Montecarlo samples and efficiency definitions for the muon system optimization

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1 Introduction

The aim of this note is to define the MC samples and the variables to be used to

- optimize the detector configuration
- optimize the trigger performance
- determine the absolute beauty efficiencies

The definition of the variables should be unambiguous and allow a direct comparison among the different studies. The efficiencies of interest to characterize the detector performance are those related to the total number of beauty particles at the output of the L0 muon trigger and to the fraction of them decaying into a muon which fulfils the trigger conditions ("signal purity").

In the last section we discuss the MC sample of minimum bias (m.b.) events and the level of trigger retention to be considered in the system optimization.

2 MC samples to be used for beauty simulation

The main purpose of the muon system is to contribute to the L0 trigger maximizing the acceptance of beauty events relatively to minimum bias and charm events. Its optimization should then be done on the appropriate sample of MC events having a muon coming directly from the b decay (that in the following will be called μ_b) inside the geometrical acceptance. An optimization on a mixture of $b \to \mu$ and $b \to c \to \mu$ would not be optimal since these two samples have different p and p_T distributions and thus different trigger efficiencies.

In addition the MC should provide both the rate of $b \to \mu$ events and the total number of b events at the output of the L0 muon trigger. The latter must be evaluated on an unbiassed sample of inclusive $b\bar{b}$ events. In this case, neglecting the contribution of muons not coming from $b \to \mu$ and $b \to c \to \mu$ decays, the trigger efficiency can be written as:

$$\begin{aligned}\epsilon_{tr} = {} & \epsilon_b \cdot BR(b \to \mu) + \\ & + (1 - \epsilon_b \cdot BR(b \to \mu)) \cdot \{\epsilon_{\bar{b}} \cdot BR(\bar{b} \to \mu) + \\ & + [1 - \epsilon_{\bar{b}} \cdot BR(\bar{b} \to \mu)] \cdot \epsilon_c \cdot BR(b \to c \to \mu) + [1 - \epsilon_{\bar{b}} \cdot BR(\bar{b} \to \mu)] \cdot \\ & \cdot [1 - (1 - \epsilon_{\bar{b}} \cdot BR(\bar{b} \to \mu)) \cdot \epsilon_c \cdot BR(b \to c \to \mu)] \cdot \epsilon_{\bar{c}} \cdot BR(\bar{b} \to \bar{c} \to \mu)\}\end{aligned} \tag{1}$$

Where ϵ_b, $\epsilon_{\bar{b}}$, ϵ_c and $\epsilon_{\bar{c}}$ are the efficiencies for the muons coming respectively from $b(\bar{b})$ or from $b(\bar{b}) \to c(\bar{c}) \to \mu$ decay chain (which will be called μ_c in the following). $BR(b \to \mu)$, $BR(\bar{b} \to \mu)$, $BR(b \to c \to \mu)$ and $BR(\bar{b} \to \bar{c} \to \mu)$ are the corresponding branching ratios into muons averaged over the different fragmentation products of the b and c quarks. Their values are $BR(b \to \mu) = BR(\bar{b} \to \mu) \sim 10\%$ and $BR(b \to c \to \mu) = BR(\bar{b} \to \bar{c} \to \mu) \sim 8\%$ [1]. Typical values for the trigger efficiencies (at 2% minimum bias retention) are: $\epsilon_b \sim 50\%$, $\epsilon_c \sim 25\%$. Using these values the μ_c contribution to the trigger efficiency is about 40% of that due to μ_b. This fraction is not small indicating that an optimization done on a mixture of $b \to \mu$ and $b \to c \to \mu$ can lead to trigger conditions that select charm events with high efficiency.

