LHC-B Muon Trigger

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Abstract

The LHC-B muon detector configuration and the components necessary for the LHC-B Level 0 high $p_t$ muon trigger are discussed. The Level 0 trigger algorithm necessary to achieve the desired suppression of triggers due to minimum bias events while maintaining good efficiency for semimuononic B decays is described. Results of various studies of this trigger, including effects of variation of minimum and maximum angular apertures, studies of the effect of the size of non-major components of the LHCB magnetic field, and studies of showering in the muon shield, are presented together with an evaluation of the muon pad chamber granularity required for achieving the LHC-B Level 0 trigger objectives.
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1 Introduction

The Level 0 muon trigger has a fundamental design goal of reducing the muon trigger rate due to $\pi/K \to \mu + x$ decays from minimum bias events while maintaining good efficiency for $B \to \mu + x$ decaying over $4\pi$. The muon system elements planned for LHC-B are shown in Fig. 1 along with a schematic description of the algorithm incorporated in the Level 0 trigger. The Level 0 muon trigger described below may be tuned to be relatively "loose" with $\approx 3.6\%$ retention of minimum bias events corresponding to a Level 0 trigger rate of $300 \text{ KHz}$ at a luminosity of $1.5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ (interaction rate of $\approx 10 \text{MHz}$) with an efficiency for $B \to \mu + x$ decaying over $4\pi$ of $\approx 13\%$. Alternatively, the tune of Level 0 may be relatively "tight" corresponding to minimum bias retention of $\leq 1\%$ with a B efficiency of $\approx 8.7\%$.

In order to achieve the Level 0 trigger objectives, the Level 0 trigger must impose the following conditions:

- detect the muon candidates by a triple coincidence of specified pads from $\mu 3$, $\mu 4$ and $\mu 5$.

- form the trajectories of all muon candidate tracks using the $\mu 1$ and $\mu 2$ chambers.

- require that the $\mu 1$-$\mu 2$ combinations be consistent with the $\mu 3 \cdot \mu 4 \cdot \mu 5$ triple coincidence.

- calculate the $p_t$ and the $y$ intercept of the muon candidate at the interaction point and apply appropriate cuts to achieve the desired Level 0 muon trigger rates.

These steps must be performed in less than $3 \text{ microseconds}$ to be consistent with the length of the Level 0 pipeline. Like the the hadron and electron Level 0 triggers, the Level 0 muon trigger requires the determination of the $p_t$ of the candidate muons. Unlike the hadron and electron Level 0 triggers, which rely on the electromagnetic and hadronic calorimetry for determination of the energy of the electrons and hadrons, and, thus, the $p_t$, the Level 0 muon trigger requires the determination of the trajectory of muon in order to ascertain the the momentum and, therefore, the $p_t$ of the muon candidates from magnetic bending. Hence, there are special concerns associated with the formation of this trigger. Among these are sensitivity to the homogeneity of the magnetic field, the effect of showering in the muon shield on trajectory formation, and the requirements on granularity of the pad structure of the muon pad chambers.

The Level 0 muon trigger rate estimates which are quoted below are the result of simulations which include, unless otherwise specified, the following:
• event simulation done with the standard SICB package using PYTHIA minium bias
  and B semimuonic decay events propagated in a full GEANT simulation of the
  LHC-B spectrometer which includes multiple scattering, photon conversions and
  hadronic interactions.

• a muon shield composed (as indicated in Table 1) of the electromagnetic and
  hadronic calorimeter and five steel shielding segments covering from 8.5 mrad to
  267 mrad in both x and y projections.

• five muon detector planes, one of which is positioned upstream of the electromagnetic
  calorimeter; the other four planes are buried in the shield as shown in Fig. 1.

• the magnetic field map appropriate to the 1996 LHC-B magnet design by Paul
  Scherrer Institute.

