PROCEEDINGS OF SCIENCE

# Luminosity determination at LHCb during Run 3

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During Runs 1 and 2, the LHCb detector optimized its performance by stabilizing the instantaneous luminosity throughout each fill, adjusting the distance between the colliding beams using a hardware-based trigger system. In Run 3, the LHCb experiment underwent a major upgrade to accommodate a fivefold increase in luminosity, transitioning to a fully software-based trigger. A new luminometer, PLUME, was installed and successfully commissioned, providing enhanced real-time luminosity measurements. Furthermore, new online proxies from nearly all sub-detectors are now utilized to deliver real-time luminosity measurements, both integrated and per bunch crossing. Additionally, dedicated offline counters are recorded via a specialized data stream operating at a rate of 30 kHz, enabling precise offline luminosity calibration. These proceedings will provide an overview of the upgraded luminosity measurement capabilities at LHCb and of the systems employed to perform such measurements, presenting the first results obtained from data collected during 2023 and 2024, including the measurement of the ghost charge fraction using the beam-gas imaging technique.

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## 1. Introduction

The LHCb experiment is a forward spectrometer optimized for studying the decays and properties of heavy hadrons. A key ingredient for safe and efficient data taking is the control and monitoring of instantaneous luminosity. To ensure stable detector performance, LHCb operates at a constant luminosity using a technique known as luminosity leveling [1]. For this reason, reliable luminosity measurements are essential: they protect the detector and provide the precise offline calibration needed for physics analyses, particularly for cross-section measurements [2].

For Run 3, the LHCb detector was substantially upgraded to cope with a luminosity five times higher than in Run 2 [3]. As part of this upgrade, a dedicated detector for luminosity measurement, PLUME (Probe for LUminosity MEasurement) [4], was installed and now serves as the main LHCb luminometer. PLUME consists of a hodoscope of 48 photomultiplier tubes (PMTs) arranged around the beam pipe in a cross-shaped geometry. Each PMT detects Cherenkov light generated by particles traversing a quartz radiator coupled to the sensor. In addition to PLUME, several other LHCb subdetectors also contribute to luminosity monitoring, either as backups or to provide complementary information, for example through beam condition measurements.

Luminosity is inferred from a set of observables known as luminosity counters, which act as proxies. For PLUME, these counters include the total ADC sum per channel and the number of events exceeding a given threshold. Other subdetectors, primarily designed for tracking or particle identification, also supply useful proxies, such as cluster multiplicities, numbers of reconstructed tracks or vertices, and deposited energy. To convert these counters into an absolute luminosity scale, calibration procedures such as beam–gas imaging (BGI) [5] and van der Meer (vdM) scans [6] are employed, allowing the determination of the counters effective cross-sections.

## 2. Luminosity determination with PLUME

To extract instantaneous luminosity from detector measurements, a calibration procedure is required that relates the observed interaction rate to the underlying physics process. The relation between the average number of detected interactions, $\mu$, and the instantaneous luminosity, $\mathcal{L}$, is expressed as

$$\mathcal{L} = f\frac{\mu}{\sigma_{\text{vis}}}, \tag{1}$$

where $f = 11.245$ is the LHC bunch revolution frequency, and $\sigma_{\text{vis}}$ represents the visible cross-section, which incorporates both the detector efficiency and its geometrical acceptance.

In the case of PLUME, where the PMT occupancy remains relatively low, $\mu$ can be determined using the fraction of events with no detected interaction, $P_0$. This is known as the *logZero* method [7], which yields

$$\mu = -\log(P_0). \tag{2}$$

The LHCb detector also hosts SMOG2, a 20 cm-long storage cell [8] that allows for fixed-target data taking in parallel with standard $pp$ or PbPb collisions. For accurate luminosity measurements, the contribution from interactions with the injected gas must be removed. The subtraction procedure is based on

$$\mu_{\text{bkg.sub.}} = \mu_{\text{bb}} - \mu_{\text{be}} - \mu_{\text{eb}} + \mu_{\text{ee}}, \tag{3}$$