[1] Here we assume $BR(b \to c) = 100\%$

Table 1: *The starting number of events in the MC sample is 10000.* $\mathrm{N_E}$ *is the number of events with at least one muon, of the specified origin, hitting station M3.* ϵ_{trig} *is the trigger efficiency of the specified muon track.*

μ origin	$\mathrm{N_E}$	ϵ_{trig}
1. B$\rightarrow \mu$	5783	49%
2. B$\rightarrow$ D $\rightarrow \mu$	746	24%
3. B$\rightarrow \cdots \rightarrow \mu$	847	12%
4. non-B$\rightarrow \cdots \rightarrow \mu$	4583	6.6%

So far we have adopted, for practical reasons, a "forced MC " where the b inside an angular cone of 600 mrad is forced to decay into μ. This choice is appropriate for the optimization purpose but we have to be careful when defining a "purity". Let's consider the total trigger efficiency computed on a sample of forced $b \rightarrow \mu$ sample:

$$\begin{aligned}\epsilon_{tr} = \epsilon_b + \\ &+ (1-\epsilon_b)\cdot\{\epsilon_{\bar{b}}\cdot BR(\bar{b}\rightarrow\mu) + \\ &+ [1-\epsilon_{\bar{b}}\cdot BR(\bar{b}\rightarrow\mu)]\cdot\epsilon_c\cdot BR(b\rightarrow c\rightarrow\mu) + [1-\epsilon_{\bar{b}}\cdot BR(\bar{b}\rightarrow\mu)]\cdot \\ &\cdot[1-(1-\epsilon_{\bar{b}}\cdot BR(\bar{b}\rightarrow\mu))\cdot\epsilon_c\cdot BR(b\rightarrow c\rightarrow\mu)]\cdot\epsilon_{\bar{c}}\cdot BR(\bar{b}\rightarrow\bar{c}\rightarrow\mu)\}\end{aligned} \tag{2}$$

In this case the weight of the μ_c with respect to μ_b is of the order of only 5% very different from the realistic 40% estimated from (1). This shows that using the forced MC we don't spoil significantly the optimization by extending the prompt muon definition including μ_c's (as it has been done sometimes), simply because their contribution is small. On the contrary if, once having decided the optimization cuts, we express our trigger performance quoting also a "purity" this can lead to very wrong numbers.

Notice that, for simplicity, in these formulae we have disregarded the fraction of triggers not due to b or to c daughter muons. Let's now look at the complete picture. Table 1 reports the result obtained with the forced MC showing the trigger efficiencies of muons coming from the b decay chain either directly from the b particle itsef (row 1) or from one of its decay products (rows 2 and 3). It also shows the contribution due to the decays of π and K not coming from b (row 4). The efficiencies here do not include the geometrical acceptance of the apparatus which, evaluated on the sample of b's inside a 600 mrad cone, is of about 60%.

In Table 2, instead, is shown the cumulative trigger efficiency (including geometrical acceptance) by adding each contribution one by one. It shows for instance that the fraction due to charm, with respect to the main $b \rightarrow \mu$, is $\frac{(29.6-28.4)}{28.4} = 4.2\%$ in agreement with the 5% evaluated on the basis of equation (2). The total fraction of trigger efficiency not due to μ_b is $\frac{(32.4-28.4)}{28.4} = 14\%$. Extending equations (1) and (2) to include all sources of trigger this fraction computed on $b\bar{b}$ inclusive would be greater than 100%. In other words it is meaningless to evaluate a purity on a "forced" MC sample since the relative contributions of the various sources to the muon trigger rates are very different from the true ones obtained with an unbiassed beauty sample.

Table 2: *Cumulative efficiency including trigger and geometrical acceptance. The MC sample and the definition of the muon origin are the same as in table 1.*

μ origin	events	$\epsilon_G \cdot \epsilon_{trig}$
1	2844	28.4%
1+2	2964	29.6%
1+2+3	3031	30.3%
1+2+3+4	3235	32.4%

3 Absolute beauty efficiencies to define physics performance

The total detector and trigger efficiency for generic beauty events is:

$$T = \frac{\text{number of beauty events triggered by the L0 muon trigger}}{\text{number of beauty events in } 4\pi} \tag{3}$$

The **signal purity, P**, can be defined as the fraction of events having a triggering μ_b over all the b's triggered by the muon L0 trigger [2]

$$P = \frac{\text{number of b} \to \mu \text{ events where a } \mu_{\text{b}} \text{ hits the detector and gives trigger}}{\text{number beauty events triggered by the L0 muon trigger}} \tag{4}$$

