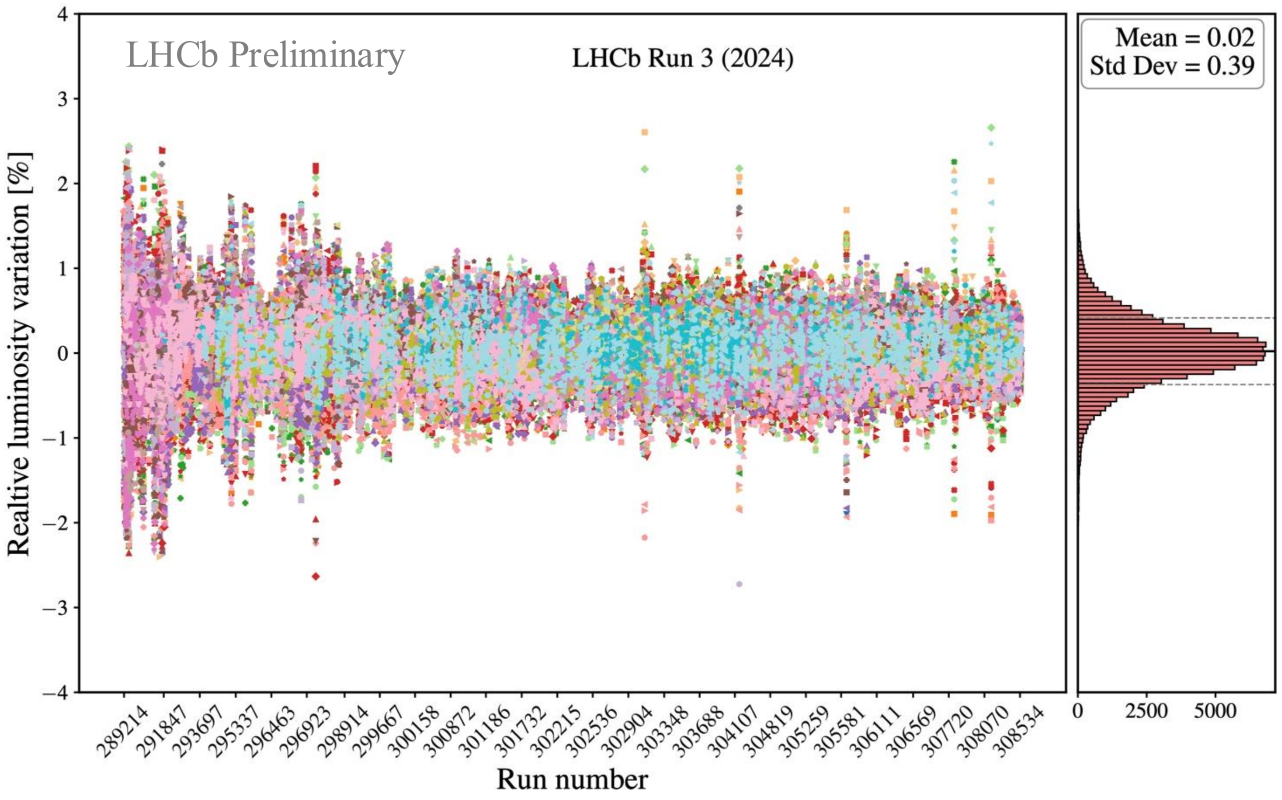
Valley-like shape reflects the VELO acceptance

- Combination strategy: trimmed mean of all available counters to provide a unique luminosity value

After all the calibrations...

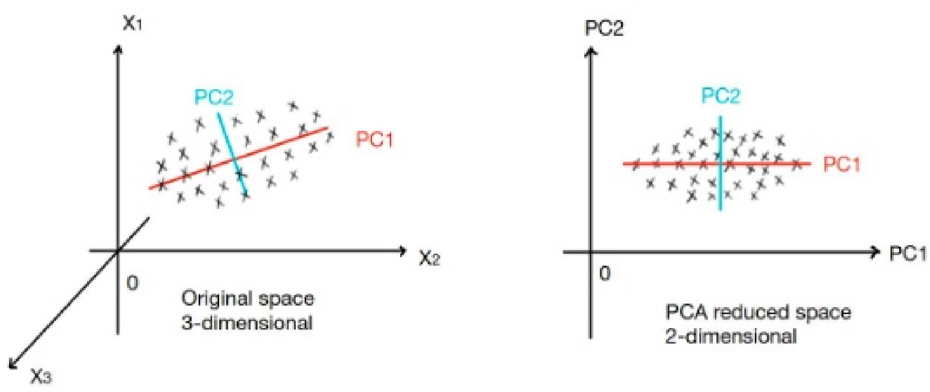
1 colour = 1 counter

- Luminosity variation wrt PLUME luminosity
- Excellent agreement of per-run integrated luminosity, on average difference of 0.02%
- Spread of all the counters is around 0.4%
- Outliers due to issues in single runs for a given detector
- More detailed studies ongoing