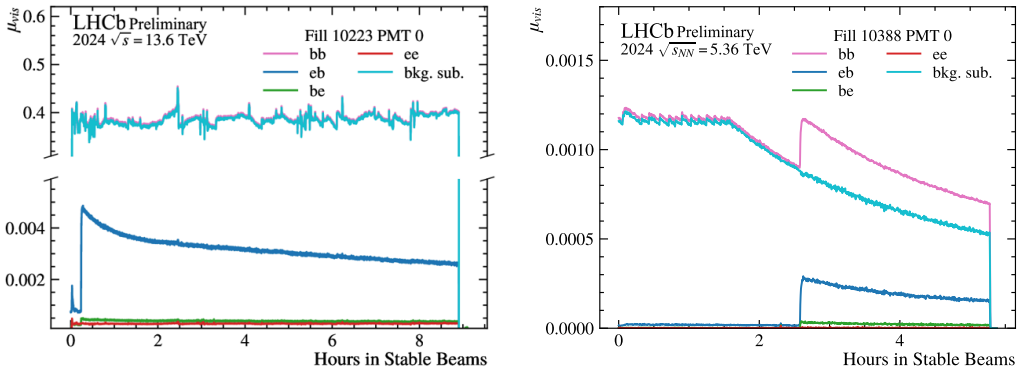


**Figure 1:** Average number of visible interactions measured by PMT 0, separated by bunch-crossing type and combined to obtain $\mu_{\text{bkg.sub.}}$ for (left) a $pp$ and (right) a PbPb fill. Gas was injected in the SMOG2 storage cell in both cases (dark blue line).

where $\mu_x$ with x = bb, be, eb, or ee corresponds to the average number of detected interactions in beam–beam, beam–empty, empty–beam, and empty–empty bunch crossings, respectively.

The $\mu_{\text{bb}}$ term includes contributions from both beam–beam collisions and beam–gas interactions. The latter are estimated from $\mu_{\text{be}}$ and $\mu_{\text{eb}}$, which contain only beam–gas and gas–beam contributions, respectively. Because the beam populations in these crossing types evolve differently from those in bb crossings, correction factors are applied to $\mu_{\text{be}}$ and $\mu_{\text{eb}}$. Finally, residual gas interactions in the LHC vacuum are accounted for by the $\mu_{\text{ee}}$ term.

Figure 1 shows the background-subtracted $\mu$ together with the individual components of Eq. (3), for representative $pp$ and PbPb fills from 2024 [9]. In the ion run, where the instantaneous luminosity is substantially lower than in $pp$ collisions, the background subtraction becomes particularly critical. In some cases, when gas is injected in SMOG2, mismodeling of up to 7% of the $\mu_{\text{eb}}$ component is observed in $\mu_{\text{bkg.sub.}}$, depending on the gas species used. The source of this discrepancy is not yet fully understood and is the subject of ongoing studies.

Maintaining detector stability over the whole data-taking period is of primary importance. Even small, uncorrected variations in PMT gain can compromise the accuracy of the vdM calibration, making stable operating conditions essential. To monitor and preserve this stability, a dedicated procedure has been established. At the end of each physics fill, the ADC spectra from all PMTs, as recorded by the LHCb monitoring system, are collected and fitted. An illustration of such a fit is shown in the top-left panel of Fig. 2. The fit is used to determine the position of the peak in the ADC spectrum, which corresponds to particles striking the PMT window at nearly perpendicular incidence. For stable operation, this peak is expected to lie at 300 ADC counts, consistent with a PMT gain of $1.5 \times 10^5$. As an example, the right panel of Fig. 2 shows the evolution of the peak position with LHC fill number during 2024 for PMT2. The average deviation from the nominal target value is about 1%.

## 3. Luminosity determination with the RICH detectors

The LHCb experiment is equipped with two Ring Imaging Cherenkov (RICH) detectors, whose primary role is to provide particle identification over a broad momentum range. In addition, the

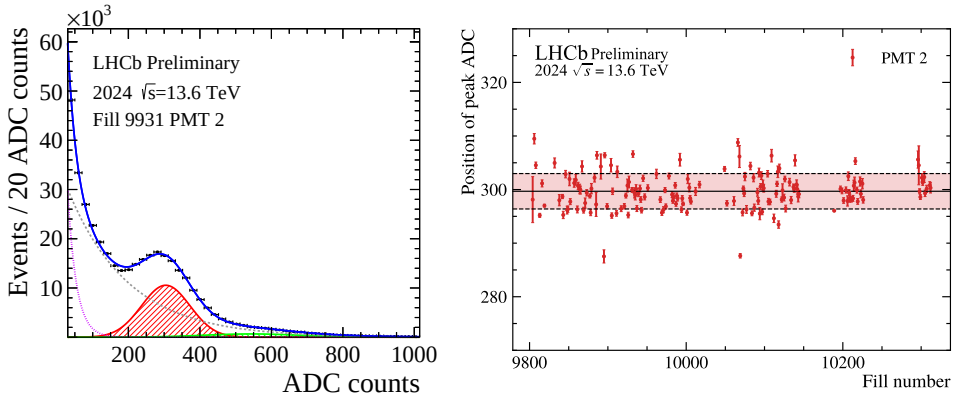


**Figure 2:** Left: ADC spectrum obtained from the LHCb monitoring system for PMT 2 during LHC fill 9931, with the fit results overlaid. The Gaussian function (red dashed) describes the peak due to particles impinging quasi-perpendicularly on the PMT window. The other Gaussian function (green dashed) describes events in which 2 particles enter the PMT. The exponential components are used to model events in which one or more particles impinge on the PMT window with angles larger or smaller than 90 degrees. Right: peak position for PMT 2 as a function of the LHC fill number. The central value and half-width of the red band are 299.7 and 3.3 ADC counts, respectively.