Both T and P must be evaluated on a $b\bar{b}$ inclusive MC sample with no forced decays. In the numerator of P we require the μ_b hitting the detector and triggering. To characterize the detector performance, however, the fraction of $b \to \mu$ events where the μ_b hits the detector but it doesn't trigger is also important since these events can be identified as $b \to \mu$ as well at a later stage and be useful for the analysis

$$F = \frac{\text{number of b} \to \mu \text{ events where a } \mu_{\text{b}} \text{ hits the detector and gives trigger}}{\text{number of b} \to \mu \text{ events where a } \mu_{\text{b}} \text{ hits the detector and the event gives trigger}} \tag{5}$$

In this way the ratio P/F will provide the fraction of $b\bar{b}$ triggered events having a μ_b in the detector acceptance therefore useful for physics.

In Table 3 the typical values of P, F and T can be found together with other useful numbers. They have been evaluated on a sample of 11,500 $b\bar{b}$ inclusive events using the fields of interest and the p_T cut optimized for a m.b. retention of 2%. The first row, second column, shows T ,the total detector and trigger efficiency for generic $b\bar{b}$ events. The fraction of triggered events where the trigger is due to a μ_b, is reported in the third column and coincides with the purity P defined above.

In the second row the same efficiencies are given for the subsample of events, about 20%, where at least one of the b's decays into a muon. The fraction of the triggers not

[2] We notice that another definition of purity is the fraction of $b \to \mu$ over the total events, including m.b., accepted by the L0 muon trigger. This purity, important for the higher trigger levels, depends on the cross-sections and it is not addressed here.

Table 3: *Trigger efficiencies calculated on $b\bar{b}$ events (first row), events where at least a b decays into a muon (second row) and events where at least a μ_b hits station M3 (third row). In the second column the detector+trigger efficiency is given without any requirement on the triggering particle. In the last column the condition that the trigger is fired by a μ_b is imposed.*

	ϵ_{det+tr}(%)	ϵ_{μ_b} (%)
$b\bar{b}$ in 4π	5.7± 0.2 (T)	34.0 ± 2.0 (P)
$b \to \mu$ in 4π [(20± 0.4)%]	12.2± 0.7	79.0 ± 3.0
$b \to \mu$ hits M3 [(19 ± 1)%]	54.5 ± 3.0	94.5 ± 1.5 (F)

due to the μ_b is about 21%. Comparing the first two rows it can be seen that in more than half of the cases the beauty events are triggered in absence of $b \to \mu$ decays. Most of these triggers are due to high p_T muons from charm or from other decay products of the b.

In the third row the sample consists of those events where at least a μ_b falls inside the detector acceptance, i.e. when it leaves a hit in station M3, as explained in the next section. This requirement has an acceptance of about 19%. In the last column the value for F is reported showing that once the μ_b is in the acceptance it is almost always the triggering particle. We notice that the product of the two efficiencies in the third row is equal to ϵ_{trig} defined in the next section.

4 Efficiency definitions

While the intrinsic trigger performance has to be determined on muons hitting the chambers, the optimization of the detector configuration must be done on a sample of data which is not defined by the size of the detector itself (this is particularly relevant now that we are playing with gaps/overlaps in the realistic geometry). We think that in order to compare different studies, we must have a common reference sample. The natural choice is the standard sample of events contained inside 600 mrad acceptance (corresponding to about 40% of the production rate inside 4π). We then propose to define two quantities. The first is the **geometrical acceptance,** ϵ_G, of the detector defined through:

$$\epsilon_G = \frac{\text{number of b} \to \mu \text{ events where a } \mu_\text{b} \text{ hits the detector}}{\text{the full b} \to \mu \text{ sample}} \tag{6}$$

The second is the **trigger efficiency,** ϵ_{trig}, defined as

$$\epsilon_{trig} = \frac{\text{number of b} \to \mu \text{ events where a } \mu_\text{b} \text{ hits the detector and gives trigger}}{\text{number of b} \to \mu \text{ events where a } \mu_\text{b} \text{ hits the detector}} \tag{7}$$

The system (detector+trigger) optimization should be done maximizing the product $\epsilon_G \cdot \epsilon_{trig}$. We notice that typical values of these efficiencies are $\epsilon_G \sim 20\%$ and $\epsilon_{trig} \sim 50\%$ for 2% m.b. retention.

