IL NUOVO CIMENTO **47 C** (2024) 97
DOI 10.1393/ncc/i2024-24097-8

Colloquia: IFAE 2023

The Upgrade II of the LHCb muon detector(*)

F. Debernardis on behalf of the LHCb Collaboration
University and INFN Bari - Bari, Italy

received 13 February 2024

Summary. — LHCb is one of the large experiments operating at the LHC collider, mainly dedicated to b quark physics studies. To date, it contributed significantly to the *Flavor Physics* and *Electroweak Physics* in the forward region, thanks to its excellent performance during the LHC Runs 1 and Run 2, at an instantaneous luminosity $\mathcal{L}_{peak} = 4 \times 10^{32}$ cm^{-2}s^{-1}. The apparatus has recently been upgraded to efficiently work at $\mathcal{L}_{peak} = 2 \times 10^{33}$ cm^{-2}s^{-1} for the current Run 3 data taking. Moreover, the further luminosity increase planned for the LHC Run 5 will open up new opportunities for LHCb in the field of precision flavor physics and physics beyond the Standard Model, making necessary the Upgrade II of the apparatus. From 2035, LHCb is expected to work at $\mathcal{L}_{peak} = 1.5 \times 10^{34}$ cm^{-2}s^{-1}, collecting 300 fb^{-1} data. Several options are under study for the muon detector Upgrade II, aiming to manage such an increase in luminosity and the expected rates of incident particles, while preserving its excellent muons detection efficiency. In this article, the state of the art of the muon detector Upgrade II is presented.

1. – The LHCb muon detector and the Upgrade II

The LHCb upgrade II is a unique opportunity for the flavor physics research in the future LHC high luminosity (HL) era. A luminosity of $L = 1.5 \times 10^{34}$ cm^{-2}sec^{-1} would be indeed reached from Run 5 in 2035, consisting in a big leap that would allow an enormous data accumulation. The LHCb experiment can thus profit from high-precision measurements in a very broad field of flavor physics [1], thanks to specialised data processing technologies and detectors. Among them, the muon detector is one of the most important, which will contribute mostly to the flavour physics reaches of the future era.

The layout of the LHCb muon detector, located at the far end of the LHCb apparatus [2], is shown in fig. 1 (centre) and consists of four rectangular stations (M2÷M5) interleaved with 80 cm thick iron absorbers. Each station is divided into four regions (R1÷R4), all equipped with 4-gaps multi-wire proportional chambers (MWPCs). A double system of anodes and cathodes is installed in each gap of the chambers (fig. 1, left), where the anodes consist of grouped wires in the gap. The cathodes are instead etched pads on the gaps cathodic planes. Moreover, logical pads are defined in the gaps as a logical AND between grouped wires and strips (or cathodes pads). However, logical pads