RICH detectors can also be exploited for luminosity measurements [10]. The anode currents from the installed multi-anode PMTs are directly proportional to the instantaneous luminosity and can therefore serve as proxies.

The main limitation, however, is that the sensitivity of the power-supply current readout prevents these proxies from being calibrated during vdM scans, where the activity is too low and the corresponding currents are below the measurable range. To overcome this, the anode currents are instead calibrated against the PLUME luminosity determination during dedicated physics runs known as $\mu$-scans. In these runs, the average number of interactions per bunch crossing, $\mu$, is varied between approximately 1 and 10 by displacing the LHC beams, with enough bunches circulating in the LHC to produce measurable anode currents. The calibrated luminosities obtained from RICH currents compared with PLUME determination are shown in the left part Fig. 3. The agreement of all the measurements is excellent.

In addition, the RICH detectors can provide an offline luminosity measurement using the *logZero* method. The number of over-threshold hits can be recorded and calibrated through vdM scans to extract a visible cross-section. This calibration then allows an offline determination of the luminosity, as illustrated in the right panel of Fig. 4, where results from several RICH counters are compared with the luminosity obtained from the LHCb Vertex Locator (VELO) track proxy.

## 4. Luminosity determination with the VELO

With the firmware upgrades introduced for Run 3 [11], the VELO can now use reconstructed hits to provide an online luminosity measurement. Hit counting is a powerful luminosity proxy, as it is largely insensitive to radiation damage and variations in high voltage that may affect the number of active pixels. While potential non-linearities could arise at high occupancy due to hit merging,

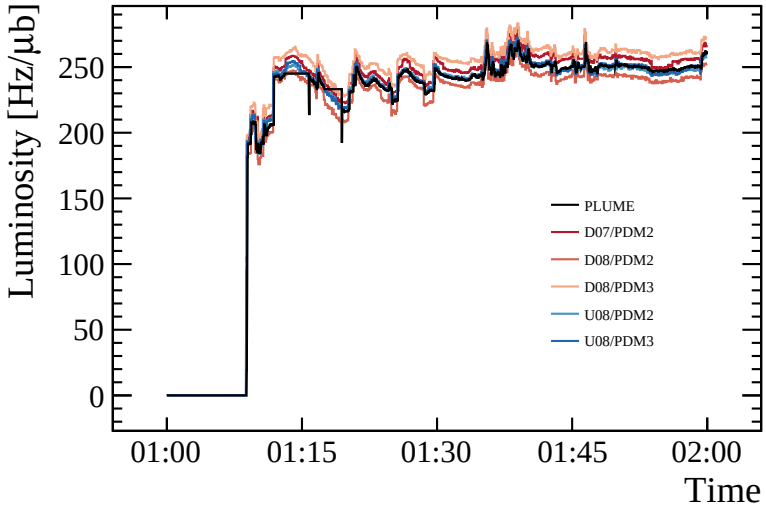


**Figure 3:** Online luminosity obtained from different RICH anode current measurements compared with PLUME determination.

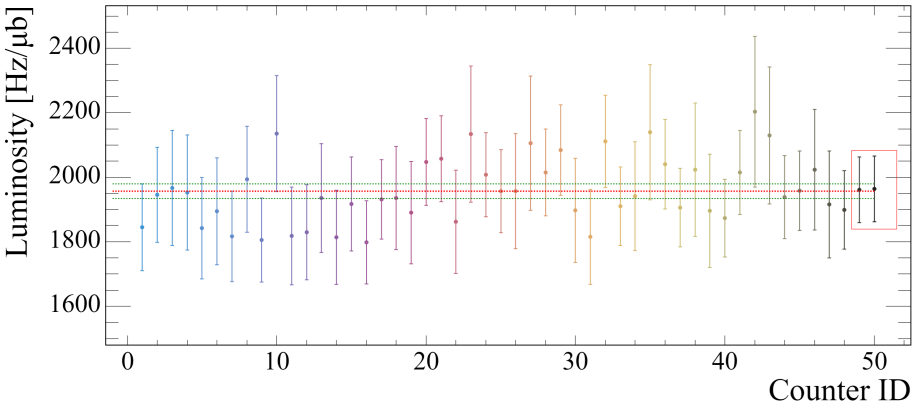


**Figure 4:** Offline luminosity computed with the logZero method for a reference run for different RICH counters compared with the determination by the VELO tracks counter (last two points on the right).

simulations indicate that under the operating conditions expected for Runs 3 and 4 such effects are negligible.

