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The LHCb Muon Detector Upgrades

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After three years of shutdown (LS2), the LHC restarted in April 2022 and the plan is to run at an average instantaneous luminosity of $2.0 \times 10^{33} \text{cm}^{-2}\ \text{s}^{-1}$ at the LHCb interaction point, a factor of five higher than the previous runs. In order to cope with the increased luminosity and to take data at the full bunch crossing frequency (30MHz visible interaction rate) in trigger-less mode, the LHCb Detector has just undergone a major upgrade, which will allow LHCb to collect approximately 50 fb^{-1} in the next 10 years. The LHCb Muon Detector has performed exceptionally well in the last ten years, providing Muon track detection efficiency of 99% in Run 1 and 97.4% in Run 2. Its main upgrade consists in the new off-detector and control electronics, able to cope with the full LHC bunch crossing frequency in trigger-less mode. A phase 2 upgrade of the LHCb Detector has also been proposed, for the further increase of the instantaneous luminosity foreseen by LHC (High Lumi LHC). The upgraded Muon Detector is presented, with particular focus on the installation and commissioning activities, the results of the functional tests performed during the LS2 and the very first and preliminary performance studies with new data. An overview of the proposed Upgrade 2 Muon detector is also given.

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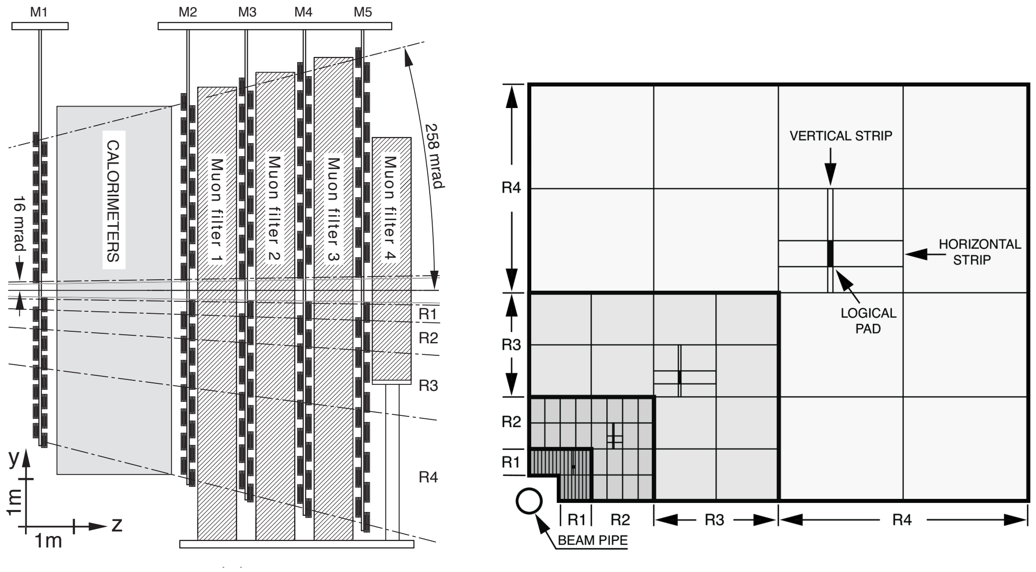

Figure 1: Left: Configuration of the Muon Stations during the 2011-2018 data taking period. Right: Definition of the four regions R1-4 of one station; the grid corresponds to the MWPCs in each region; the logical pads are defined from the physical horizontal and vertical strips. Figures taken from [2] and [3].

1. The Muon Detector at the LHCb Experiment

The Muon system [1, 2] of the LHCb Detector is composed of four (five, during the 2011-2018 data taking period) stations, alternating with layers of iron absorbers. It stands furthest from the interaction point, at the end of the LHCb spectrometer, with the purpose of stopping and detecting high transverse momentum (p_T) muons. It also contributes to the reconstruction and particle identification (PID) of detected particle tracks. Additionally, during the 2011-2018 data taking period, it provided fast trigger information to the lowest level (L0) hardware trigger. As many interesting physics channels are identified by a clear muon signature, it is crucial that the Muon system performs at its highest performance to ensure the success of the LHCb physics programme.