(*) IFAE 2023 - "New Technologies" session

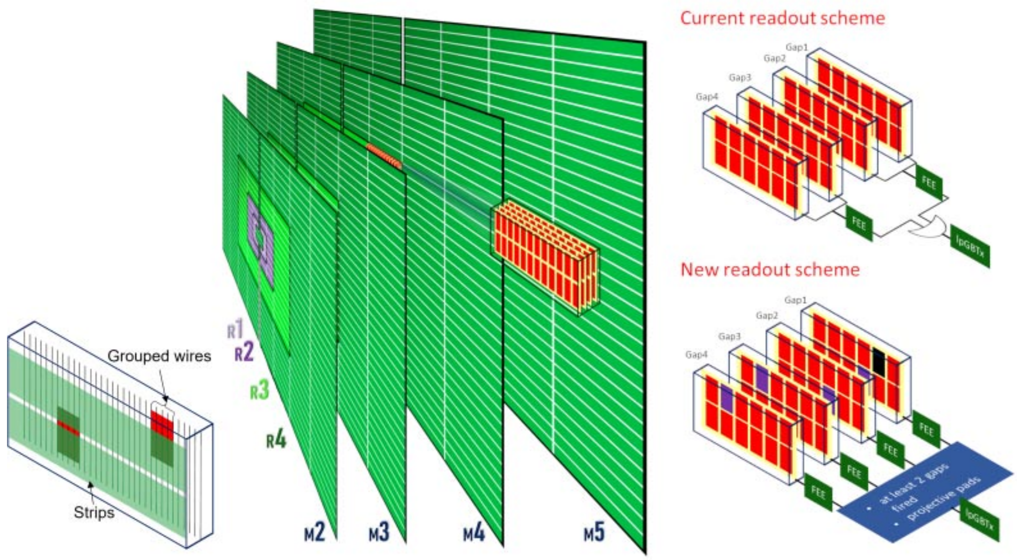

Fig. 1. – (Left): current layout of the LHCb muon detector active volumes. An expanded view of a R3M4 chamber is shown, together with the detail of its (red) logical pads. At left, the sketch of logical pads, defined as logic AND of grouped wires and strips, is shown too. (Right): the current and the proposed readout schemes are shown. Projective pads are shown in violet.

are used only in inner regions R1-R2 of the stations M2-M4. Instead, only the anodes or only the cathodes are used elsewhere.

In the future high luminosity conditions, very high rates are expected in the muon detector, far exceeding those for which it was designed [3]. These rates cannot be supported by the current chambers, inducing then several significant inefficiency effects. High mis-identification of muons signals can be induced indeed at high rates, considering the expected crowded environment of background hits between the muons ones. Moreover, significant inefficiency effects by the electronics dead-time are expected at high luminosity, mostly due to the great sizes of the current physical pads, anodes and cathode, mostly in inner regions R1-R2. Therefore, as shown in the next sections, the Upgrade II of the muon detector is necessary to guarantee in the new HL era the same Run 1 and Run 2 excellent performance, aiming at first to reduce the background signals in the chamber by means of an opportune filter in front of the first (M2) station. Then, a new readout scheme is proposed, that would significantly reduce the signals by the background particles without losses in the muon identifications performance of the detector. The new scheme would be applied considering the muRWELL technology in the inner regions, and the present MWPCs in the outer regions. This new technology has indeed an higher efficiency on the signal generations at the particles passage, as well as an higher granularity that improves the electronics dead time effects.

2. – Estimation of expected rates at high luminosity

The LHC Run 3 start, on 5 July 2022, has been a good occasion to carry out measurements with the muon detector of the LHCb experiment. In particular, the number of hits

TABLE I. – *Table of the maximum rates measured at the LHC Run 3 and extrapolated at Run 5 luminosity. The rates decrease in the R1-R3 regions of M2 is evident, due to the hypothesis of installing an appropriate absorber in front of M2* [4].

	Maximum chamber rate (kHz/cm²)				
	At Run 3	At Run 5			
	M2	M2	M3	M4	M5
R1	33.1	594.0 → 344.5	274.5	203.5	232.7
R2	12.2	255.6 → 79.2	64.2	34.1	39.0
R3	3.0	53.4 → 19.2	8.9	6.2	8.9
R4	0.4	9.9	3.0	1.7	6.8

in each gap in a time window of 20 sec has been measured at several LHC luminosity configurations. Then, after the noisy counting channels removal, by means of a specifically built software, the mean rates per square centimeter of each chamber have been calculated at present luminosity configurations. A linear fit in the $(luminosity, rates/cm^2)$ plane has been thus performed for each chamber, extrapolating the rates/cm^2 at Run 5 luminosity, $L = 1.5 \times 10^{34}$ cm^{-2}s^{-1}. In table I, the comparison between the maximum extrapolated rates for each region of the M2 station, and the ones at the luminosity $L = 4.36 \times 10^{32}$ cm^{-2}s^{-1} to which are measured are shown. Here, a large mean increase factor of ~ 20 is evident, very critical for the current chamber technology (fig. 1), especially considering that they were designed([1]) for rates of the order of few kHz/cm^2 [3]. Moreover, note that a rate reduction is also shown in table I, deriving from the hypothesis of installing an opportune filter in front of the M2 station [4]. This hypothesis is indeed under discussion for the detector Upgrade II, contributing in particular to the reduction of background particles rates. However, the overall estimated rates increase definitively confirms the need of studying a new design for the Upgrade II of the muon detector and the need for a new readout scheme to cope with the future high luminosity environment.

