PROCEEDINGS OF SCIENCE

Luminosity determination at LHCb during Run 3

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The LHCb detector optimized its performance in Runs 1 and 2 by stabilizing the instantaneous luminosity during a fill by tuning the distance between the two colliding beams using a hardware-based trigger. In Run 3, the LHCb experiment has been upgraded to cope with the 5-fold increase of luminosity and now features a fully software-based trigger. A brand new luminometer, PLUME, has been installed and successfully commissioned. Additionally, new online proxies from nearly all sub-detectors are now used to provide measurements of luminosity, both integrated and per bunch-crossing. In addition, new offline counters are stored via a dedicated stream running at 30 kHz rate to allow for a precise offline calibration of luminosity. This talk presents an overview of the new luminosity measurements at LHCb. The first results obtained using data collected during 2023 will also be shown, including the ghost charge fraction measurement using the beam-gas imaging technique.

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1. Luminosity in LHCb

The LHCb experiment is a forward spectrometer designed to study the properties of heavy hadron decays. Luminosity is a critical parameter for efficient data collection, as LHCb maintains optimal performance by operating at a constant luminosity, achieved through a technique known as luminosity leveling [1]. The reliable monitoring of luminosity guarantees the safety of the detector (since beams are being displayed) and the precise offline luminosity measurement, which is a key ingredient of LHCb physics analyses aiming at measuring cross-sections [2]. For Run 3, LHCb underwent a major upgrade to deal with a five-fold increase of luminosity with respect to Run 2 [3]. In particular, a new detector dedicated entirely to luminosity measurement, PLUME (Probe for LUminosity MEasurement) [4], has been installed and it is currently the main LHCb luminometer. PLUME is a hodoscope made of 48 Photomultiplier Tubes (PMTs) placed around the beampipe in a crossed shape. Each PMT measures the Cherenkov light produced by particles passing through a quartz glued to the it detector. On top of PLUME, other subdetectors are involved in luminosity measurements, acting AS a backup or providing complementary information, such as the beam monitoring.

Luminosity is measured using various observables known as luminosity counters, employed as proxies. PLUME luminosity counters include the sum of ADC counts for each channel and the number of events over a threshold per channel. Also, the other LHCb subdetectors, mainly dedicated to tracking and particle identification, are providing their own counters (such as number of clusters, number of track and vertices, deposited energy etc..) which can be exploited as luminosity proxies. Calibration of the counters to measure their own effective cross-section and provide the absolute luminosity is achieved through specific procedures, such as beam-gas imaging (BGI) [5] and Van der Meer (vdM) scans [6].

2. Interaction counting

Luminosity in LHCb requires a good accuracy both online (with a goal of at least 10%) and offline (ideally < 2%). Subdetectors provide useful variables as counters, and ratios of different counters help check stability against changes in calibration and data taking conditions over time, apply corrections, and control systematics. Some counters are available via the Experiment Control System (ECS): they are useful for cross-checks, backups, and online monitoring, in addition to PLUME. More precise counters are provided by high-level reconstructed variables and they are used for offline analysis and online monitoring. A good luminosity counter should demonstrate linearity with respect to luminosity, good time stability, and a well-understood dependence on pile-up, spillover, and bunch spacing. In Run 1 and Run 2, the most stable luminosity counters were provided by the VELO through its measurements of primary vertices (PVs) and tracks in proton-proton collisions. For each counter, the measurement of luminosity is given by its visible cross section σ_{vis} and by the measurement of the rate of visible interactions μ_{vis}. Under the assumption that number of interactions is Poisson distributed around μ_{vis}, the number of visible interactions can be measured by estimating the probability of empty events (zero visible interactions) $P(0 \mid \mu_{vis})$ with the log0 method by counting the number of total (N_{evts}) and empty (N_{empty}) events, which mitigates potential non-linearities and instabilities:

$$P\left(0 \mid \mu_{vis}\right) = e^{-\mu_{vis}} \implies \mu_{vis} = -\log P(0) = -\log\left(\frac{N_{\text{empty}}}{N_{\text{evts}}}\right) \tag{1}$$