The detector is equipped with Multi-Wire Proportional Chambers (MWPC), which can be read-out at vertical anode strips, which define the x resolution, and cathode pads, which define the y resolution. These physical channels can be combined with a logical "and" to define pixels in each station, which send binary information, the hits, to the DAQ system. To account for the varying expected hit occupancy across the detector, the stations have different granularities.

During the 2011-2018 period, the system has performed extremely well. Operating at an instantaneous luminosity of up to $4 \cdot 10^{32}$ cm^{-2}s^{-1}, twice its design value, the reported detection efficiency was over 99% across the detector [2]. The measured PID efficiency was very high as well, of about 97%, with very low mis-identification rates. Over the nine years of operation, the detector has shown no significant signs of ageing [4].

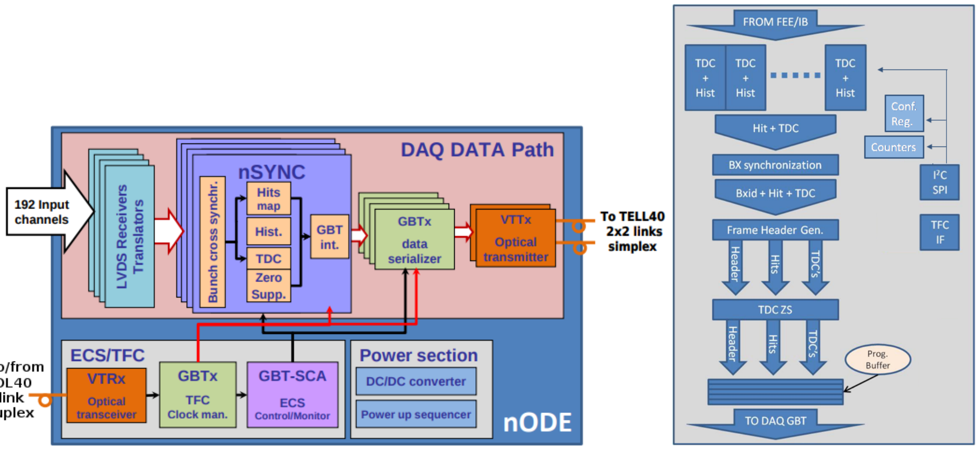

Figure 2: Left: Schematic of the architecture of the new Off-Detector Electronics (nODE) board, for the Muon system. Right: Scheme of how data, in the form of digital signals coming from the muon Front-End (FE) boards, is processed by a nSYNC chip, before being sent to the rest of the DAQ system.

2. LHCb Upgrade Phase I

The LHCb Detector underwent under its first major upgrade in the Shutdown period between 2018 and 2022 [5]. The goal of such an upgrade is to expand the physics reach of the experiment, and in particular to increase the statistical power of the collected data, for precision heavy flavour physics studies. The instantaneous luminosity at the LHCb interaction point was increased by a factor of five, and now can reach up to a value of $2 \cdot 10^{33}$ cm^{-2}s^{-1}. Furthermore, the readout rate was matched to the LHC bunch crossing rate of 40MHz, with the removal of the lower level hardware trigger, in favour of a purely software trigger. The new trigger system greatly improves on the previous one on the efficiency for hadronic final states, and is much more versatile.

Many of the sub-detectors have been upgraded to sustain the higher pile-up and occupancy rates. Most of the Front-End (FE) electronics have been replaced, and the DAQ network has been improved alongside. A new Vertex Locator (VELO), a scintillating fibre tracker (Sci-Fi), and a new Upstream Tracker (UT), have been installed, replacing most of the old tracking system. The Ring Cherenkov detectors (RICH1-2), have also had their hardware significantly upgraded. The upgraded detector will be able to collect 50 fb^{-1} of collision data over the next two data taking runs (2022-2032).

As part of the LHCb upgrade, the first station of the Muon Detector (M1) has been removed. Its main purpose was to provide fast measurements of the track's p_T for the lower level trigger, and the detection and tracking efficiencies are unaffected by its removal. New off-detector electronics (nODE) have been installed, which feature the new nSYNC chipsets for signal processing. Each nODE reads 192 digital channels coming from the FEs, and is responsible for measuring the hit arrival time, and for the hit time alignment.

