Article

A Method Based on Muon System to Monitor LHCb Luminosity

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Abstract: LHCb is one of the four main experiments running at the Large Hadron Collider (LHC) of the European Organization for Nuclear Research. Since 2010, it has been collecting data to study the Physics of b and c quarks. For the past three years, the experimental apparatus underwent significant upgrades to be ready for a new round of data collection, expected to start in June 2022. The new apparatus is designed to be able to run at an instantaneous luminosity five times larger than the previous one, which was 2.0×10^{32} cm^{-2}s^{-1}, and the whole detector readout will be at a 40 MHz rate. It is worth noticing that the luminosity at the LHCb interaction point, for the characteristics of the detector, needs to be reduced with respect to the luminosity provided by LHC. Major changes in the different subdetectors were required, along with complete modifications of the trigger schemes. The LHCb collaboration is developing and studying different methods for the on-line measurement of luminosity at the LHCb impact point, crucial for the monitoring of correct machine operation and for most experimental physics studies. The present work describes a procedure based on hit counting in the muon detector for an on-line luminosity monitor. The performance and the precision achieved with this method in tests carried out on past data collected are presented, together with proposals for future upgrades.

1. Introduction

The Large Hadron Collider beauty experiment (LHCb) is a single arm spectrometer designed to measure the decay properties of heavy hadrons and study CP violation [1]. The apparatus is made with a vertex locator [2], ring imaging Cherenkov (RICH) and tracking systems [3–5], an electromagnetic and a hadronic calorimeter [6] and a muon detector [7]. Data presented in this paper were collected with a muon detector composed by five stations, four placed downstream of the calorimeters (M2–M5) and the first (M1) positioned upstream, with the purpose of quickly providing information to measure muon transverse momentum for the hardware trigger, L0.

A precise measurement of LHC luminosity ($\mathcal{L}$) at the LHCb interaction point is needed for any cross-section measurement. In the first years of data collection (Run 1: 2009–2013 and Run 2: 2015–2018), online luminosity measurement was mainly based on the released transverse energy provided by the calorimeters through the hardware trigger system. This method will not be available in the next data collection campaign (Run 3: 2022–2025), due to the implementation of a software only trigger [8–10]. In particular, the first station (M1) has been removed and the muon detector is now composed of four stations (M2–M5), comprising 1104 multi-wire proportional chambers (MWPC). The new software trigger, together with the expected increased occupancies, is also the reason for the upgrading of the muon system [11].

A luminosity control system was developed to stabilize the data-collection conditions and to maximize the efficiency of the data acquisition. The instantaneous luminosity at LHCb is continuously controlled and tuned to be within ±3% of its target value. This process is often referred to as *luminosity levelling*.

Different studies have demonstrated an efficiency larger than 95% in detecting minimum ionising particles with a single muon multi-wire proportional chamber [12–16] remaining essentially stable even in case of small changes in the working conditions.

Therefore, the signal rate recorded by the muon system per time unit is potentially a good tool to estimate the value of the luminosity. The aim of this work is to evaluate the precision that those rates can provide to directly infer luminosity and to quantify linearity lack effects or instabilities due to other contributions such as, for example, radiation not originating from beam–beam interactions or electronics noise and detector inefficiency variations.

A first study in this direction has been carried out by analyzing the data collected during special *runs* performed in 2012 at different luminosities. The method, based on previous studies of the performance of MWPC chambers in high luminosity runs [17], realizes a new approach to online luminosity measurements. Its main results will be discussed in the following.

In the future, the use of the new data readout based on optical links [18] will allow to collect the information on hit rates from the whole muon system in a few seconds, making this method a useful tool for Run 3 or future Runs at even higher luminosities, to provide a reliable online luminosity monitoring.

These measurements will be of crucial importance to provide even better luminosity levelling for LHCb. The purpose of this research is to show how a precision of the order of 1% in luminosity evaluation can be achieved on-line using the hit rate of the muon system, without any further software analysis.

2. Experimental Setup

In the LHCb muon detector, each station is divided into 4 regions (R1–R4), at increasing distances from the beam pipe (Figure 1). During Run 1 and Run 2 of the LHC operation, all regions were instrumented with MWPCs except the most irradiated region, R1 of station