• a pad structure for $\mu_1$ with pad sizes varying as given in Table 2 by factors of 2 over
  five regions from 0.5 cm x 0.5 cm in the region closest to the beam to 8 cm x 8 cm in
  the outer most angular region of the muon detector. The pad structure of $\mu_2$ is the
  same except the pad sizes are scaled by the z position of $\mu_2$. $\mu_3$, $\mu_4$ and $\mu_5$ have pad
  sizes which are a factor of 2 larger in x and y allowing for z scaling but otherwise
  follow the same strategy as $\mu_1, 2$

In this document, all the efficiencies we quote for B signal acceptance are to be in-
terpreted as absolute efficiencies for $B \rightarrow \mu + x$ generated over $4\pi$. Moreover, unless
otherwise specified, the efficiencies are evaluated while demanding that the triggering
muon is the actual muon from direct $B \rightarrow \mu$ decay.

2 The LHC-B Muon Detector

2.1 The Muon Shield

The muon shield is composed of several components including the electromagnetic and
hadronic calorimeter and five segments of shielding steel covering an aperture extending
from 8.5 mrad to 267 mrad in both the x and y projections. There are five muon detectors,
$\mu_1 - \mu_5$, that provide the measurement of the muons. Four of these, $\mu_2 - \mu_5$, are embedded
in the muon shield. $\mu_1$ is positioned at 11.5 meters from the target, just immediately in
front of the electromagnetic detector.

The thickness of the shield is constrained by the extent of the existing Delphi experi-
mental area which will be used for LHC-B. The extent of the angular coverage is
Table 1: Muon Detector Components

determined by consideration of the twin functions of the LHC-B muon detector, muon ID and muon trigger. Table 1 below details the thickness of the shield and the placement of the chambers within the shield.

2.2 The Muon Chambers

As discussed above, the necessity of forming the Level 0 muon trigger in 3 μs has resulted in the decision to incorporate a pad structure in μ1 – 5 which would make the 3D position of hits in the chambers available very rapidly to the Level 0 muon trigger. The granularity of the pad structure is still under study but, based on studies performed so far, pad structure given in Table 2 below has been chosen for μ1. The pad structure and granularity of μ2 is the same as for μ1 except the pad size are scaled by the z position of μ2. Allowing for scaling to take into account their different z positions, the pad sizes in μ3, 4 and 5 are twice as large in both x and y as the pads of μ1 and μ2 but follow the same general philosophy with the five regions. Therefore, the overall pad structure of the entire five chamber system is projective to the interaction region in both the x and y view.

Table 2: μ1 Chamber Pad Structure.
With this choice of pad structure, the $\mu_1$ and $\mu_2$ chambers have 24000 pads each, and the $\mu_3$, 4 and 5 chambers have 6000 pads each, making a total of 42,000 pad channels for the muon detector. However, although studies are not yet complete, it is possible that we may be able to use rectangular pads. Since more precision is required in the bend plane ($x$) than in the non-bend plane ($y$), we are investigating whether a $y/x$ aspect ratio $\geq 2$ will meet the trigger requirements. This would reduce the channel count to less $\leq 21,000$ for the entire system.

### 2.3 Muon Chamber Technology

While no decisions have been made to date about the baseline technology to be used for the LHC-B muon detector technologies, two techniques are under consideration at the present time: Cathode Pad Chambers (CPC’s) and multigap Resistive Plate Chambers (MRPC’s). Both kinds of chambers will be studied as a part of the LHC-B R&D program.

The Cathode Strip Chamber (CSC) technique has been discussed in the LHC-B LOI [1] and in the literature [2]. The Cathode Pad Chamber is similar except that the intermediate cathode plane will be used to support pads on the unused cathode surface. Since chamber $\mu_1$ sits in front of the muon shield and presumably will have to bear a higher rate of particles than $\mu_2 - 5$, it is thought that the CPC technique is more suitable for use in this position than MRPC’s.