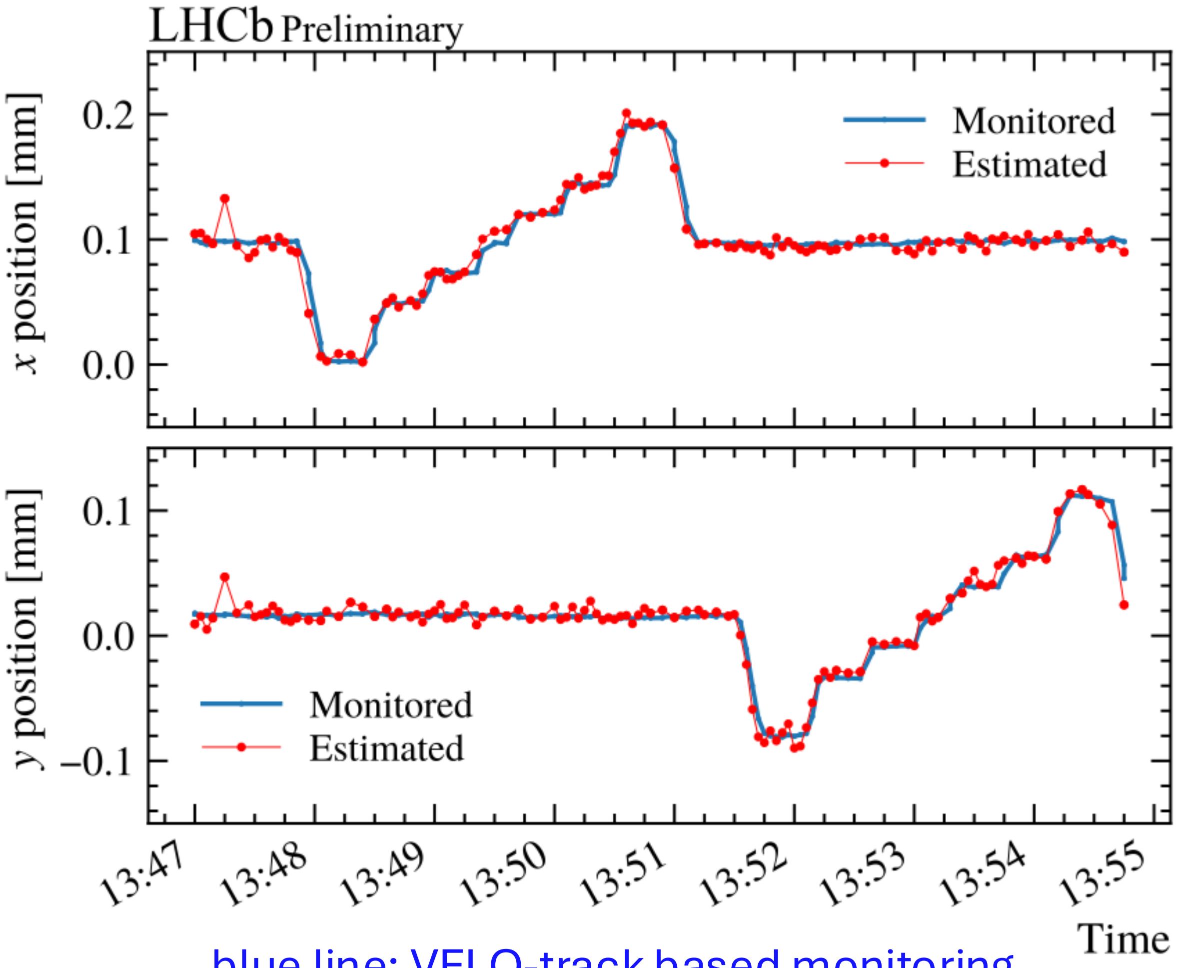
Beam spot monitor

- VELO-hit counters can be used to reconstruct the beam spot position
  - Possible to correct the online luminosity measurement accounting for the beam spot displacements
- Method relies on defining a linear estimator for each direction $x_i = \{x, y, z\}$ using the normalized VELO-hit counters $\vec{c}$: $x_i = \alpha_i \vec{c} \cdot \overrightarrow{w_i} + \beta_i$
  - The $\overrightarrow{w_i}$ weights obtained from MC samples using a Principal Component Analysis (PCA) technique, that informs the user about the optimal combination of counters to estimate the position x_i
  - α_i and β_i are obtained from data (e.g. during length scale calibrations)



Beam spot monitor

- Preliminary results compared with VELO track based monitoring are very promising
- Tested during dedicated length scale calibration scans in low-intensity PHYSICS fill, resolution of ~4 μm every 3s
- Extrapolation of statistical uncertainty to nominal pp-running conditions: ~4 μm every O(ms)



