Study on Muon Detection Performances at Upgrade Conditions

CERN SUMMER STUDENT REPORT

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1 Introduction

After Long Shutdown 2 (LS2), a luminosity of $L = 2 \cdot 10^{33} cm^{-2} s^{-1}$ is expected in the LHCb detector, five times as high as the current value. Because of the high particle flux expected in certain regions of the muon stations, the dead time in electronics will increase and this will cause a loss of efficiency in detecting muons and therefore in the ability to detect certain decays. A study was performed on what the effect of the increase in luminosity has on certain benchmark physics channels, such as $B_s \to \mu^+\mu^-$. The results are given in section 2.

A higher particle flux also means a higher mis-identification rate. High muon detection efficiency and the separation of signal from background remains a crucial aspect for the analyses done by the LHCb collaboration. In section 3, the results are given of a study on muon identification algorithms. A conclusion on both studies is given in section 4.

2 Study on muon detection inefficiencies

During LS2, some of the electronics in the muon system will be changed to cope with the increase in particle flux [2]. The current plan to increase the granularity is to remove the Intermediate Boards (IB) which perform logical OR decisions of smaller physical readout channels. This will require the installation new Off Detector Electronics (nODE) to accomodate for the increase in readout channels. A maximum of 190 nODEs are available for the upgrade. The goal of this study was to see how the inefficiency decreases for different IB removal scenarios (section 2.1), such as the planned scenario for LS2 “baseline” scenario, removing IB in M2 and M5R4)[1] . More extreme scenarios were also investigated, such as the removal of all the IB. As a case study, it was also investigated what the effect of the installation of high granularity pad chambers in the most affected regions is on the inefficiency (section 2.2). This is currently not foreseen at upgrade, but could in principle be realized at LS3. All results in section 2 were obtained by calculations based on the deadtime induced inefficiency maps (fig. 1).

2.1 IB removal

The possibility to detect a muon at a specific point of each station was corrected for by using the single hit inefficiency from the map at that point, and combining all the station inefficiencies according to the muon identification algorithm (“IsMuon”). The removal of the IB can lead to an increase in granularity up to a factor 24. This is simulated by dividing the corresponding inefficiency in the map by the same factor. The inefficiency was calculated for 5 different decays ($B_s^0 \to \mu^+\mu^-$, $B_s^0 \to J/\psi\phi$, $D^0 \to \mu^+\mu^-$, $K_S \to \mu^+\mu^-$, $\tau^+ \to \mu^+\mu^-\mu^-$), scoping a broad range of p and p_T. In each case, the total inefficiency of the two- or three-muon event was calculated as the product of the single muon inefficiencies, and the sample averages were computed by analyzing a large number of events. The results for all decyas and the different scenarios investigated are shown in Tab. 1.

[1]The muon detector of LHCb after LS2 will be composed by four walls equipped with MWPC (M2,M3,M4 and M5), interleaved with iron filters; each stations is divided in four concentric regions, starting from the beam pipe: R1,R2,R3 and R4.

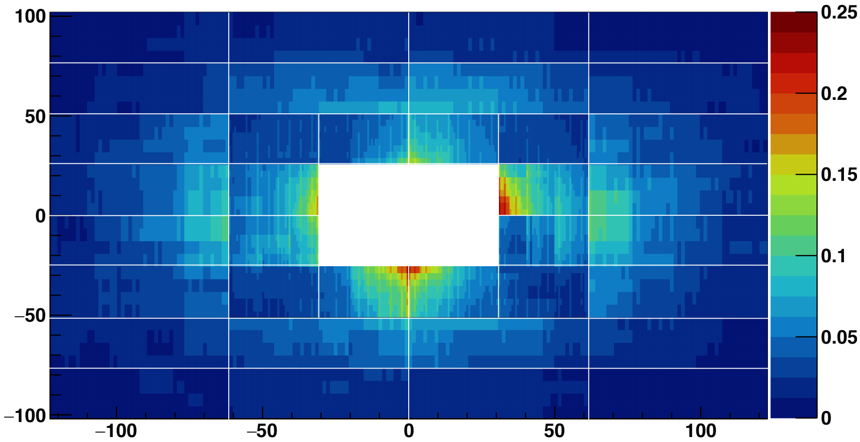

Figure 1: Deadtime induced inefficiency maps for M2R1 and M2R2 [2]. The white lines indicate for both regions where new high granularity pad chambers can be installed. With the current geometry 12 can be installed in M2R1 and 24 in M2R2. The geometry of M3R1 is similar to that of M2R1, being capable of housing 12 slightly larger chambers.

Table 1: Average value of the inefficiencies (in %) for different physics channels in several IB removal scenarios, with statistical errors; the total number of nODEs to be installed in each case is also shown. The baseline scenario corresponds to the current plan of IB removal for LS2.