M1, where 12 triple-GEM chambers were used. The MWPC chambers in station M1 are composed by only two sensitive gaps, while the chambers in stations M2–M5 have four sensitive gas gaps (Figure 2). Each chamber gap is segmented into pads whose size is constrained by constructional reasons, or by requirements for their electrical capacitance and rate capability. Pads are made of cathodes segments or grouped anode wires, depending on the readout type. In the four-gap chambers, two gaps are ganged in pairs to form a physical channel [13]. In M1, every pad forms a single physical channel.
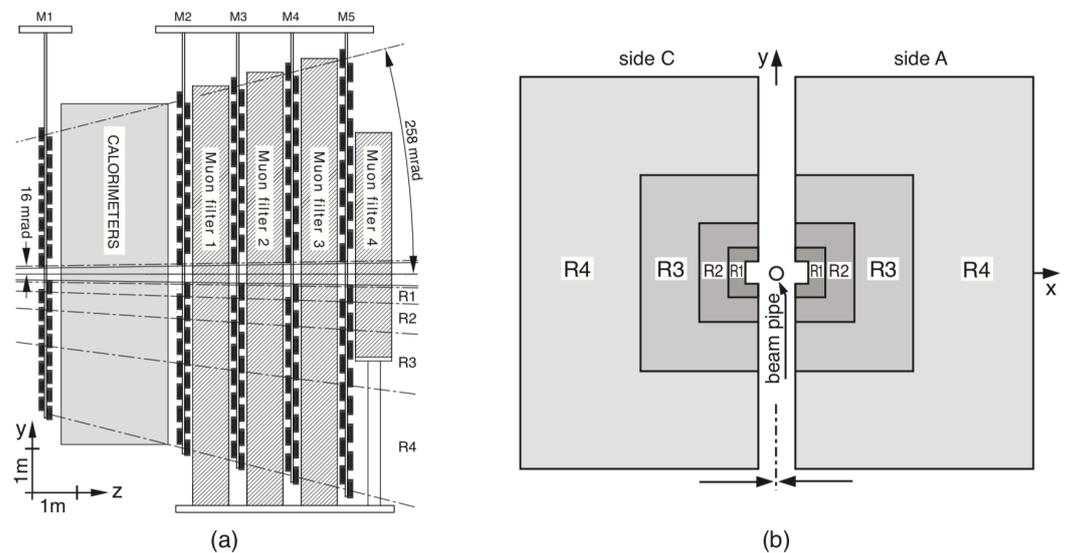

Figure 1. Side view of the LHCb muon detector with stations M1–M5 (**a**). The station layout with the four regions, R1–R4, indicated (**b**).
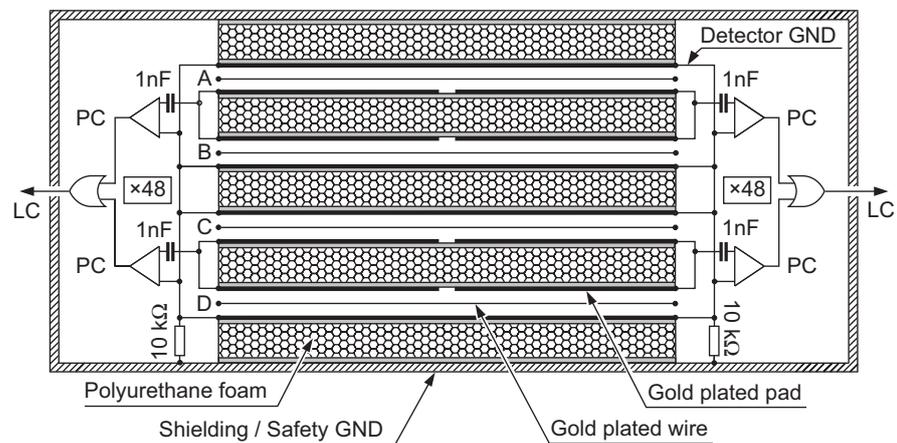

Figure 2. Cross section of a muon MWPC with four gaps. Two corresponding pads in gaps A (C) and B (D) are hard-wired and define a physical channel (PC). The OR of two corresponding physical channels defines a logical channel (LC).

Every chamber is equipped with multiple front-end boards (FEB) to perform the readout. Each FEB has 16 inputs connected to the physical channels, up to 8 outputs (logical channels) and is equipped with two CARIOCA [19] chips and one DIALOG [20] chip. CARIOCA (CERN and RIO Current-mode Amplifier) is an 8 channel Amplifier-Shaper-Discriminator (ASD) and DIALOG (Diagnostic, time Adjustment, and LOGics) is a custom integrated circuit that works right after the ASD, and provides thresholds for the CARIOCA discriminators and different logical functions on the input signals to build logical channels of the required granularity. Each one of the $\sim 10^5$ DIALOG input physical

channels is equipped with a 24-bit counter (or scaler) capable of counting the number of times the analog signal crosses a threshold set. These scalers can count in various modes, including the counting in a pre-set time window (*gate* in the following). The DIALOG chips are connected in I^{2}C chains (for details about I^{2}C protocol, see [21]) and can be configured and readout by service boards (SB—[22]), hosted in custom crates and controlled by the experimental control system (ECS—[23,24]).

3. Principle of Operation

Crucial for the results of the LHCb experiment is a measurement of the luminosity with a precision at a 1%, or even better, level. The assessment of absolute luminosity is based on different ingredients, measured in independent ways and discussed in detail in Ref. [25].

In Runs 1 and 2, the most effective information for on-line luminosity evaluation was provided by the hardware trigger of the calorimeter system at a frequency of about 1 Hz. Those data, stored in the LHCb database every 3 s, are used in this paper and are referred as $\mathcal{L}_{LHCb}$.

To study the muon hit rate, a dedicated ECS procedure was developed. This procedure allows to:

1. Configure the SB to be ready to send a proper gate to start and stop hit counting;
2. Enable the scaler operation on FEBs;
3. Reset possible previous counts registered in FEBs' memory;
4. Send a command to SB to provide a gate to the FEBs;
5. Download the counts of all FEBs' channels and save the values to files.