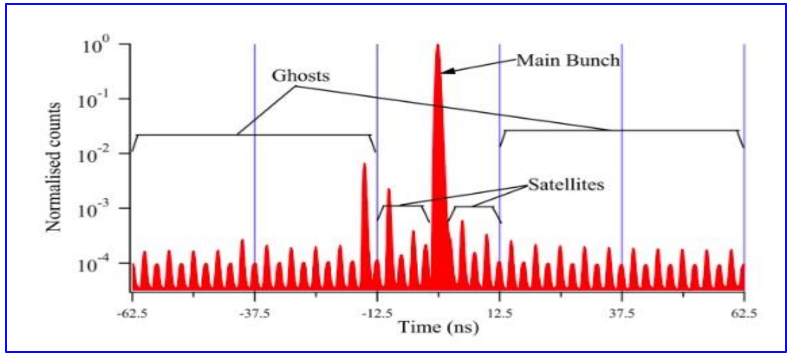
blue line: VELO-track based monitoring
red points: VELO hit based monitoring

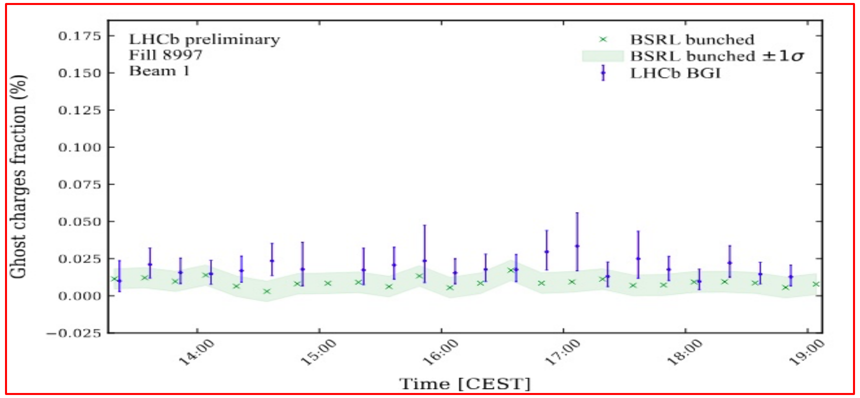
[LHCb-FIGURE-2024-001]
[LHCb-FIGURE-2023-003]

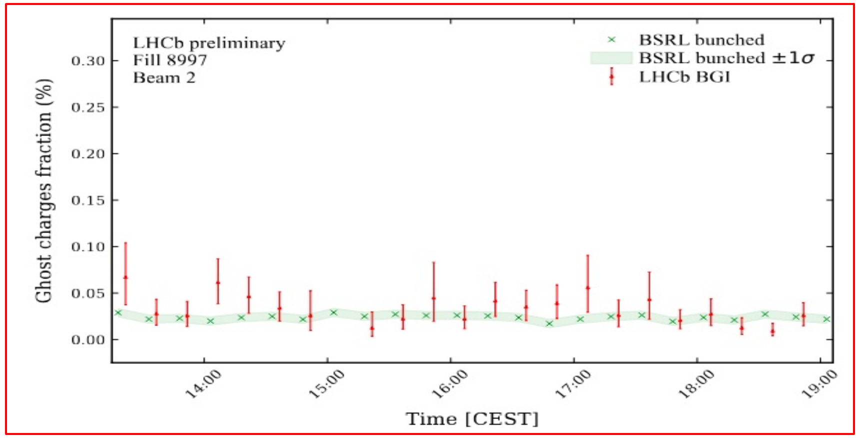
[CERN-ATS-Note-2012-029]

Ghost-charge results

- Ghost charges are charges outside nominally filled bunches, can bias the currents measured by LHC
  - Measured by LHCs BSRL counters, LHCb can perform an independent validation
- Dedicated trigger lines to reconstruct vertices for every bunch crossing, inject gas with SMOG2 to enhance the rate of beam-gas interactions







Ratio of reconstructed beam-gas vertices in empty/filled bunches

Scale to total charge in the LHC

Correction for lower trigger efficiency outside central RF bucket

Assumptions:
- $N_{\text{vertices}} \propto N_{\text{protons}}$
- Selection/reconstruction efficiencies equal for filled/empty bunch slots

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

Very good agreement between LHC BSRL and LHCb measurements, ghost charge fraction well below 0.1%

Conclusions

- LHCb definitely shifted paradigm with Run 3 for what concerns luminosity measurements
  - Hundredths of counters to measure luminosity wrt to the few used during Run 1 and 2
- A dedicated luminometer (PLUME) has been installed and it's running smoothly
- Many detectors contribute together with PLUME to precise luminosity measurements, exploiting a variety of techniques
  - RICH: currents and hit counting
  - VELO: hit counting and average method
- Several luminosity related measurements have been performed in Run 3 and are being refined
  - Beam spot position
  - Ghost charge fraction