Every nODE is equipped with four nSYNCs, which are the custom radiation tolerant ASICs. An nSYNC reads 48 digital channels, and measures the arrival times with Time-to-Digital converters (TDC), as a phase difference with the master LHC clock, working at a nominal resolution of 1.56 ns (one sixteenth of the nominal LHC clock cycle of 25 ns). The master clock is handled and

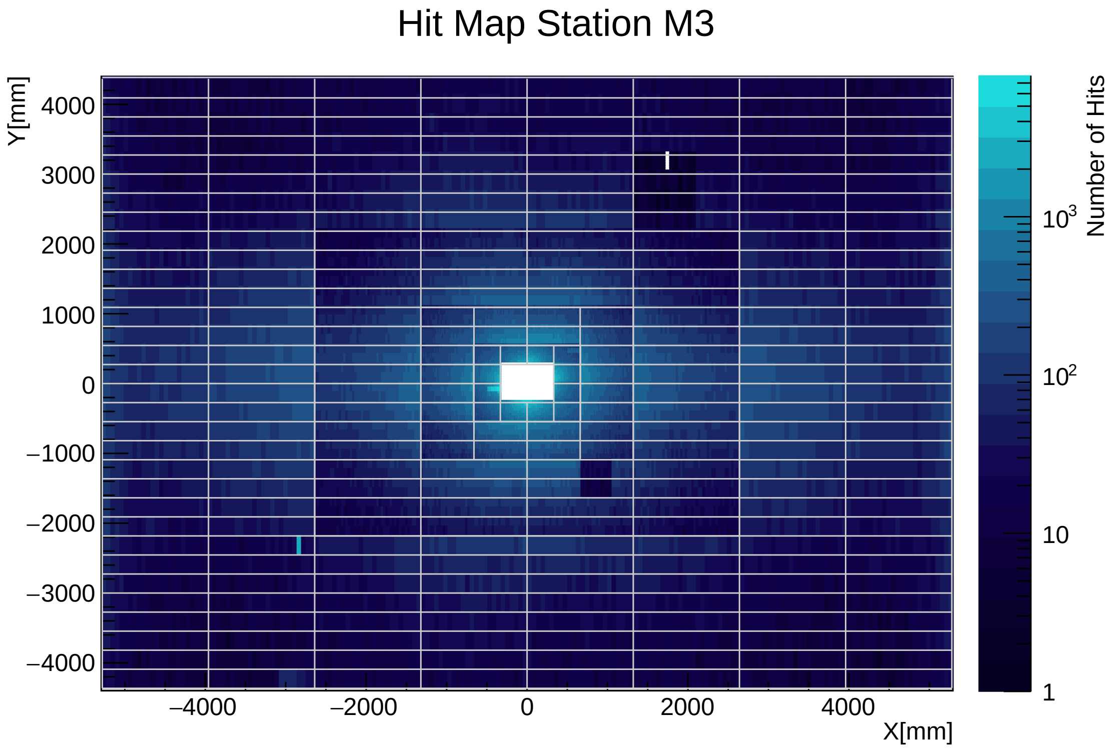

Figure 3: Integrated illumination map of the third Muon station M3, taken during October 2022, at a LHC beam energy of 6.8 TeV. The overlayed grid shows the positions of the Multi-Wire Proportional Chambers.

distributed on the nODE board by GigaBit Transceivers (GBTs). The GBTs also interface with the Experimental Control System, to configure the various chipsets on the board. The data processed by the nSYNCs is then sent to the rest of the DAQ system, based on the Tell40 readout boards.

Furthermore, the new data taking run sees the introduction of the Muon system as a luminosity monitor, along several other sub-detectors. Good knowledge of the instantaneous luminosity $\mathcal{L}$ at the LHCb collision point is necessary to achieve high precision physics measurements. A new dedicated luminometer, the Probe for LUminosity MEasurement (PLUME), has been installed. PLUME measures the number of visible pp interactions at the collision point μ_{vis}, to which $\mathcal{L}$ is directly proportional:

$$\mathcal{L} \propto \frac{\mu_{vis}}{\sigma_{vis}},$$

where σ_{vis} is the visible pp interaction cross-section. σ_{vis} is measured during special LHC runs, with the Van Der Meer scan method. The other LHCb sub-detectors can provide cross-checks to PLUME's measurement, by using "counters", measurements of the observed activity (*e.g.* number of hits, tracks, clusters etc.); these counters are directly proportional to μ_{vis}. In the case of the Muon system, the counter is the total number of hits recorded per collision [6]. It was shown, using data collected in previous runs, that for varying luminosities, the detector response was linear, with only a relative difference of $< 2\%$ to the measured reference luminosity. Systematic effects are still under study.