LHC-B interest in multigap resistive pad chambers has developed more recently because of the work of M.C.S. Williams et al. [3]. The MRPC technique resembles the classic RPC technique except that the MRPC, as the name suggests, consists of several layers of RPC. The use of multiple layers has several beneficial results, solving traditional RPC problems. In particular, the use of multiple layers dramatically reduces the loss of efficiency at high rates. Chambers with 3 gaps of 3 mm thickness or 4 gaps of 2 mm thickness are under consideration at this point in time for the LHC-B muon chambers $\mu_2 - 5$. The various advantages of the MRPC’s are listed below:

- better behaved showers because of lessened fluctuations due to the summing of independent showers in each gap.

- lower dynamic range of gain resulting in higher rate capability ($\geq$ few KHz/cm$^2$ with less than a few % loss of efficiency).

- ease of construction due to more relaxed tolerances because of the multiple gaps.

- good time resolution ($\text{FWHM} \approx 3.5$ ns, baseline scatter of $\leq 20$ ns resulting in single bucket performance).
• Good timing stability with voltage variations and rate.

Finally, it is worth noting that the efficiency of each individual muon chamber plane is at a premium. The algorithm outlined below implies a five fold coincidence of the five muon chambers implying an efficiency of $e^5$ for a single muon. This becomes $e^{12}$ for a dimuon trigger. This almost certainly requires that each muon chamber is really a set of planes or’ed to achieve efficiencies $\geq 99\%$.

3 The Muon Trigger

3.1 The Muon Trigger Algorithm

Several different aspects of the Level 0 muon trigger have been studied since the submission of the LHC-B LOI. In particular, attention has been given to comparing algorithms in which the trajectory is determined using pad planes $\mu_0-\mu_1$ (here $\mu_0$ is a pad chamber situated just downstream of the LHC-B analysis magnet) vs a trigger in which the trajectory is determined using $\mu_1-\mu_2$. Given the difficulty of design of a low mass, pad chamber with single bucket resolving power that is able to stand high rates at the position of $\mu_0$, an alternative algorithm that uses $\mu_1-\mu_2$ for muon trajectory determination has been developed. Although $\mu_1$ is also in front of the muon shield, it can be be more massive. Therefore, $\mu_1$ can be constructed using techniques (such as the Cathode Pad Chamber technology) that would produce chambers too massive for use at the required position of $\mu_0$.

However, good resolution for the muon trajectory is harder to achieve using $\mu_1 - \mu_2$ because of multiple scattering, the smaller separation of $\mu_1$ and $\mu_2$ compared to $\mu_0$ and $\mu_1$, and the longer lever arm for projection to the center of the LHC-B analysis magnet. The penalty for use of $\mu_1-\mu_2$ vs. $\mu_0-\mu_1$ is the need for better precision in the measurement of the hit positions in $\mu_1-\mu_2$ combinations than would be necessary if a $\mu_0-\mu_1$ chamber combination could be used. The same resolution will require finer pad chamber granularity and, therefore, more channels of electronics.

The present muon trigger algorithm involves the following steps in chronological sequence:

• form triple coincidences of all pad hits in the $\mu_3$ plane with pads in the $\mu_4$ and $\mu_5$ planes in specified search regions ($\pm 1$ pad in $y$ and $\pm 10$ pads in $x$ relative to the index pad in $\mu_3$).

• open search regions in $\mu_1$ and $\mu_2$ ($\pm 1$ pad in $y$ and $\pm 10$ pads in $x$) and form all $\mu_1 - \mu_2$ combinations as potential muon candidates.
• compare the $\mu_1 - \mu_2$ combinations with the $\mu_4 - \mu_5$ triple requiring agreement between the $x$ and $y$ slopes of the two vectors of 60 and 30 mrad respectively as well as requiring $\mu_1 - \mu_2$ to project to within $\pm 1$ pad in the $x$ projection and to the $\mu_3$ "index" pad in the $y$ projection that is the "seed" of the $\mu_3 \cdot \mu_4 \cdot \mu_5$ triple coincidence. If more than one combination satisfies this condition, take the best combination.

• from the $\mu_1 - \mu_2$ trajectory, calculate the $p_t$ and the $y$ intercept of the muon candidate at the interaction point and apply appropriate cuts to achieve the goals stated above ($p_t \geq 1.25$ GeV/c and $dy \leq 5.0$ cm for the "tight" cuts).