We have to define now what we mean by **hitting the detector**. We propose a loose condition requiring that the muon **hits station M3**. This station is the best since the

Table 4: *Rates of single and multiple interactions in MHz at the nominal luminosity for different cross sections*

	$\sigma = 80$ mb	$\sigma = 102.4$ mb	$\sigma = 55$ mb
$< N_{int} >$	0.533	0.683	0.371
R_0	17.6	15.2	20.7
R_1 ($\otimes$ Pile-up Veto)	9.4 (8.9)	10.3 (9.8)	7.8 (7.5)
$R_{>1}$ "	3.0 (0.6)	4.5 (0.9)	1.5(0.3)
$R_{\neq 0}$	12.4 (9.5)	14.8 (7.8)	9.3 (7.8)

M3 hits are used as seeds for the trigger algorithm startup. The condition used so far in the trigger studies (hitting M1 and M2) introduces a larger artificial trigger inefficiency in the outer regions of stations M3 to M5. Requiring hits in stations M1 to M5 is, in principle, the correct geometrical definition matching the trigger but it is too stringent and limits the possibility to explore more loose/flexible trigger conditions (4/5 stations, etc).

5 MC samples of the minimum bias events

The generation of minimum bias events for the muon analysis has been done so far under conditions similar to those of the Technical Proposal (TP) where only one interaction per bunch crossing has been considered and the cross section has been assumed to be due essentially to QCD high p_T processes (MSEL=1 in the Lund language, [1]). The retention rate, for a given signal efficiency, was computed attributing to these processes a total cross section of 80 mb.

We notice here that the machine cycle structure foresees sequences of colliding bunches (typically 81) followed by sequences of empty cycles. In the simulation we have then to consider two luminosities. The **average luminosity**, nominally $L_{av} = 2 \times 10^{32} cm^2 s^{-1}$, is relevant for the m.b. retention and for the bandwidth allowed for the muon trigger. The **instantaneous luminosity** during the sequence of effective crossings has to be considered in the pile-up probability and in the dead-time simulation. For the simulation of the spill-over both luminosities are important. The instantaneous luminosity determines the spill-over of the events in the previous few bunch crossings while the average luminosity is relevant for the long time scale flat component.

The average interaction multiplicity at the nominal luminosity can be expressed as

$$\bar{N}_{int} = \frac{\sigma_{inel} \cdot L_{av}}{40\ MHz \cdot (1 - F_{empty})} = 0.533 \quad (8)$$

where $F_{empty} \sim 0.25$ is the average fraction of empty cycles. In the first column of Table 4 the average number of interactions/crossing and the absolute rate of crossings with 0, 1 and > 1 interactions are indicated.

Since the MC version SICB v220 the collaboration has moved to a more realistic model that foresees the generation of inelastic scattering, single/double diffractive and elastic processes (MSEL=2). The total cross section, estimated to be of 102.4 mb, is shared as follows: $\sigma_{inel} = 55$ mb, $\sigma_{diffr} = 25$ mb and $\sigma_{el} = 22.4$ mb. The 80 mb of the TP have