All data presented in this paper were taken with a gate of 1 s. Due to the different number of chambers and FEBs in the different stations, the time needed to perform the configuration steps (1, 2 and 3) is highly station-dependent. Therefore, step number 4 is issued first on M1, after 2–3 min on M4 and M5 and, after an additional 2–3 min, on M2 and M3. Each acquisition process lasts about 5 min, with the consequence that the rates on the various stations are not simultaneously collected.

As a result of luminosity variation over time, differences of a few percent between the values of $\mathcal{L}_{LHCb}$ are expected when different stations are tested.

The readout of all recorded counts (step number 5) requires the downloading of all data through the slow ECS buses and, therefore, takes about 15 min. In the upgraded version of the experiment, a new, incomparably faster, reading system will be available and all data will be available in a few seconds.

It is worth noting that the described procedure can be performed independently of the LHCb data collection, which is a crucial feature for an on-line LHC luminosity monitor.

4. Dataset

The LHC activity is divided in periods conventionally referred to as fills. In every fill, thousands of bunches, with an order of 10^{11} protons each , enter the accelerator complex, are accelerated and then are kept circulating in the LHC ring and colliding at the interaction points. After some time (1–35 h), the bunch content is significantly depleted and the proton beams are dumped, making the ring ready for another fill.

The data analyzed in this paper belong to a set of special *runs*, where a luminosity larger than usual was set, referred as *HL tests* in the following. The data were collected in December 2012 during fill 3350 and 3374 with a bunch clock time spacing of 50 ns, 70% of the clocks and with bunches colliding at the LHCb interaction point. The average values of $\mathcal{L}_{LHCb}$ recorded by M1 and M2–M3 are reported in Table 1.

Table 1. Values of average luminosity in different stations ($\mathcal{L}_{LHCb}^{s}$) at the acquisition time and average μ (average number of visible pp interactions per bunch crossing) for the *runs* of the *HL tests*.

Fill	*run*	$\mathcal{L}_{LHCb}^{M1}$ (cm^{-2}s^{-1})	$\mathcal{L}_{LHCb}^{M2-M3}$ (cm^{-2}s^{-1})	μ
3350	1	4.01×10^{32}	3.96×10^{32}	1.73
3350	2a	4.93×10^{32}	4.88×10^{32}	2.14
3350	2b	4.86×10^{32}	4.93×10^{32}	2.14
3350	3a	5.83×10^{32}	5.91×10^{32}	2.58
3350	3b	5.82×10^{32}	5.94×10^{32}	2.58
3374	3c	5.93×10^{32}	5.88×10^{32}	2.58
3374	4	7.77×10^{32}	7.98×10^{32}	3.48
3374	5	9.97×10^{32}	9.80×10^{32}	4.32

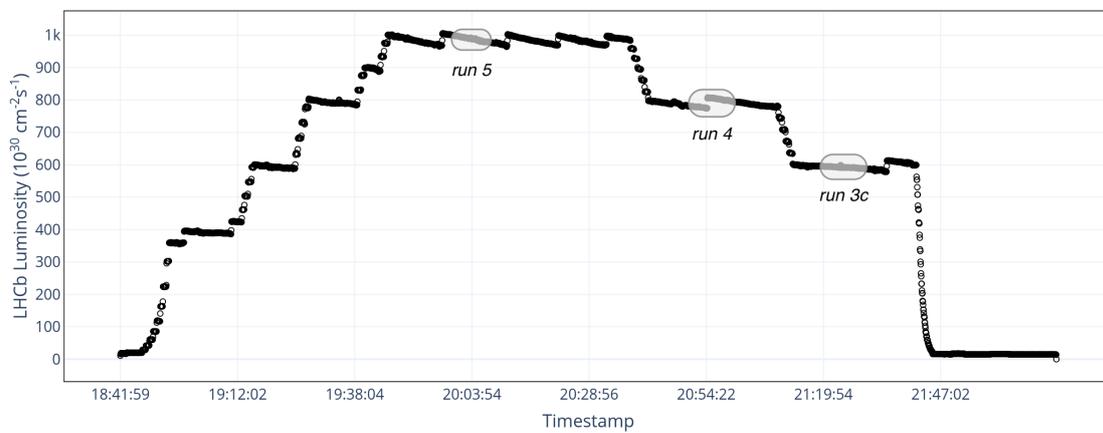The behavior of $\mathcal{L}_{LHCb}$ during fill 3374 is shown in Figure 3.

Figure 3. Luminosity data as recorded during fill 3374. The periods of studied *runs* are indicated.

The plateaus corresponding to different nominal luminosity settings are visible. In each plateau, gradual decreases in luminosity can be observed as the bunch content is depleted, followed by rapid increments when the beam separation at LHCb was changed by the luminosity levelling system.