3.2 Muon Trigger Studies

Not all of the studies discussed below have been done under the same conditions. In particular, some of the studies have been done with the "$\mu_0 - \mu_1$" version of the trigger algorithm as opposed to the "$\mu_1 - \mu_2$". In addition, most studies have not been done with showering in the shield. However, in most cases where there are differences between the conditions of the study and our "nominal" algorithm and granularity, we do not expect the results to vary greatly. Eventually all studies will be performed with the "$\mu_1 - \mu_2$" algorithm and "nominal" conditions.

3.2.1 Muon Trigger Geometric Acceptance

A critical issue in the optimization of the LHC-B spectrometer is the trigger acceptance of the muon detector, both in minimum and maximum angle coverage. We have studied the effect on both B efficiency and minimum bias rejection of reducing the maximum angle of coverage and increasing the minimum angle of coverage. These studies have been done using the $\mu_0 - \mu_1$ algorithm and with no shield showering. The trigger required that the muon candidates point at the target and have a trigger $p_t \geq 1.25$ GeV/c.

The variation of B efficiency (normalized to the LOI coverage; $\theta_{\text{min}} = 8.5$ mrad, $\theta_{\text{max}} = 267$ mrad) is shown as a function of both $\theta_{\text{min}}$ and $\theta_{\text{max}}$ in Fig. 3. As can be seen, the loss of good triggers is much more dramatic as the minimum angle of the Level 0 trigger is increased. Decreasing the maximum angle of Level 0 has a much less severe effect on the B efficiency. There are not many trigger muons in the outer region of the muon detector, leading to the possibility of eventually decreasing the size of the muon detector if the extra aperture is not needed for muon ID (for $J/\Psi \rightarrow \mu\mu$ decays for example). Conversely, this study emphasizes the need to go to as small an angle as possible to achieve maximum B efficiency.

The retention of minimum bias events is shown in Fig. 4. There seems to be little reduction in trigger rate by increasing the minimum angle of the Level 0 muon trigger. In addition, Fig. 4 shows that the reduction of trigger rate generated by reducing the
maximum angular coverage seems to match the reduction in B efficiency closely, so no
advantage is gained by decreasing the maximum angle.

We have examined the effect of the minimum and maximum angle variation as a
function of the $p_t$ of the trigger. Fig. 5 shows the variation of minimum bias retention
as a function of required $p_t$ for various maximum angle cuts. As can be seen, there is
little difference in the curves and no obvious advantage to changing the $p_t$ requirement.
Similarly, the variation of minimum bias retention with minimum angle as a function of
$p_t$ is shown in Fig. 6. Here we can see that, if we are at low $p_t$, we would gain in rejection
by eliminating the small angle region. However, since the $p_t$ threshold will normally be
above 1 GeV/c, there is no appreciable reduction in minimum bias trigger rate generated
by eliminating the small angle region.

3.2.2 Pad Chamber Granularity

We have studied the effect of varying the granularity of the $\mu 1$ and $\mu 2$ pad structure.
Fig. 2 shows the difference of the trigger $p_t$ as determined by the nominal "$\mu 1 - 2"$ trigger
algorithm and the true $p_t$. The muon chamber granularity used for this simulation is our
nominal pad structure, i.e., that described above in Table 2 (0.5 cm x 0.5 cm in Region
1 of $\mu 1$, etc.). As can be seen, the trigger $p_t$ resolution is reasonable.

We have varied this nominal granularity to study the effect of grosser and finer seg-
mentation of $\mu 1$ and $\mu 2$. Fig. 7 shows the variation of the rms of the muon trigger $p_t$ as
determined by the $\mu 1 - \mu 2$ algorithm as a function of $\mu 1,2$ chamber granularity (as labeled
by the granularity of the small angle region of $\mu 1$). As can be seen, the rms decreases
rapidly in decreasing the $\mu 1,2$ pad sizes from a "1 cm x 1 cm" granularity down by a factor
of 2 to "0.5 cm x 0.5 cm" granularity. However, there is relatively little gain in $p_t$ rms in
going down to 0.33 cm x 0.33 cm or lower. Therefore, we have made a preliminary choice
of the "0.5 cm x 0.5" cm as the nominal granularity of the LHC-B muon pad chambers.

