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Muon triggers in the High Level Trigger of LHCb

Roel Aaij[1] and Johannes Albrecht[2].

[1] *NIKHEF*
[2] *CERN*

Abstract

The muon trigger selections for both levels of the LHCb software trigger (HLT1 and 2) are described and their performance is evaluated using $B^+ \to J/\psi K^+$ signals reconstructed in $330\,\mathrm{pb}^{-1}$ of data which were collected in the first half 2011.

Contents

1 Introduction

The LHCb experiment has a two level trigger [1]. The first level (L0) is a hardware trigger, implemented using custom made electronics to reduce the input rate to a maximum of 1 MHz. At this rate the whole detector can be read out. The second trigger level (High Level Trigger, HLT) is a C++ application running on an *Event Filter Farm* (EFF) composed of several thousands CPU nodes. It reduces the L0 output rate to a maximum rate of about 3 kHz. The HLT selected events are then saved on permanent storage. The HLT itself is divided in two parts: HLT1 and HLT2. HLT1 reduces its input rate to about 40 kHz using a partial reconstruction of the data to save computing time. At the HLT2 level, events are reconstructed and selected by a set of inclusive and exclusive algorithms. The reconstruction performed in HLT2 is as similar as possible to the one performed offline, where the limitations come from computing time requirements.

In this note, a brief introduction of the data sample and signal selection will be followed by a discussion of L0. The main part of the note describes the algorithms and selections used to trigger muons in both HLT1 and HLT2 and gives their performance figures.

1.1 Determination of trigger efficiencies on data

The trigger performance in this note is evaluated on events which are accepted by the signal selection discussed in section 3. For these events, the trigger efficiency can be measured using the method described below.

The first step in the procedure to estimate trigger efficiencies is to classify events in two categories according to the information required to trigger [2]:

- **TIS** (Trigger Independent of Signal): the event would also have been triggered without the signal under study;
- **TOS** (Trigger On Signal): the signal under study is sufficient to trigger the event.

Note that an event can also be TIS and TOS simultaneously (TIS&TOS), or neither TOS nor TIS. The LHCb trigger system records all the information needed for such a classification.

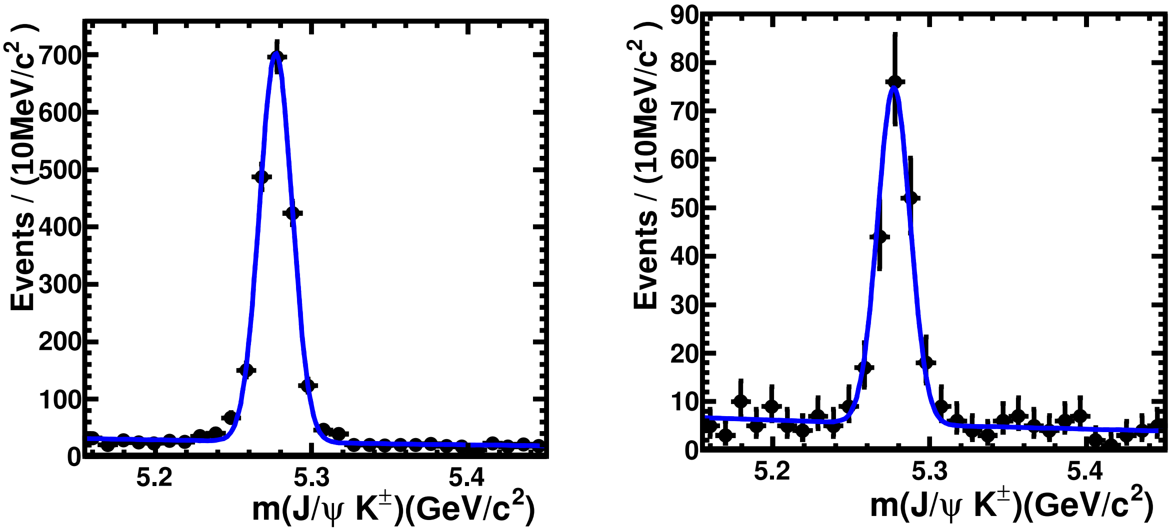
The efficiency to trigger an event independently of the signal particles, ϵ^{TIS}, is given by

$$\epsilon^{\mathrm{TIS}} = \frac{N^{\mathrm{TIS\&TOS}}}{N^{\mathrm{TOS}}} \,. \tag{1}$$

The total trigger efficiency for a given channel can then be computed as

$$\epsilon^{\mathrm{TRIG}} = \epsilon^{\mathrm{TIS}} \times \frac{N^{\mathrm{TRIG}}}{N^{\mathrm{TIS}}} = \frac{N^{\mathrm{TIS\&TOS}}}{N^{\mathrm{TOS}}} \times \frac{N^{\mathrm{TRIG}}}{N^{\mathrm{TIS}}} \,. \tag{2}$$

This method is discussed in further detail in [2] and has successfully been used in several LHCb publications, *e.g.* [3].