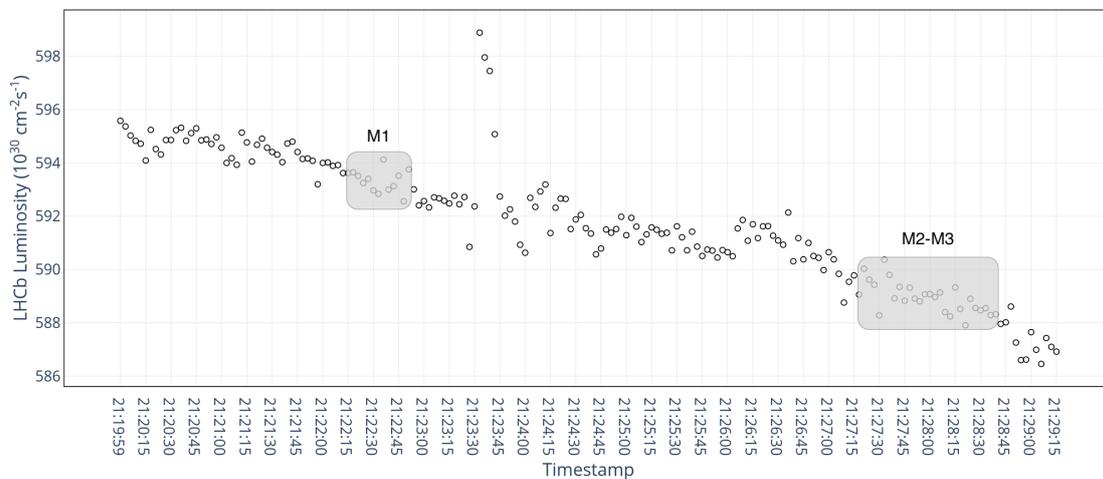The zoom of *run 3c* period is shown in Figure 4.

Figure 4. Luminosity data for *run 3c*. The rectangles highlight the period during which the channels in the different stations were configured, read and the corresponding data stored.

5. Analysis Method

In Figure 5, the distribution of the number of counts recorded in one second in *run 3a* by the physical channels of station M1 region R2 is reported as an example.
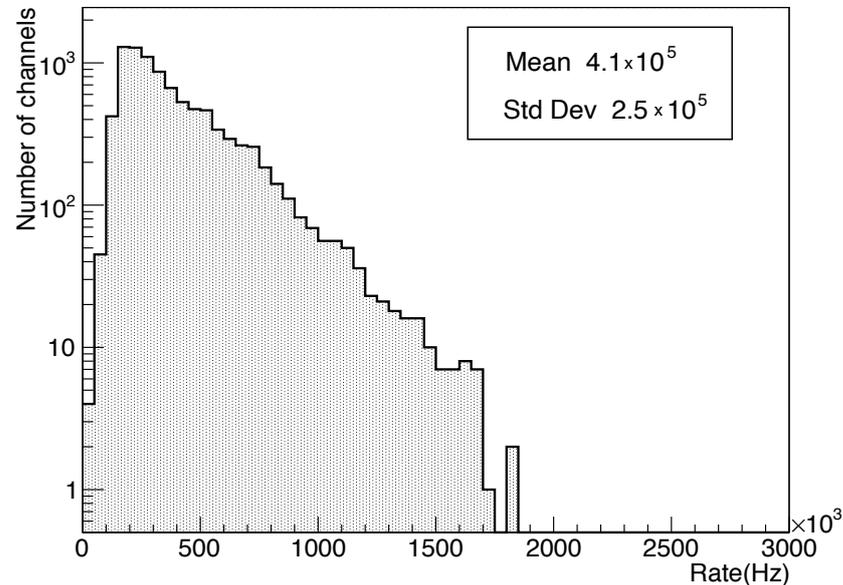

Figure 5. Distribution of the channel counting rates for region R2 of station M1 in *run 3a*.

While the particular shape of this distribution is due to the different positions of the physical channels relative to the interaction point and, thus, to the different particle fluxes received, the mean value for a given detector region is expected to be directly related to the luminosity.

5.1. Dead-Time Correction

Given the high values of $\mathcal{L}$ reached, the effects of possible inefficiencies related to the particle rate should be taken into account. In a previous work [17], it was demonstrated that, in these *HL tests*, the main contribution to inefficiencies was due to the dead time δ_C of the CARIOCA, while other effects (e.g., space charge around the wires) were negligible.

The value of δ_C depends on the total charge amplified and changes in the different detector regions, from about 70 ns to 100 ns.

A method, illustrated in [26], involving the simulation of the beam structure and the chamber response, was developed to evaluate the value of δ_C directly from the rates measured at different luminosities and to perform a channel by channel correction.

In the current analysis, a simplified procedure was used. The instantaneous effective rate R_M in each channel during the trains of consecutive bunch crossings was estimated by dividing the average rates measured in 1 s gate by 0.7. Two constant values of δ_C (100 ns for M1 and 70 ns for M2 and M3) were assumed to correct the values of the rate (R) for the dead-time effect:

$$R = \frac{R_M}{(1 - \delta_C R_M)} \qquad (1)$$

In Figure 6, the same distribution as Figure 5 (region R2 of station M1 in *run 3a*) is reported after correction for the dead-time effect. The mean value results increased by about 5%.
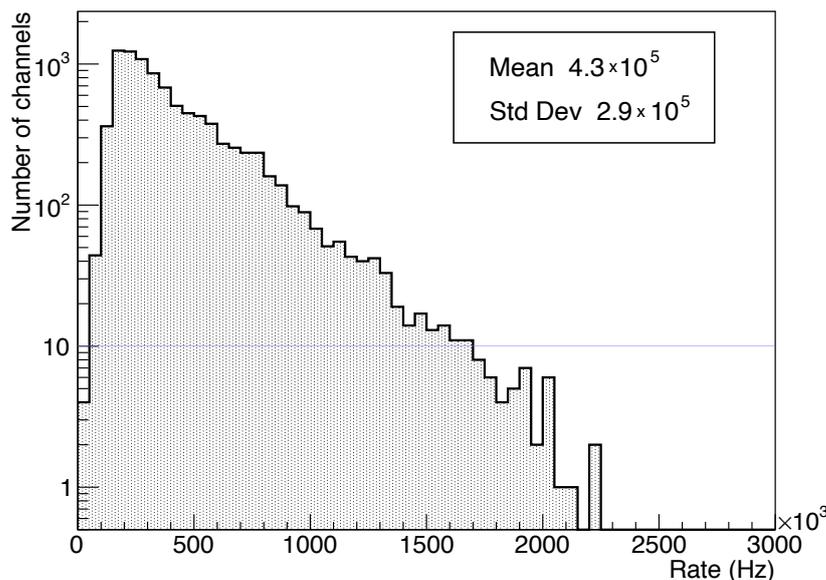
Figure 6. Counting rates distribution for region R2 of station M1 in *run 3a* after dead-time correction.

5.2. Luminosity Evaluation

After evident abnormal counts (due to hot, dead channels) were eliminated, the mean values of the histograms of the corrected rates were evaluated for all regions and used as indicators of the luminosity.

In particular, the ratio between the LHCb luminosity value in a *run 0*, chosen from the available ones in which the rates of station s were acquired ($\mathcal{L}_{0-LHCb}^{s}$), and the corresponding mean rate of counts ($R_0^{r,s}$) was used as a calibration factor for the measurements performed on station s and region r.

In this way, the mean values $R^{r,s}$ provide a luminosity value estimated as:

$$\mathcal{L}_{Muon}^{r,s} = \left(\frac{\mathcal{L}_{0-LHCb}^{s}}{R_0^{r,s}} \right) R^{r,s} \tag{2}$$

The behavior of $\mathcal{L}_{Muon}^{r,s}$ as a function of $\mathcal{L}_{LHCb}^{r,s}$ can thus provide an indication of the muon detector's capability to monitor luminosity.

The first station of the muon system (M1), as explained in the introduction, will not be present in the upgraded version of the LHCb apparatus; nevertheless, it plays an important role in these *HL tests*. As reported in Table 2, the rate of particles in the 10% most irradiated channels of M1 reached, in *run 5*, almost 2 MHz per physical channel, allowing to test the performance of the electronics and the accuracy of the proposed method up to the luminosity foreseen for regions R2–R4 in run 3 [8].

Table 2. Average rates on the 10% most irradiated channels of each region of M1 without dead-time correction.

run	M1R2 (MHz)	M1R3 (MHz)	M1R4 (MHz)
1	0.70	0.73	0.78
2a	0.84	0.89	0.95
2b	0.84	0.88	0.94
3a	0.98	1.02	1.10
3b	0.98	1.04	1.10
3c	1.01	1.04	1.11
4	1.27	1.32	1.41
5	1.57	1.65	1.76

In this study, data acquired in R1 are not used. Chambers in these regions are close to the beam pipe and can be, thus, affected by nonlinear effects due to the radiation emerging from it.

5.3. Accuracy Evaluation

In order to evaluate the intrinsic accuracy of the described method, the ratio $\mathcal{Z}$ between the hit rates recorded by the same channel in two different *runs* can be exploited. In each channel, the value of $\mathcal{Z}$ is expected to depend only on the ratio between the values of $\mathcal{L}$ in the two involved *runs* and, therefore, its fluctuation is a direct indication of the reliability of the measurements.

Two examples of those distributions obtained from data recorded by M2R3 channels in *run 2a* and *Run 1* and by M1R4 channels in *run 4* and *run 3c* (see Table 1) are shown in Figure 7.

As can be seen, the mean values of the distributions reproduce very well the ratio of $\mathcal{L}_{LHCb}$ for the considered *run* pairs (1.23 and 1.31, respectively). The standard deviations were found to be of the order of 1% of the mean value, in reasonable agreement with the statistical fluctuations expected from counts, of the order of 10^4.
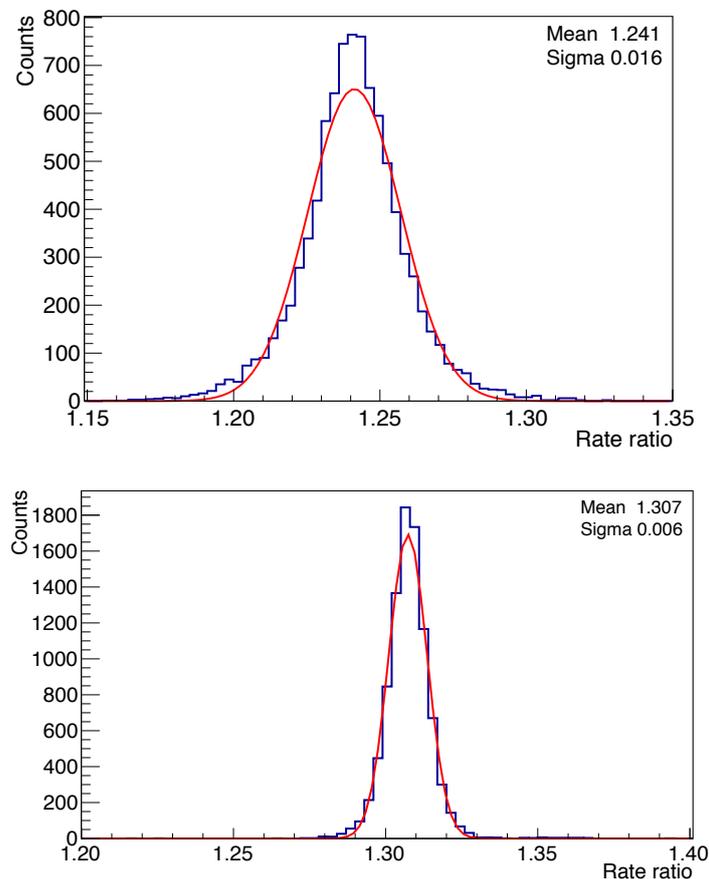