3.2.3 Effect of the $B_x$ and $B_y$ Components of the Magnetic Field

If the LHC-B analysis magnet were to have significant components in the bend plane ($x,z$
plane), then dispersion, especially in the y direction, could lower the efficiency of the Level
0 trigger by disturbing the pointing at the interaction region in the y projection. The
present design of the LHC-B magnet incorporates features that minimize the $B_x$ and $B_z$
magnetic field components such that the non-major components present no problem to the
Level 0 muon trigger. However, given the cost of minimizing $B_x$ and $B_z$ components, it is
useful to investigate how much larger these components can be without overtly damaging
the rejection of minimum bias triggers or the $B\rightarrow \mu$ efficiency.

In order to study this, we have arbitrarily multiplied the $B_x$ and $B_y$ components of the
current LHC-B field map by factors of two and four and generated new sets of minimum
bias and B semimuonic decays, passing them through the modified magnetic field. Fig. 8
shows the variation of the $B\rightarrow \mu$ efficiency and the minimum bias rejection as a function
of the size of $B_x$ and $B_y$. As can be seen, the B efficiency is unaffected by the increase
in the non-major magnetic field components, but the rejection of the min bias triggers is
degraded from 1.1% to almost 1.8%.

As a note of caution, this study was done with the $\mu_0 - \mu_1$ version of the trigger
algorithm and with no showering in the shield. While the study should be repeated with
the $\mu_1 - 2$ version of the trigger algorithm, we do not expect the results to be significantly
different.

3.2.4 Showering in the Muon Shield

The effects of showering of hadrons in the muon shield have not yet been fully studied at
this time. Due to the long compute times required to generate events in which hadron
showers have been tracked down to 0.1 MeV fragments, only limited statistics have been
 complied. Based on a sample of 200 events, showering seems not to affect the trigger rates
due to minimum bias events or the efficiency of the B semimuonic decays if the Level 0
trigger is tuned as stated above. Further studies with higher statistics will be necessary
to precisely estimate the effects on trigger rates and efficiencies however.

3.2.5 Muon Triggers from Machine Generated Backgrounds

While the machine associated muon backgrounds for LHC-B are approximately two orders
of magnitude larger per interaction than for Atlas and CMS when the high luminosity
interaction regions are operating at $10^{34}$ cm$^{-2}$s$^{-1}$, our preliminary estimates are that
they still will provide, worst case, a small addition to the trigger rate due to interactions when
LHC-B operates at $1.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$.

Using the most pessimistic estimate of the two calculations [4] done thus far for the
muon flux from machine associated sources and assuming that all muons from such sources
would be effective in producing a trigger, we estimate that triggers from such sources would
contribute less than 15% of the Level 0 rate due to the interactions themselves. These
crude estimates will be improved in the future with actual simulations of the interaction
of machine backgrounds with the LHC-B detector elements.

3.2.6 Future Muon Trigger Studies

Each of the trigger studies described above will need to be repeated with higher statistics.
The studies of the effect of showering in the muon shield will certainly require more
statistics. Those studies that have not been done with the $\mu_1 - \mu_2$ algorithm will need
to be redone using the nominal pad granularities. Before these studies are initiated, we
must determine if we can use rectangular pads and, if so, what aspect ratio is suitable.