	Run2 - like	IB removed in			
		M2, M5R4 (baseline)	M2, M3, M5R4	M2, M4, M5	All
$B_s^0 \to \mu^+\mu^-$	9.56 ± 0.04	7.63 ± 0.04	7.10 ± 0.03	6.59 ± 0.03	6.06 ± 0.03
$B_s^0 \to J/\psi\phi$	9.77 ± 0.05	7.89 ± 0.05	7.36 ± 0.05	6.86 ± 0.05	6.31 ± 0.05
$D_0 \to \mu^+\mu^-$	10.33 ± 0.17	8.43 ± 0.15	7.89 ± 0.15	7.32 ± 0.14	6.77 ± 0.14
$K_S \to \mu^+\mu^-$	8.48 ± 0.22	6.27 ± 0.19	5.59 ± 0.18	5.51 ± 0.18	4.83 ± 0.17
$\tau^- \to \mu^+\mu^-\mu^-$	12.60 ± 0.22	9.81 ± 0.19	9.02 ± 0.19	8.58 ± 0.18	7.74 ± 0.17
# nODEs	104	148	188	176	216

For the $B_s^0 \to \mu^+\mu^-$ decay, the inefficiency with the current electronics is expected to be 9.6%. This can be reduced to 7.6% in the baseline scenario, which corresponds to an improvement of 20%. This can be further reduced to 6.1%, or another 20%, if all of the IB are removed. However, in the latter scenario a total of 216 nODEs will be needed which is more than the 190 available. This does however indicate that the current baseline scenario is a good compromise between the number of nODEs needed and the corresponding gain, namely half of the maximum. All decays investigated give similar results.

2.2 Pad chamber installation

There are no IB installed in the innermost regions (R1) of the muon stations. As these regions are affected the most by the increase in particle flux, another method is needed to increase the granularity. The installation of new high granularity pad chambers has been considered. Only the simulation of installation in M2R1, M2R2 and M3R1 has been done, as these regions contribute the most in the expected loss of efficiency. The results for M2R1 and M3R1, for all decays investigated, are listed in Tab. 2 and Tab. 3, respectively.

Table 2: Results of inefficiency (in %, with statistical errors) from the installation of PAD chambers in M2R1. The number of PAD chambers installed in each scenario is shown in brackets.

M2R1	No PADs	left/right (4)	top/bott. (4)	No corners (8)	All (12)
$B_s^0 \to \mu^+\mu^-$	7.63 ± 0.04	6.98 ± 0.03	6.93 ± 0.03	6.27 ± 0.03	5.99 ± 0.03
$B_s^0 \to J/\psi\phi$	7.89 ± 0.05	7.29 ± 0.05	7.09 ± 0.05	6.49 ± 0.05	6.18 ± 0.04
$D_0 \to \mu^+\mu^-$	8.43 ± 0.15	7.87 ± 0.14	7.50 ± 0.14	6.93 ± 0.14	6.63 ± 0.14
$K_S \to \mu^+\mu^-$	6.27 ± 0.19	6.01 ± 0.19	5.95 ± 0.19	5.69 ± 0.19	5.41 ± 0.18
$\tau^- \to \mu^+\mu^-\mu^-$	9.81 ± 0.19	9.41 ± 0.19	8.82 ± 0.18	8.41 ± 0.18	7.98 ± 0.18

Table 3: Results of inefficiency (in %, with statistical errors) from the installation of PAD chambers in M2R1 and M3R1. The number of PAD chambers installed in each scenario is shown in brackets.

M2R1 and M3R1	No PADs	left/right (8)	top/bott. (8)	No corners (16)	All (24)
$B_s^0 \to \mu^+\mu^-$	7.63 ± 0.04	6.63 ± 0.03	6.59 ± 0.03	5.59 ± 0.03	5.22 ± 0.03
$B_s^0 \to J/\psi\phi$	7.89 ± 0.05	6.99 ± 0.05	6.71 ± 0.05	5.80 ± 0.05	5.39 ± 0.04
$D_0 \to \mu^+\mu^-$	8.43 ± 0.15	7.58 ± 0.14	7.05 ± 0.14	6.17 ± 0.13	5.78 ± 0.13
$K_S \to \mu^+\mu^-$	6.27 ± 0.19	5.93 ± 0.19	5.82 ± 0.19	5.48 ± 0.18	5.12 ± 0.18
$\tau^- \to \mu^+\mu^-\mu^-$	9.81 ± 0.19	9.22 ± 0.19	8.37 ± 0.18	7.76 ± 0.17	7.20 ± 0.17

For geometrical reasons, 12 pad chambers can be installed in both M2R1 and M3R1. The minimum possible inefficiency for the $B_s^0 \to \mu^+\mu^-$ is 5.2%. This corresponds to an improvement of 32% with respect to the baseline scenario of IB removal. When 8 pad chambers are installed in M2R1 only, excluding the corners, the inefficiency is 6.3%, and this corresponds to a gain of 18%, or 56% of the maximum possible gain, with one third of the chambers installed. If 8 chambers are added in M3R1, i.e. 16 chambers in total, the inefficiency drops to 5.6%, which corresponds to a gain of 26%, or 81% of the maximum possible gain with two thirds of the chambers installed. From the above we can conclude that the relative weight of M2 for the gain is two thirds of the total. For all other decays, similar results are found.