Figure 7. Distribution of channel by channel rate ratio $\mathcal{Z}$ for two luminosities. **Top**: *run 2a* over *run 1* for M2R3 chambers. **Bottom**: *run 4* over *run 3c* for M1R4 chambers with superimposed gaussian fits.

This result, obtained with a gate of 1 s, demonstrates the high potential and the high sensitivity of this method to monitor luminosity changes.

6. Results

The behavior of $\mathcal{L}_{Muon}^{r,s}$ for several regions of stations M1, M2 and M3 evaluated according to Equation (2) is shown in Figure 8 as a function of LHCb luminosity $\mathcal{L}_{LHCb}$ superimposed to the ideal behavior.

The first acquired *run* was chosen for calibration to better check for possible "drifts" with time or with increasing rate values, as could result from an inadequate correction of dead-time inefficiencies.
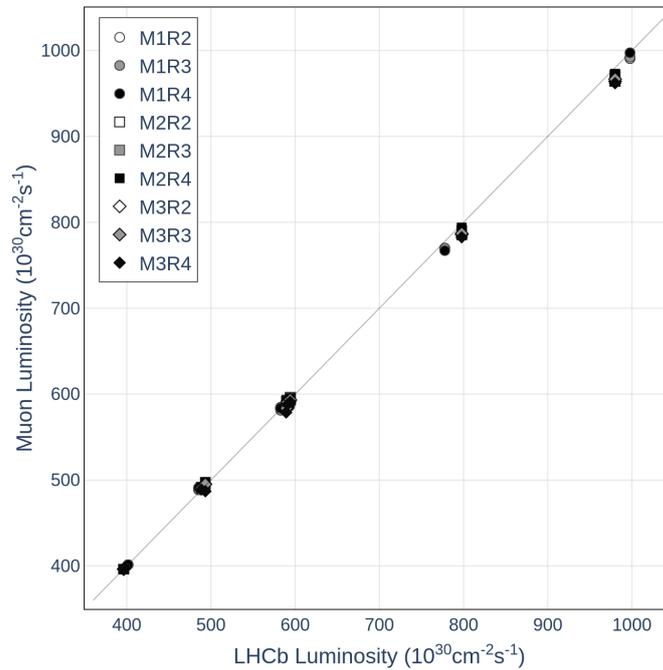

Figure 8. Values of $\mathcal{L}_{Muon}^{r,m}$, as defined in Equation (2), as a function of the LHCb luminosity $\mathcal{L}_{LHCb}^{r,m}$. The line represents the ideal behavior.

Given the measured rates and the high number of channels per station (10^3–10^4), statistical errors on the points shown in Figure 8 are less than 1‰ and thus not visible. Moreover, points of measurements in the different regions overlap.

A good correlation between $\mathcal{L}_{Muon}$ and $\mathcal{L}_{LHCb}$ was found. To better visualize the effective accuracy of the proposed method, the relative differences between $\mathcal{L}_{Muon}^{r,s}$ and $\mathcal{L}_{LHCb}^{r,s}$ are reported in Figure 9.
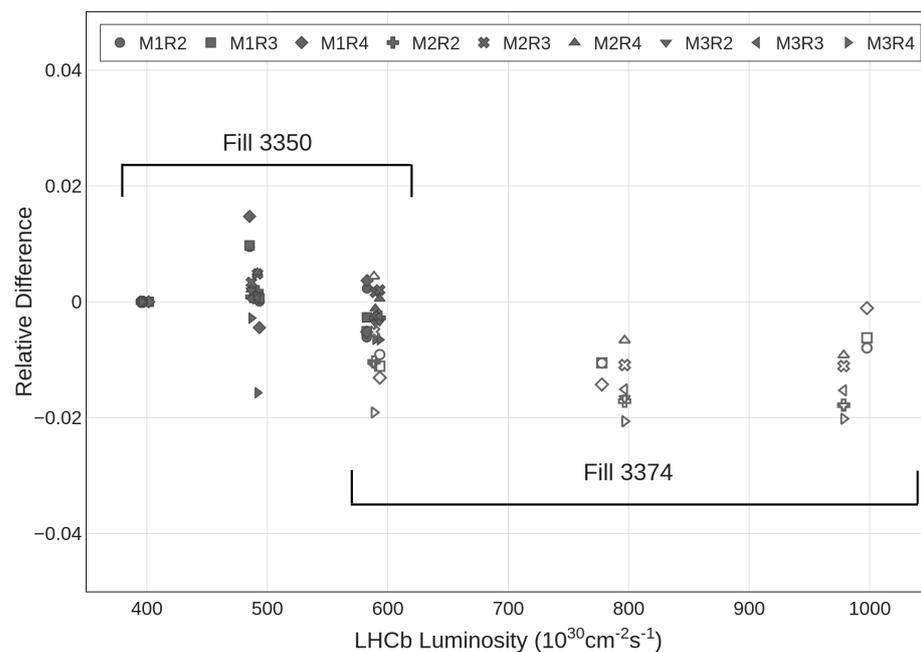