Beyond the general studies that we have discussed, attention must be turned to more
realistic simulations of actual Level 0 trigger hardware. The $\mu_0 - \mu_1$ trigger algorithm
has been simulated in the hardware context of the 3D-Flow trigger processor [5]. Other
hardware options should be investigated and simulated to get more realistic estimates of
the time required for a Level 0 state machine.
3.3 Muon Trigger Rate Estimates

Based on our studies, we have generated, using the "$\mu_1 - \mu_2$" algorithm and the "0.5 cm x 0.5 cm" granularity, the correlation of the minimum bias rejection and the $B \to \mu$ efficiency shown in Fig. 9 for the Level 0 muon trigger. If the Level 1 trigger is able to handle 300 KHz from each of the three Level 0 triggers (the muon, electron and dihadron triggers), then Level 0 retention of minimum bias events can be as large as 3% corresponding to an $B \to \mu$ efficiency of approximately 13% (our "loose" setting of the Level 0 trigger). If on the other hand, the Level 0 muon trigger is required to reduce the interaction rate by a factor of 100 (1% min bias retention rate; $\approx 100$ KHz Level 0 output rate), the efficiency for $B \to \mu$ will be approximately 8.7%.

4 Future Muon Detector and Trigger R&D

As stated above, R&D is planned for both the CPC and MRPC chambers by the LHC-B collaboration. In particular, the performance of both types of chambers at high rates must be studied. The pad chamber "0.5 cm x 0.5 cm" granularity central to the algorithm will require R&D to determine cross talk and charge sharing effects for both CPC and MRPC chambers. In addition, we will have to learn how to achieve single bucket resolution with large pad sizes.

5 Conclusions

We have tentatively decided on the "$\mu_1 - \mu_2$" algorithm for the Level 0 muon trigger and will investigate possible hardware implementations. We have made a preliminary choice of a pad structure with the "0.5 cm x 0.5 cm" granularity.

Our studies have indicated that we may be able to decrease the maximum angular coverage of the muon detector by a significant amount. The same studies indicate that we must work hard to extend the muon trigger to small angles. In addition, other studies indicate that the restrictions on the size of non-major components of the LHC-B analysis dipole can be somewhat relaxed.

Finally, if the Level 1 trigger can accommodate as much as 300 KHz from the Level 0 muon trigger, the Level 0 trigger efficiency can be as high as 13% for $B \to \mu$ decays occurring over $4\pi$.

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Several members of the LHC-B collaborations have contributed to the continuing development of the muon trigger. We especially acknowledge the contributions of D. Crosetto, Rice University, M.C.S. Williams, CERN/LAA, A.P. McManus, University of Virginia, and A. Tsaregorodtsev and A.Vorobyov of the Gatchina Institute, St. Petersburg.
References


[3] M.C.S. Williams et al., ref ???

[4] Molkov et al. ref ??; Hulthein et al. ref ??

Figure 1: Muon trigger schematic.
Figure 2: Muon Trigger $P_t$ - Muon True $P_t$. 
Figure 3: $B \to \mu$ Trigger Acceptance vs (a) $\theta_{\text{min}}$ and (b) $\theta_{\text{max}}$. 
Figure 4: Minbias Retention vs (a) $\theta_{\text{min}}$ and (b) $\theta_{\text{max}}$. 

Minimum Bias Triple Retention

$\theta_{\text{min}}$ (mrad)

$\theta_{\text{max}}$ (mrad)
Figure 5: Min Bias Retention vs Trigger $p_t$ (various $\theta_{\text{max}}$)
\( \theta_{\text{min}} = 8.5 \text{ mrad} \)

\( \theta_{\text{min}} = 10.2 \text{ mrad} \)

\( \theta_{\text{min}} = 15.3 \text{ mrad} \)

\( \theta_{\text{min}} = 20.5 \text{ mrad} \)

\( \theta_{\text{min}} = 25.6 \text{ mrad} \)

\( \theta_{\text{min}} = 29 \text{ mrad} \)

Figure 6: Min Bias Retention vs Trigger \( p_t \) (various \( \theta_{\text{min}} \))
Figure 7: Muon Trigger $p_t$ vs. Granularity of the $\mu$ Chambers.
Figure 8: $B \rightarrow \mu$ Efficiency and Min Bias Retention vs $B_x, B_y$ Field Component Size
Figure 9: Minimum Bias Retention vs. B→μ Efficiency

Min Bias Retention vs B→μ Efficiency
("0.5cm x 0.5cm" Granularity)