(a) TIS&TOS (b) exclusive TIS

Figure 1: Result of a simultaneous fit to $B^+ \to J/\psi K^+$ candidates, separated by (a) TIS&TOS and (b) exclusive TIS, where TOS is with respect to `Hlt2DiMuonJpsi`. The PDF and data have been projected onto the B candidate invariant mass.

To obtain an average efficiency, a simultaneous fit to the invariant mass of candidates in two independent samples is performed. The full sample is split by selecting candidates which are either exclusively TIS or TIS&TOS. To best separate signal from background, the fit is performed in two dimensions: the invariant mass of the B candidate and the J/ψ daughter candidates. This split yields three different categories of candidates and their respective efficiencies: signal, background including a J/ψ and purely combinatorial background. Since the shapes of the PDFs describing these categories are expected to be the same in the exclusive TIS and TIS&TOS samples, they are fixed from a fit to the combined sample; as are the total yields per category. The fit procedure is described in detail in section 3. Figure 1 shows the result of the simultaneous fit to a $B^+ \to J/\psi K^+$ sample (the signal selection is discussed in 3) where the TOS criterion is with respect to the trigger line `Hlt2DiMuonJpsi`. All efficiency figures quoted in this note have been obtained following this procedure.

2 Data sample and software used

The performance of the trigger system is evaluated using a dataset which corresponds to an integrated luminosity of $330\,\mathrm{pb}^{-1}$ of data recorded with the `MOORE` versions v12r5 and v12r6 and dominantly with the trigger configurations `TCK_0x005a0032`, `TCK_0x006d0032` and `TCK_0x00730035`. No changes which are relevant for the trigger lines discussed here were done in between these configurations. The average number of visible pp interactions per bunch crossing of this dataset was $\mu = 1.4$ and the data was reconstructed by the Reco10-Stripping13 processing pass.

3 Signal selection

To evaluate the performance of the muon trigger system, a clean sample of decays of $B^+ \to J/\psi K^+$ has been selected, the criteria used are given in tables 1 and 2. The left side of Fig. 2 shows the distribution of events after applying the listed selection criteria and in addition the requirement that an event is TIS in L0, HLT1 and HLT2. The selection used is identical to the $B^+ \to J/\psi K^+$ selection used for the calibration of the flavour tagging in the ϕ_s analysis [4].

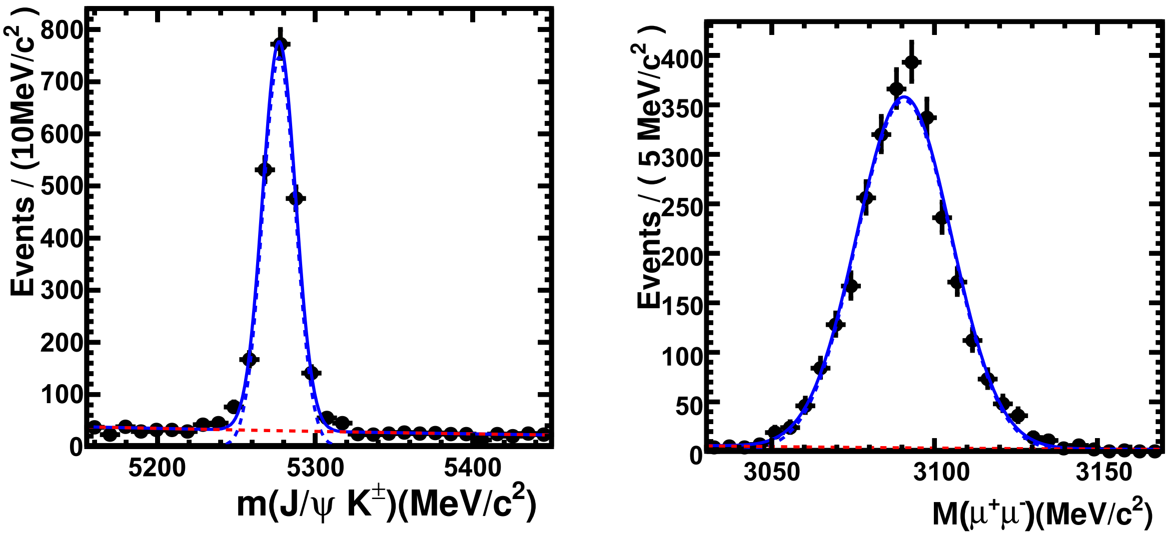
Cut parameter	Stripping value	Final value
$\Delta \ln \mathcal{L}_{\mu\pi}$	> 0	> 0
$\chi^2_{\text{track}}/\text{nDoF}(\mu)$	< 5	< 4
$min(p_T(\mu^+), p_T(\mu^-))$	-	$> 0.5\,\text{GeV}/c$
$\chi^2_{\text{vtx}}/\text{nDoF}(J/\psi)$	< 16	< 11
$\lvert M(\mu^+\mu^-) - M(J/\psi)\rvert$	$< 80\,\text{MeV}/c^2$	$< 80\,\text{MeV}/c^2$

Table 1: $J/\psi \to \mu\mu$ selection. A '-' implies that no cut was applied on the corresponding parameter. In the stripping, the J/ψ is reconstructed first in each event and is used as the common starting point for reconstructing the $B^+ \to J/\psi K^+$.