Figure 9. Relative differences between $\mathcal{L}_{Muon}^{r,s}$ and $\mathcal{L}_{LHCb}^{r,s}$. Full symbols refer to fill 3350 and open ones to fill 3374.

In the whole explored range, an agreement within ±2% was found.

In Figure 10, the correlation between $\mathcal{L}_{Muon}$ obtained from the average rates measured in each station and $\mathcal{L}_{LHCb}$ is shown.
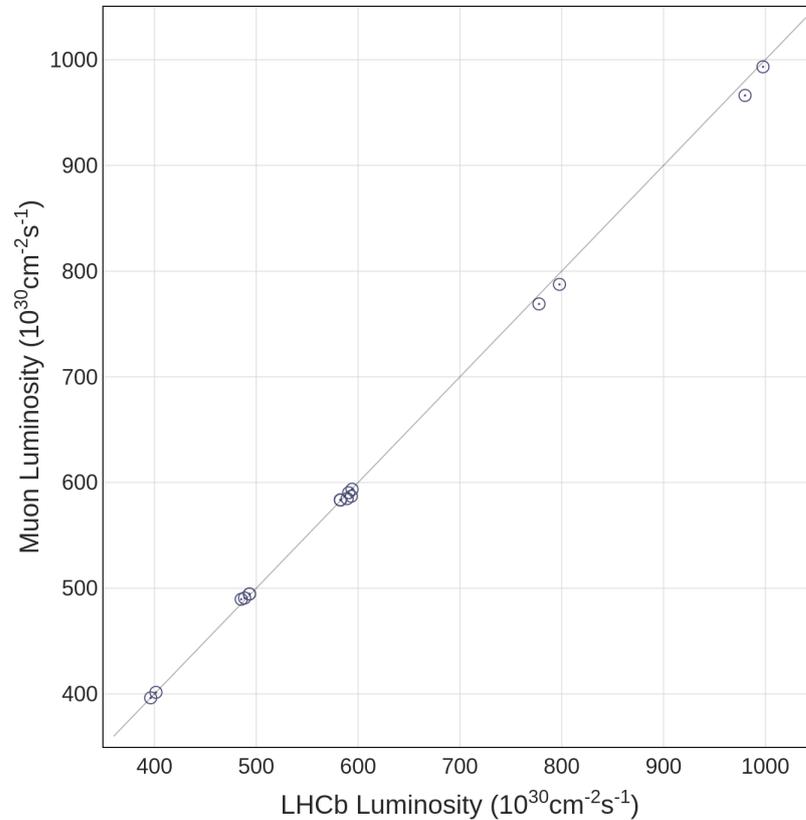

Figure 10. Behavior of $\mathcal{L}_{Muon}$ obtained from the average rate of each station as a function of $\mathcal{L}_{LHCb}$ (see text) superimposed to a line indicating the ideal behavior.

The residuals with respect to the ideal response are shown in Figure 11. In the overall range an accuracy better than ±1.5% was found.

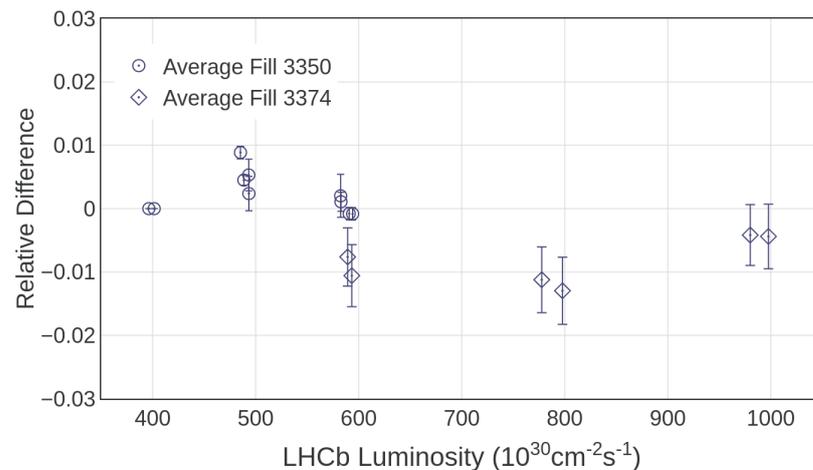**Figure 11.** Relative difference between $\mathcal{L}_{Muon}$ and $\mathcal{L}_{LHCb}$ (see text).

7. Systematic Effects

The relatively high value of the data dispersion shown in Figures 9 and 11, requires a careful investigation of the systematic effects, and, eventually, their variation over time.