3. – The new readout scheme for the muon detector Upgrade II

In the current readout scheme, the pad systems of one chamber are projectively OR-coupled to form bi-gaps, that are again OR-coupled at Front End Electronics (FEE) level, as shown in fig. 1 (top right). A four gaps with projectively OR-coupled pads is then obtained, that would generate a very large (up to 80%) input rate, particularly due to single hit particles. Therefore, a new scheme is proposed (fig. 1, bottom right) where each gap is read out separately and a signal is generated when projective physical pads have been fired in at least 2 gaps (out of 4).

An accurate analysis of the new readout scheme effects has been performed, by mean of a dedicated software able to simulate all chambers in the detector, considering all the physical pads in the corresponding gaps. Then, starting from Monte Carlo data

([1]) The original LHCb apparatus was designed to operate at an instantaneous luminosity up to 2×10^{32} cm^{-2}s^{-1}.

TABLE II. – *Efficiency losses of individual muons identification with the new readout scheme, as a functions of their momentum. The specified stations must be passed by particles to be identified as muons at the first IsMuon selection level.*

p [GeV/c]	efficiency loss
$3 < p < 6$ (M2 & M3)	$\mathbf{1.13\% \pm 0.08\%}$
$6 < p < 10$ (M2 &M3 &(M4 || M5))	$\mathbf{1.06\% \pm 0.06\%}$
$p > 10$ (M2 & M3 & M4 & M5)	$\mathbf{2.23\% \pm 0.04\%}$

of the pp collisions at LHCb, the tool accurately simulates the signals generation in the chambers due to background particles and muons. It takes account of the detector efficiencies, as well as of the crosstalk phenomena between the physical pads in the gaps. In particular, the efficiency and the pads size of the μ-RWELL detector technology [5] has been simulated in inner regions R1-R2 of all the stations, in place of the present MWPCs. The latter having single-gap efficiency of $85 \div 88\%$ and equip instead outer regions R3-R4. The μ-RWELLs would be indeed appropriate for the future era, being characterized by a high single-gap efficiency of 95% and a rate capability up to 1 MHz/cm^2. Moreover they can provide higher granularity than the current one, thanks to pads approximately 10 times smaller [5]. Preliminary results of this analysis show that the new readout scheme would induce a reduction up to 84% of signals from background particles in the chambers per event, at high luminosity. The muon loss per event induced by the new readout scheme is shown in table II. It does not exceed the 2% per event for muons with energy greater 10 GeV, while reaching about 1% for muons of lower energy. Note that the energy ranges reported in table II are linked to the LHCb muon identification algorithm *IsMuon* [3] which identifies a particle as a muon based on the particle energy and the crossed stations as shown in table II.

The muon losses per event are extremely low compared to the background particles reduction. This implies that the new readout scheme is a valid option to improve the overall detector performance, in particular in view of future high luminosity.

Once confirmed the new readout scheme validity for the Upgrade II, it is necessary to deepen the study to take into account the effects of the electronics dead time, which could be significant.

4. – Estimation of electronics dead time effects at Upgrade II

The electronics dead time corresponds to an inactivity period of physical pads, anodes and cathodes, starting from their firing by the passing particles. The inactivity period is thus characteristic of the electronics coupled to the interested physical pads and it currently corresponds to ~ 100 nsec [6]. A very high value, four times the LHC bunch crossing period (25 nsec), that would really affect the detector performance at high

TABLE III. – *Maximum dead time inefficiency extrapolated for each region/station at present detector condition in case of MWPCs (left) and considering μ-RWELLs in the inner regions R1-R2 of all the stations.*

Maximum deadtime inefficiency % MWPC				
	M2	M3	M4	M5
R1	17.14	6.65	7.50	8.66
R2	17.81	4.62	5.69	7.34
R3	7.21	1.72	3.49	5.68
R4	8.24	3.37	2.30	8.55

Maximum deadtime inefficiency % μRWELL				
	M2	M3	M4	M5
R1	1.18	0.48	0.79	0.95
R2	1.22	0.32	0.31	0.41
R3	7.21	1.72	3.49	5.68
R4	8.24	3.37	2.30	8.55

luminosity conditions. Indeed, the higher the rates the chambers are exposed to, the larger the chambers inactive areas will be during the dead time period, inducing losses of signals from muons of interest for the LHCb physics. Therefore the study of these effects on the LHCb muon detector efficiency is a priority, especially considering the large physical pad size in the chambers [2], ranging from a few centimeters up to tens of centimetres [2].