An extra computation has been done to include pad chamber installation in M2R2, only for the $B_s^0 \to \mu^+\mu^-$ decay. The average inefficiency in this region can be as large as 10% closer to the beam pipe. However, as this region is four times the size of M2R1, it contributes significantly to the overall efficiency drop of the decay. If all 24 pad chambers are installed, the inefficiency drops to 6.2%, which is roughly an 18% gain with respect to the baseline scenario. However, from figure 1 it can be seen that, as was the case for M2R1, the corners are less affected. Therefore, it seems as only 12 pad chambers can be installed to cover most of the loss. In that case the inefficiency drops to 6.5%, which is a 15% gain, or 80% of the maximum gain in M2R2.

From these numbers it can be seen that a very good compromise between gain and number of pad chambers installed would be: 8 in M2R1, 12 in M2R2 and 8 in M3R1. The final inefficiency for $B_s^0 \to \mu^+\mu^-$ in that case is 4.4%, which is a gain of 40% with respect to to the baseline. In this scenario, a total of 28 pad chambers are installed, versus a maximum of 48 that could be installed in these regions, while 80% of the gain is achieved.

3 Study on muon identification algorithms

At upgrade conditions, not only does a high particle flux mean a higher inefficiency to detect muons, it also means a higher rate of mis-identification, mainly due to combinatorial background. Better muon identification (MuonID) algorithms are under study to improve the signal over background ratio. Several multivariate algorithms (MVA) can be developed and recently a boosted decision tree (BDT) has been trained which improves on the existing muon delta log likelihood (DLL) method. In section 3.1, the results of the training of a variety of other algorithms is given.

3.1 MVA optimization

The Toolkit for Multivariate Analysis (TMVA) [3] was used to train several MVAs to separate muons (signal) from pions (background), using real data calibration samples from run 1. They include rectangular cuts, likelihoods and Multilayer Perceptrons (MLP). The focus was on the MLP, as it could in principle outperform the BDT. The Variables (20 total) used for training include information on hit time arrival, pad or strip hit and spatial residuals normalized to the error, taking into account multiple scattering. Also a variety of configurations of the MLP have been tested, such as different amounts of hidden layers, total number of neurons and different neuron types. Fig. 1 shows the ROC curves for the best configuration for each of the methods trained.

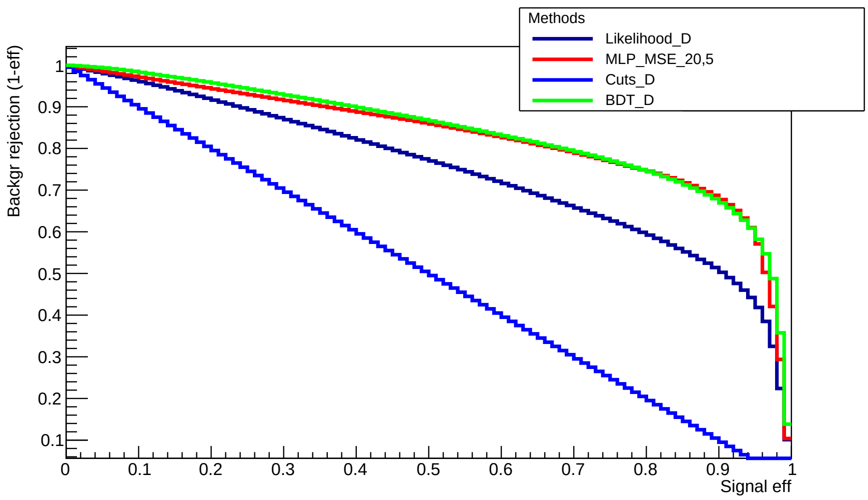

Figure 2: ROC curves of best configuration for different MVAs investigated

As the main interest is high signal efficiency and high background rejection, the BDT and MLP methods perform best and similar. In the region of high signal efficiency ($80-95\%$), the MLP has a background rejection that is 1% higher than that of the BDT. In the region of ($>95\%$) signal efficiency, the BDT still performs better with $5-6\%$ more background rejection.

4 Conclusions

Two separate studies were performed on muon detection performances at upgrade conditions. The inefficiency of the physics channels investigated, due to higher luminosity, will be in the order of 10% if the electronics remain unchanged. The current plan of the removal of IB will reduce this by 20% with a good compromise on the number of needed nODE. This could in principle be reduced by another 40% if new high granularity pad chambers are installed in the most affected regions, close to the beam pipe. This is currently not foreseen at the upgrade, but could be realized in LS3.

Multivariate algorithms have been trained and used to separate signal from background. Best and similar performances so far by the newly investigated MLP and already existing BDT. The performance of the MLP may be improved further and the performances of the MLP and BDT may be tested on real data. However, the limited scope of this research project did not allow for it and this could to be done later.

References

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