No indication of a possible instrumental origin was found. The fluctuations between the results of different regions shown in Figure 9 can be explained in terms of small $\mathcal{L}_{LHCb}$ variations in the different regions at the acquisition time, as described in Section 3.

Both in Figures 9 and 11, residuals show a two-fold behavior, with an evident dependence on the fill: mostly positive in the first three *runs* (fill 3350) and negative in the other *runs* (fill 3374).

Looking at the distribution of the channel by channel rate ratios obtained for all pairs of *runs* belonging to the two different fills, non-Gaussian structures appear. For example, Figure 12 shows the channel by channel ratio of *run 3c* and *run 5* over *run 1* for region M1R4.
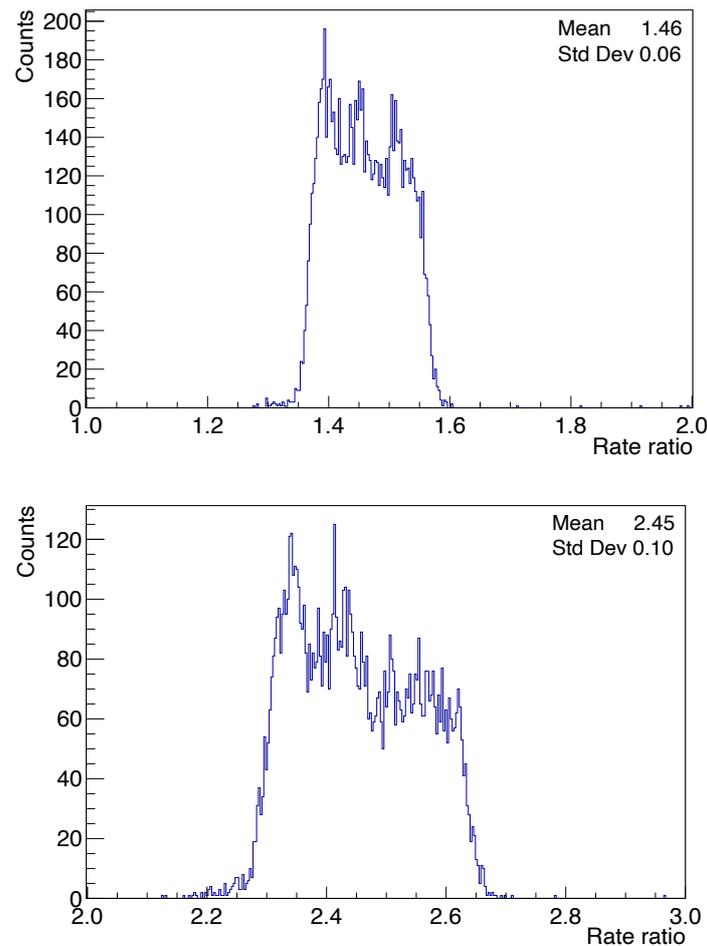

Figure 12. Distribution of channel by channel rate ratio Z for two values of $\mathcal{L}$ for M1R4. **Top**: *run 3c* over *run 1*. **Bottom**: *run 5* over *run 1*.

These plots suggest the presence of underlying systematic effects related to different beam settings at different fills that change the hits distribution in the muon detector.

A further implementation of a system allowing the counters to measure the rates in coincidence with selected clocks *beam–beam* interactions (*bb*), *beam-empty (be)* and *empty-empty (ee)* is under study. This system would not only allow to better measure the hit rate due to beam–beam interactions and make more precise dead-time corrections, but it also would permit an interesting measurement of the level of radiation in the different detector regions. In particular, a flat in time significant contribution is expected from thermalized neutrons capture events.

Further tests are foreseen in Run 3 with the new fast readout system, to assess the validity of the proposed method and further investigate the sources of systematic effects.

8. Conclusions

Luminosity measurement is important for LHCb operation and several independent methods are being developed. For operations in Run 3, a new dedicated luminometer PLUME (Probe for LUminosity MEasurement) [27] has been designed to perform online measurements of luminosity and the number of visible interactions per bunch crossing. Moreover, several off-line strategies are foreseen: LHCb will continue to use information from different subdetectors, increasing the number of monitored quantities with reference to those used in the past (i.e., velo hits/tracks/vertices in the high level trigger and calorimetric transverse energy deposition, N hits in the scintillator pad detector and number of muons from the level 0 trigger). In Run 3, similar counters from the new VELO (vertex locator), as well as the counters from PLUME, RICH, ECAL (electromagnetic calorimeter), HCAL (hadronic calorimeter), SciFi (scintillating fibres) and muons will be exploited. All these counters (excluding PLUME), though, will use the LHCb software trigger, not available during periods of no global run.

In this paper, a method was proposed for the on-line monitoring of the luminosity regardless of the LHCb data collection. Data from *runs* taken in 2012 at different luminosities were analyzed and the behavior of the average rates, corrected for the readout dead-time, measured in different regions of the muon detector was studied.

Those rates showed to be a good estimator of the LHCb luminosity with an accuracy better than 1.5% and even better inside one single fill. Systematics are to be further explored. A high speed readout in Run 3 will allow collecting larger statistics to further confirm the capability of the muon system to monitor the luminosity at LHCb. Upgrades in the muon system readout electronics aiming to cope with higher luminosities are currently under study.

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