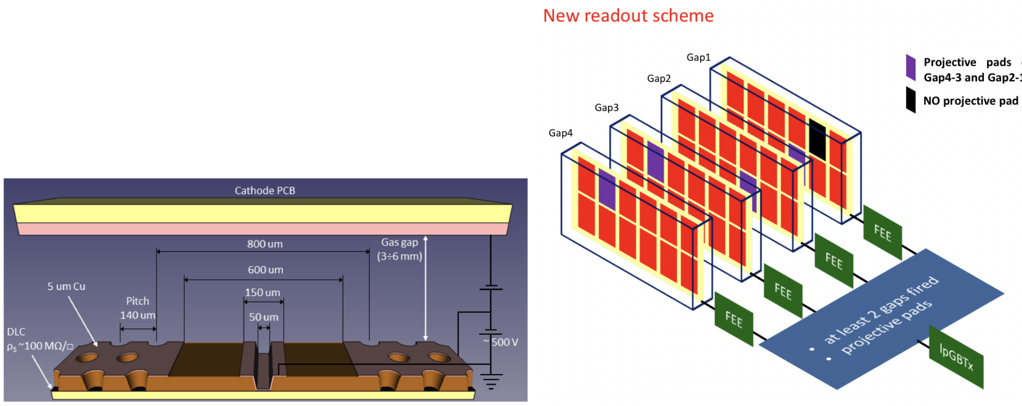

Figure 4: Left: Schematic of the proposed μ-RWell detector for the second Upgrade of the Muon Detector. Right: New proposed readout scheme for the MWPCs in the outer regions of the Upgraded Muon system.

3. Commissioning of the detector

The Run 3 commissioning period started in 2021 with the October Beam Test, when beams of an energy of 450 GeV were injected in the LHC. For the first time, the Muon system was included in the “global” data-taking mode of LHCb, and a coarse time alignment of hits with the LHC clock was achieved. The beam test set the path to the 2022 period of commissioning, putting the entire DAQ and ECS system to the test. The luminosity counters were also tested, showing similar results to what was previously observed.

The final stretch of commissioning begun in March 2022. After some “Cosmic runs”, meant to deal with the issues encountered the previous October, the LHC beam energy was ramped up to its highest ever value, hitting 6.8 TeV on the 5$^{\text{th}}$ of July. The Muon system has been smoothly running, and now the focus is on ironing out smaller issues, and the finer time alignment of the detector. The commissioning period is expected to end at the beginning of 2023.

4. Prospects for LHCb Upgrade Phase II

Work is already ongoing for the next phase of the LHCb Upgrade [7, 8]. Planned for the data taking period in 2032 and beyond, the Upgrade will tackle the challenge of the higher luminosity delivered by the High Lumi LHC (HL-LHC), which will reach a value of $1.5 \cdot 10^{34}$ cm^{-2}s^{-1} at the LHCb interaction point. The almost tenfold increase in luminosity will mean an expected increase of the same factor in the hit occupancy across the Muon Detector.

The MWPCs in the most inner regions of the detector would see a significant increase in occupancy and dead time inefficiency, and additional shielding in front of the system would only slighty reduce these effects. Thus, a detector based on micro-pattern technology is being tested, the new micro-Resistive Well Detector, μ-RWell [9]. In the outer regions, the MWPCs are expected to be able to cope with the hit rate increase, and to reduce inefficiency, the FE scheme is being redesigned to be able to readout each chamber plane separately. This will allow for the reuse of a good fraction of the existing chambers, reducing costs. The improved readout scheme is being tested with simulated data.

5. Conclusions

The Muon system has performed exceptionally well in the first two data-taking runs of LHCb. It has also shown little ageing in its hardware, the Multi-Wire Proportional Chambers, which have been kept in the first phase of the LHCb Upgrade. To cope with the fivefold increase in instantaneous luminosity, the detector electronics have been upgraded, and have been tested extensively during the 2021-2022 commissioning period of LHCb. This commissioning is expected to be ending soon, and the Muon system is projected to perform just as well in the next ten years of data-taking. R&D is already ongoing for the second phase of the Upgrade, planned to start in 2032, to tackle the challenge of the expected tenfold increase in hit rates, with the planned High Lumi LHC.

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