The log0 method is the main strategy used to evaluate the number of visible interaction for each counter in LHCb. Alternatively the average method can be used if the linearity of the counter is guaranteed, where $\mu_{\text{vis}} = \frac{\sum_j^{\text{evts}} N_j}{N_{\text{evts}}}$. However, given the higher number of visible interactions in Run 3, the log0 method can be challenging for counter with an high visible cross section (close to the pp inelastic one) due to the low number of empty events, and new, alternative, methods are under study. The luminosity value for a bunch crossing is finally given by the following:

$$\langle \mathscr{L}_b \rangle = \frac{\langle \mu_{\text{inel}} \rangle\, f_r}{\sigma_{\text{inel}}} = \frac{\langle \mu_{\text{vis}} \rangle\, f_r}{\sigma_{\text{vis}}} \tag{2}$$

where μ_{inel} is the number of inelastic interactions, σ_{inel} is the pp inelastic cross section, and f_r is the revolution frequency of approximately 11245 Hz at LHC.

3. Absolute calibration

The principle of vdM scans involves scanning the beams across each other to integrate out the bunch profiles. During dedicated LHC fills, the beams are moved across the transverse plane, and collision rates are measured at each step as a function of the beam separation [6]. In vdM fills, a larger β^* value of 24 m is used (compared to the standard 2 m during data-taking), resulting in a "wider" beam and a lower average number of visible interactions. A larger crossing angle is also necessary to suppress contributions from satellite charges. During these scans, multiple luminometers are calibrated simultaneously. The simpler, one dimensional, vdM scan is performed along two perpendicular axes separately and the cross section calculation assumes factorizability, meaning the transverse betatron oscillations are expected to be well decoupled in the x and y directions. In Run 2, LHCb pioneered two-dimensional vdM scans, which proved to be the most accurate method for luminosity calibration, revealing non-factorization effects up to 2%. In Fig.1, a fit of the 2 dimension vdM scan of the VELO Retina counters (described in [7]) using 2024 data is shown. In Run 3, emittance scans were also commissioned, using the same optics as in data-taking. These scans are used to check the linearity of counters under physics conditions and their time stability.

The Beam Gas Imaging (BGI) method consists in reconstructing the interaction vertices between the beam and the gas within the beam pipe, allowing for measurements of colliding bunch positions, shapes, and crossing angles. The BGI method is employed only at LHCb, thanks to the injection of gas into the VELO vessel using the SMOG (System for Measuring Overlap With Gas) system, now upgraded for Run 3 [8]. BGI provides an independent and complementary measurement of the cross-section compared to the vdM method. Assuming Gaussian bunches, the overlap integral is calculated as

$$O = \frac{e^{-\Delta x^2/2\Sigma_x^2}\, e^{-\Delta y^2/2\Sigma_y^2}}{2\pi\Sigma_x\Sigma_y} \tag{3}$$

where O is the overlap between the two bunches, $\Delta x(y)^2$ are the bunch offsets and $\Sigma_x(y)$ the bunch widths. Given the number of bunch crossings $n_{\text{crossings}}$ and the bunches population N_1 and