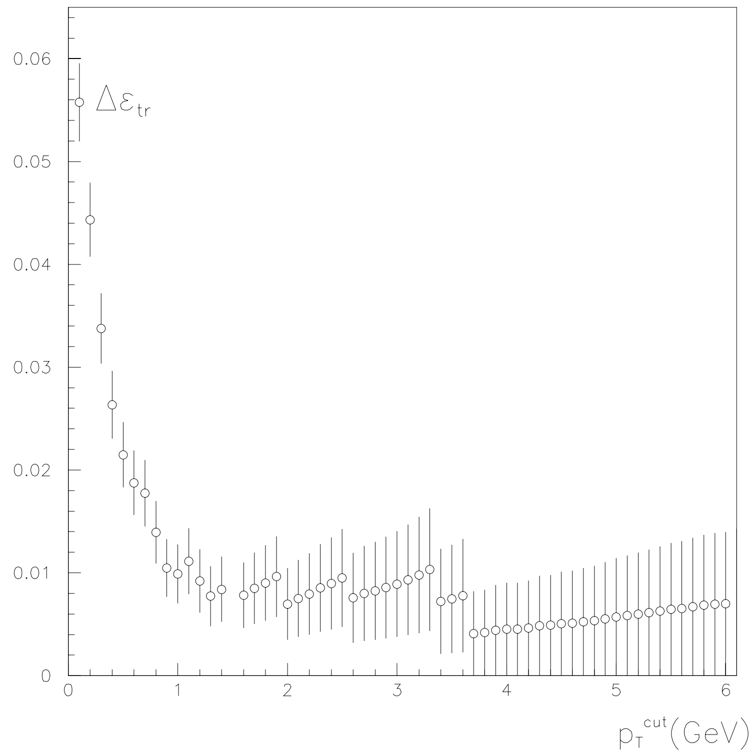

Figure 1: Contribution to the m.b. trigger rate due to elastic and diffractive events. The fields of interest are those optimized for the standard 2% retention rate and the corresponding p_T cut is about 1.05 GeV.

been split therefore in σ_{inel} and σ_{diffr}. The diffractive and elastic interactions have so low multiplicities that the probability to fire a muon trigger is expected to be negligible. This has been checked and the result is illustrated in Fig. 1 where the additional efficiency due to elastic and diffractive events is shown normalized to the efficiency due to inelastic events as a function of the p_T cut. The fields of interest used are those optimized for the 2% m.b. retention. For p_T cuts greater than 1 GeV the diffractive and elastic events modify the trigger efficiency on m.b. by less than 2%.

As a consequence the “effective” cross section is essentially due to inelastic processes and the corresponding interaction multiplicities are shown in the last column of Table 4. Since we intend to apply the pile-up veto in AND with level 0 trigger an estimate of the rate including pile-up veto is also reported. The final interaction rate is composed of 7.5 MHz of single interactions and 0.3 MHz of multiple interactions. The bandwidth assigned to the muon trigger is about 20 % of the total bandwidth, 1 MHz, foreseen for level 0. This means that the reduction we have to obtain on inelastic minimum bias events is roughly 0.2 MHz/$(7.5+0.3\times 2)$ MHz $\simeq$ 2.5 %. Notice that this translates into a fraction of about 1.3% if normalized to the m.b. sample corresponding to the total cross section.

Therefore in our trigger optimization studies we have to extend the range of possible **minimum bias retention rates**, presently between 1% and 2%, towards higher values and make sure that the detector and trigger design does not limit our possibilities in this sense.

As long as the pile-up veto condition in the trigger is kept, the results obtained so far with the single interactions are correct at the few percent level. However if we want to consider, as recently being discussed, to discard the pile-up veto condition from the level 0 trigger, a correct simulation of all the effects (multiple interactions and a realistic composition of the total cross section) is mandatory.

6 Summary

In conclusion the "forced" $b \rightarrow \mu$ MC sample can be used to optimize the detector and the trigger system provided the efficiencies are evaluated with prompt muons coming directly from the b decay. The optimization of the muon system must be done maximizing the product $\epsilon_G \cdot \epsilon_{trig}$ while the intrinsic trigger performance is described by ϵ_{trig}. On the other hand to properly evaluate quantities like the purity defined above or the total trigger efficiency on beauty events a sample of inclusive $b\bar{b}$ events is needed. These quantities are necessary to define the physical performance of the muon system.

Concerning the minimum bias background computation the MC sample used so far for the optimization studies is a suitable tool but the reference retention values for inelastic processes should be extended at least to 2.5%. However a full simulation of the multiple interactions including elastic and diffractive processes should be performed in particular to explore the possibility of operating without pile-up veto.

7 Acknowledgements

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References

[1] P. Bartalini et al., LHCb 1999-027.