Dedicated luminosity counters have been implemented directly in the VELO readout firmware, eight per VELO station, for a total of 208, and are available online [12]. These counters deliver information both per bunch type and per bunch crossing, and can be calibrated during vdM scans. The per-bunch type capability is particularly valuable, as it allows subtraction of the background induced by beam–gas interactions in SMOG2, a feature unique to the VELO and PLUME counters.

In the left part of Fig. 5 shows the background-subtracted $\mu$ measured during a vdM scan, with the results of a two-dimensional fit overlaid [13]. All counters are first calibrated, and their measurements are then combined to produce a single luminosity determination. The combination employs a trimmed mean to enhance both the robustness and stability of the measurement.

In addition to measuring luminosity, the VELO hit counters can be used to provide a real-

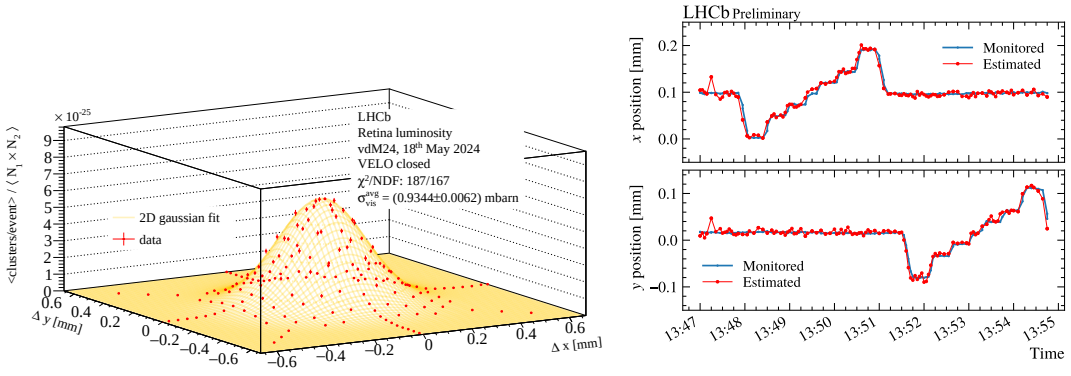


**Figure 5:** Left: average number of interactions per bunch crossing normalised to the average beam populations measured during the 2024 LHCb vdM scan with the results of a two-dimensional fit overlaid. Right: comparison of the beam $x$ and $y$ coordinates determined by the track based estimator (blue points) and the hit based method (red points).

time determination of the beam-spot position, without requiring track reconstruction as in the standard monitoring. The method relies on defining a linear estimator for each spatial direction using Principal Component Analysis (PCA) and simulated events to identify the optimal linear combination [14].

This approach has been tested during dedicated length-scale calibration fills and low-intensity physics runs during 2024. The estimated beam-spot position is shown in the right panel of Fig. 5, alongside the measurement from the track-based system. The agreement is excellent, with a resolution of approximately 4 $\mu$m every millisecond under nominal $pp$ running, providing a highly effective tool for real-time monitoring of beam conditions. These measurements are currently sampled every three seconds via the experiment control system.

## 5. Ghost charge fraction in LHCb

The LHC ring is divided into 3564 slots, each separated by 25 ns. Within every slot, a 2.5 ns radio-frequency (RF) bucket can be populated with colliding bunches. For absolute luminosity measurements in all LHC experiments, precise knowledge of the bunch populations, as measured by the LHC beam current transformers, is essential. Any charge outside the nominally filled buckets must be carefully evaluated and subtracted, particularly the satellite charge (present within the 25 ns slot but outside the central 2.5 ns RF bucket) and the ghost charge (circulating outside the nominal 25 ns slots).