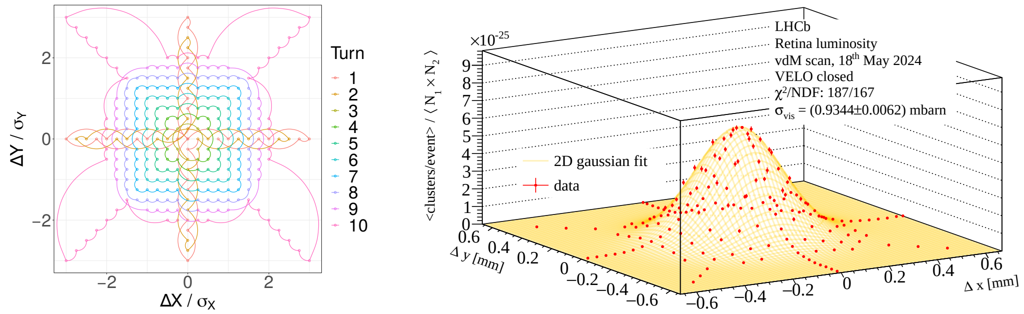

Figure 1: Left: an example of the evolution of the transverse beam separations in a two-dimensional scan expressed in bunch sigmas during the vdM scans at LHCb in Run 3 at $\sqrt{s}$ = 0.9 TeV. Right: vdM fit using one of the Retina ECS cluster counters [9]. The luminosity proxy reported here is computed by measuring the average occupancy in the selection region.

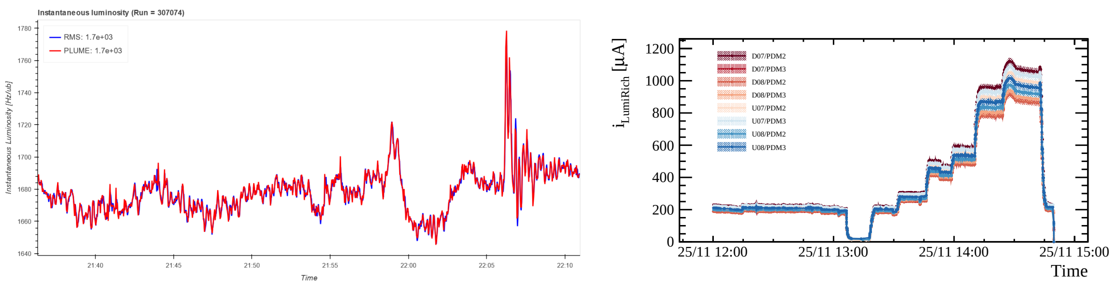

Figure 2: Examples of online luminosity measurements. On the left, the instantaneous luminosity values provided by PLUME, with RMS acting as a backup. On the right, the scaling of the MaPMT currents in the RICH detector during a luminosity scan: luminosity was increased in steps by changing the beams displacement, and the anode currents are scaling accordingly.

N_2, the cross section is then expressed as $\mathscr{L} = n_{\text{crossings}} \times N_1 N_2 O \implies \sigma_c = \frac{\mu_c}{N_1 N_2 O}$. The BGI complementary to the vdM method and the dominant systematics are related to vertex resolution.

4. Online and Offline Luminosity

The PLUME detector is computing instantaneous luminosity proxies for each bunch crossing directly in the firmware and it provides online luminosity continuously, independently of the DAQ state, by measuring luminosity per bunch crossing for each PMT. The monitored luminosity value (Fig.2 left) is sent to the LHC every 2.4 seconds to level LHCb. The Radiation Monitoring System (RMS), calibrated using PLUME, serves as a backup. Additionally, multiple counters from other subdetectors have been calibrated to provide online luminosity alongside PLUME. Examples include:

- VELO: Super Pixel Packet on ASIC, number of Retina Clusters
- SciFi (Scintillating Fibre): Number of clusters, HV currents
- RICH (Ring Imaging Cherenkov system): Multi-anode Photomultiplier Tubes anode currents (Fig.2 right)
- Muon system: Multi-Wire-Proportional-Chambers currents