For this purpose, the high rates/cm^2 previously extrapolated have been used to estimate the dead time inefficiency for each chamber at Run 5 luminosity condition. These quantities represent the probability that a muon passing through the chamber is not detected due to the inactivity of the affected physical pad/pads. The latter corresponding to the cathodes of the current MWPC in all regions, for all stations, except in the R4 ones where only the anodes are implemented. However, also the μRWELL hypothesis has been considered in the dead time inefficiency calculations. The maximum values of the dead time inefficiencies per region are shown in table III, where the benefit of having smaller pads of μRWELLs is very evident. Indeed, in the internal regions of the M2 station, the $\sim 20\%$ inefficiency estimated in the case of current configuration would be reduced to around 1%. A strong reduction is also evident for the other stations. These evaluations (table III), however, require a deeper investigation on the detection efficiency of the signal muons, defined as those generated in golden decay channels for LHCb physics. Therefore, Monte Carlo samples of four very rare decay topologies have been analysed:

- $B_s^0 \to \mu^+\mu^-$
- $D^0 \to \mu^+\mu^-$
- $K_s^0 \to \mu^+\mu^-$
- $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(K^+K^-)$

Each decay has muon pairs in the final state and an opportune software has been developed to reconstruct the hits of muons in the detector chambers. Then, the muon hits are saved in the active chambers involved in the propagation through the detector, and deleted for the inactive ones, according to the dead time inefficiencies. If at least one muon of the pair fails the *IsMuon* (sect. **3**) identification requirements due to hits losses by inactive chambers during the propagation, the full decay event is considered lost. At contrary, if both muons have not lost hits due to chambers inactivity the decay event is considered reconstructed, thus saved.

Table IV. – *Detection inefficiency for very rare decays, due to the dead time electronics. An opportune software has been developed for the extimations, that simulated three scenarios, and the muRWELL technology for each of them.*

	$B_s^0 \to \mu^+\mu^-$		$D^0 \to \mu^+\mu^-$		$K_s^0 \to \mu^+\mu^-$		$B_s^0 \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$	
Scenario	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)	1-ε (MWPC)	1-ε (μRwell)
HCAL	24.7 %	10.3 %	25.9 %	9.4 %	20.0 %	8.4 %	24.9 %	9.5 %
ABSORBER	19.0 %	8.6 %	19.4 %	7.6 %	13.9 %	6.3 %	18.7 %	7.8 %
w/o M2	13.4 %	6.0 %	13.7 %	5.3 %	8.3 %	3.2 %	13.1 %	5.3 %

The events loss by dead time inefficiencies have been calculated with the present configuration of MWPCs, and with the μRWELL option. In both cases, the effect of the additional absorber [4], eventually located upstream with respect to M2, is evaluated together with the option of the M2 station removal. The latter option is indeed under investigation again to cope with the high muon hit mis-identification on the M2 station. In table IV, the preliminary results of the dead time inefficiency effects on very rare decays detection at Run 5 are shown. The inefficiencies are at level of $\sim 24\%$ at the present configuration, remaining however high, at 10% level, considering the μRWELL detectors in the inner regions R1 and R2 of all the stations, and adding an absorber upstream from the M2 station. Only in case of M2 removal and μRWELLs in the other stations the inefficiency is $\sim 5\%$, below the 10%. At the end, note that further studies are currently ongoing to define the most appropriate scenario for the Upgrade II.

REFERENCES

[1] Aaij Roel *et al.*, *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, working paper or preprint (Nov. 2018).
[2] Alves A. A. jr. *et al.*, *JINST*, **3** (2008) S08005.
[3] LHCb Collaboration, *LHCb muon system: Technical design report*, CERN-LHCC-2001-010 (May 2001).
[4] Baldini Wander *et al.*, *Considerations on additional shielding for the muon detector phase 2 upgrade*, LHCb-INT-2019-008, CERN-LHCb-INT-2019-008 (2019).
[5] Bencivenni G. *et al.*, *JINST*, **14** (2019) P05014.
[6] Anderlini L. *et al.*, *JINST*, **11** (2016) P04010.