The LHCb experiment provides complementary information on ghost charge with respect to the Beam Synchrotron Radiation Telescope (BSRL) by exploiting beam–gas interactions in nominally empty bunch slots. This is achieved by injecting noble gases into the LHC vacuum around the interaction region using the SMOG2 system, under the assumption that the number of beam–gas interactions per bunch is proportional to the bunch charge. The ghost charge fraction is then estimated as

$$f^{1(2)}_{\text{ghost}} \approx \frac{I^{1(2)}_{\text{ghost}}}{I^{1(2)}_{\text{filled}}} = \frac{N^{1(2)}_{ee+eb(be)}}{N^{1(2)}_{be(eb)}} \cdot \frac{I^{1(2)}_{be(eb)}}{I^{1(2)}_{bb+be(eb)}} \cdot \frac{1}{\varepsilon^{1(2)}_{\text{trigger}}}, \tag{4}$$

where $I$ denotes the charge, $N$ the number of reconstructed vertices and the apex 1 or 2 refers to beam 1 and 2, respectively. The quantity $\varepsilon^{1(2)}_{\text{trigger}}$ is a correction accounting for the trigger efficiency, since LHCb is optimized for the central (main) bucket.

Recent results from 2023, shown in Fig. 6, compare LHCb measurements with those from BSRL. The agreement with the BSRL bunched measurement confirms that the ghost charge fraction is negligible for vdM calibrations and remains well below the percent level.

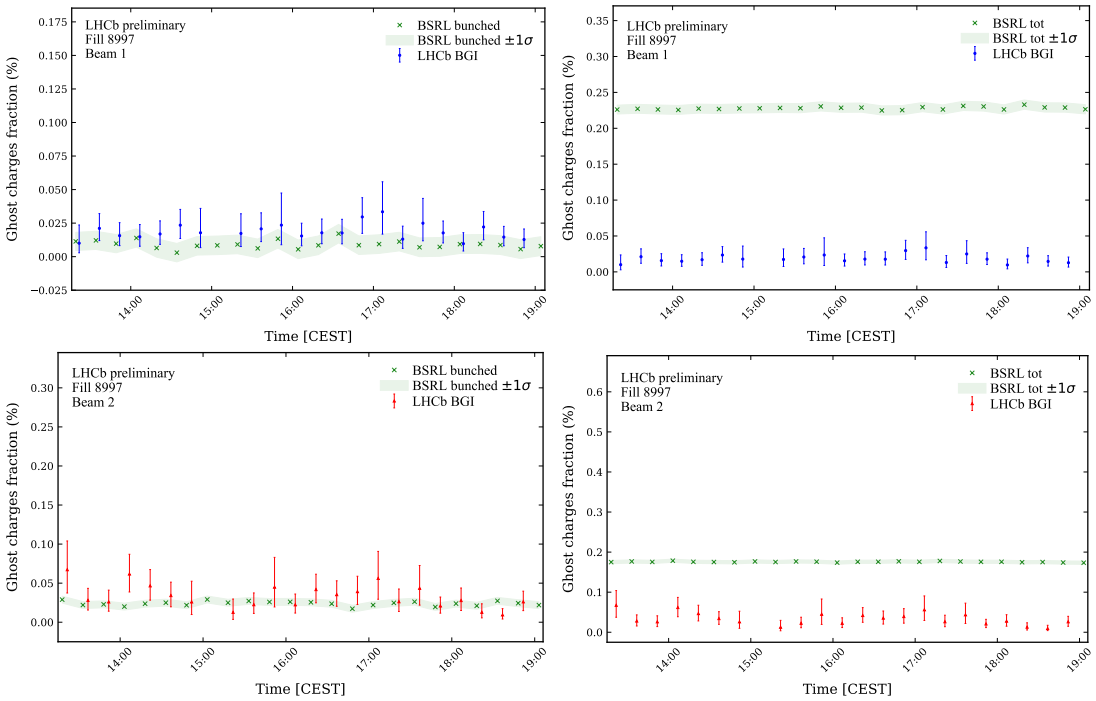


**Figure 6:** Comparison between LHCb and BSRL ghost charge measurements in June 2023 for beam 1 (top) and beam 2 (bottom). The green crosses show the BSRL bunched (left) and unbunched (right) measurements integrated over 15 minutes, with the shaded area indicating the uncertainty. Plots from [15].

## 6. Conclusions

For Run 3, the LHCb detector underwent an almost complete upgrade, providing a wide array of reliable luminosity proxies across its subsystems. All relevant counters are calibrated using both 1D and 2D vdM scans. The primary LHCb luminometer, PLUME, is fully operational, delivering continuous average and per-bunch crossing luminosity measurements to the LHC. Backup online luminosity measurements are supplied by several sub-detectors, including the RICHes and VELO, while precise offline determinations further complement the system. The entire luminosity monitoring system is now fully commissioned and performing as intended.

In addition, the LHCb experiment successfully provides independent measurements of the ghost charge fraction using beam–gas interactions, enabling cross-checks with the BSRL system to be performed and validation of the LHC's own estimations.

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