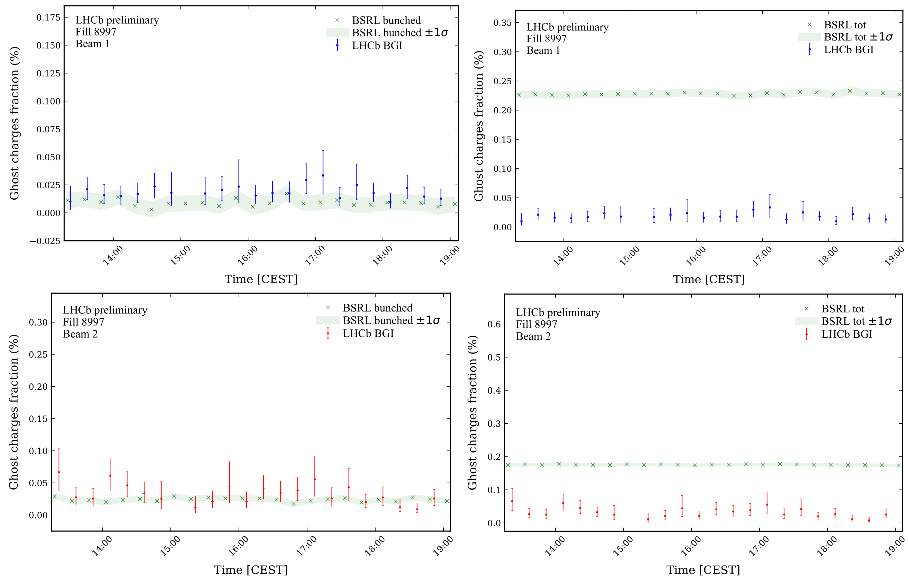

Figure 3: Comparison between LHCb and BSRL ghost charge measurements in June 2023 for beam 1 (top) and 2 (bottom). The green crosses are the BSRL bunched (left) and unbunched (right) measurements integrated over 15 minutes, and the shaded area is the uncertainty window. Plots from [10].

For offline luminosity, LHCb has a dedicated workflow in data processing. The rate R of interactions per bunch crossing is measured using luminosity events containing only counters. These events are selected with a random trigger to obtain unbiased samples at the first-level reconstruction (online in Run 3) stage, were essential counters are saved with a 30 kHz rate, and additional backup counters are stored with a 1 kHz rate. Additionally, at a second stage of reconstruction, more variables are stored alongside the 30 kHz line. Rates are selected to ensure sufficient statistics for each colliding bunch within a time interval of a few minutes, based on experience from Run 2.

5. Ghost charge fraction in LHCb

The LHC ring is divided into 3564 slots, spaced 25 ns apart, each consisting of a 2.5 ns RF (radio frequency) buckets that can be populated by colliding bunches. Bunch populations, as measured by LHC transformers, are crucial for absolute luminosity measurements across all LHC experiments. Charges outside the filled buckets must be carefully analyzed and subtracted, particularly satellite charge within the 25 ns slot but outside the 2.5 ns RF bucket, as well as ghost charge circulating in the LHC, outside the 25 ns bunch slots. LHCb provides complementary measurements of ghost charge fraction relative to the Beam Synchrotron Radiation Telescope (BSRL), by measuring beam-gas interaction rates in nominally empty bunch slots. This is made possible by injecting noble gases via the SMOG system into the LHC vacuum around the LHCb interaction region, under the assumption that the number of beam-gas interactions per bunch is proportional to the bunch's charge:

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

where $\varepsilon^{1(2)}_{\text{trigger}}$ is the efficiency correction, as LHCb is optimized for the central (main) bucket, I is the charge and N the number of reconstructed vertices. The subscripts ee, be, eb identify the empty-empty, beam-empty, and empty-beam bunch slots, respectively. Latest results from 2023, shown in Fig.3, are compatible with the BSRL bunched measurement, confirming that ghost fraction is negligible for vdM calibrations and well below the percent level.

6. Conclusion

The LHCb detector was almost entirely upgraded for Run 3, with a wide availability of good proxies for measuring luminosity from all subsystems. All relevant counters are calibrated using 1D and 2D vdM scans in Run 3. The main LHCb luminometer, PLUME, is fully operational, providing continuous average and per-bunch crossing luminosity to the LHC. A reliable and efficient infrastructure for Run 3 luminosity measurement has been established for both storing and analyzing offline luminosity. LHCb successfully provides complementary ghost charge fraction measurements using beam-gas interactions.

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