Cut parameter	Stripping value	Final value
$\Delta \ln \mathcal{L}_{\text{K}\pi}$	> -2	> 0
$\Delta \ln \mathcal{L}_{\text{Kp}}$	-	> -2
$\chi^2_{\text{track}}/\text{nDoF}(K^+)$	< 5	< 4
$p_T\ (K^+)$	$> 1\,\text{GeV}/c$	$> 1\,\text{GeV}/c$
$p(K^+)$	-	$> 10\,\text{GeV}/c$
$M(B^+)$	$\in [5100,\ 5550]\,\text{MeV}/c^2$	$\in [5100,\ 5450]\,\text{MeV}/c^2$
$\chi^2_{\text{vtx}}/\text{nDoF}(B^+)$	< 10	< 10
$\chi^2_{\text{DTF(B+PV)}}/\text{nDoF}(B^+)$	-	< 5
$IP\chi^2(B^+)$	-	< 25

Table 2: $B^+ \to J/\psi K^+$ selection.

From Fig. 2, the level of background can be seen to be low. However, substantial differences in the trigger efficiencies are expected for the samples containing signal, background with a J/ψ and purely combinatorial background. To project out the signal component, the sWeight technique is used [5]. To calculate the sWeights, a PDF describing the invariant mass of the three components is used. The PDF uses a single Gaussian to describe the mass peak of the B^+ signal, a Crystal Ball for the J/ψ invariant mass distribution and for both dimensions a single exponential to describe the purely combinatorial background. The result of a fit of this PDF to the sample where L0, HLT1 and HLT2 are required to be TIS is shown in figure Fig. 2.



(a) $B^+ \to J/\psi K^+$ (b) $J/\psi \to \mu^+\mu^-$

Figure 2: Result of a fit to the invariant mass spectrum of (a) TIS B^+ candidates and (b) J/ψ candidates. The PDF is used to determine sWeights for the dataset. The full, blue curve shows the total fit function whereas the dashed blue shows only the signal component and the dashed red the background component.

4 L0 hardware trigger

The L0 trigger [1] is the logical OR of several decisions and the veto on Global Event Cuts (GEC). The main physics triggers in L0 are

- `L0Hadron, L0Electron, L0Photon:` These are based on signatures in the calorimeter system. They are of minor importance for the muon trigger selection and will not be discussed further.
- `L0Muon:` This trigger selection is based on a standalone track, reconstructed in the muon system. Using the muon chambers alone, the transverse momentum can be reconstructed with a precision of 20%. For the trigger configurations discussed in this note, the muon candidates are required to have $P_T > 1.48\,\mathrm{GeV}$.

- `L0DiMuon`: This selection is based on two muon candidates where the product of the p_T of the two is required to satisfy a minimum $p_T^2 > (1.3\,\mathrm{GeV})^2$.

In addition to the selection described above, all events are required to be sufficiently clean. This is enforced by limiting the hit multiplicity in the SPD detector. The requirements for L0 dimuon triggers are less than 900 SPD hits, for all other L0 triggers, at maximum 600 SPD hits are allowed.

The muon trigger selection in HLT1 starts with the subset of events which pass a L0 muon or dimuon decision. The efficiency of the global L0 as well as the efficiency for L0 muon triggers is given in Tab. 3. These efficiencies have been measured using the TISTOS method, see section 1.1, requiring TIS on the full trigger chain and TOS only at L0. When calculating the L0 efficiencies, the different cut on the number of SPD hits between L0DiMuon and the other L0 channels is taken into account by ensuring that the SPD cut is the same for the channels required to be TIS and those required to be TOS. The dominant fraction ($> 99\%$) of selected J/ψ and $B^+ \to J/\psi K^+$ candidates is selected by the muon trigger lines.

Table 3: L0 trigger efficiency measured using the TISTOS method.

	global	all muons	`L0Muon`	`L0DiMuon`
$B^+ \to J/\psi K^+$	$92.5 \pm 0.7\%$	$91.6 \pm 0.7\%$	$91.0 \pm 0.7\%$	$63.3 \pm 2.6\%$

5 Muon triggers in HLT1

The first level of the software trigger, HLT1, starts after the L0 trigger has reduced the bunch crossing rate to a maximum of 1 MHz, at which the whole detector is read out into the Event Filter Farm. At this rate, Velo tracks are reconstructed for all events. Next, the sequence of algorithms is split up according to the L0 decision and the event is further processed using partial event reconstruction.

The muon triggers in HLT1 are executed only on events which have been triggered by `L0Muon` or `L0DiMuon`. As was shown in section 4, these selections cover 99% of the signal events and reduce the rate at which the next reconstruction step is executed by approximately a factor of two.

The sequence of reconstruction and selection steps of the HLT1 muon trigger lines after the L0 filter is sketched in Fig. 3. A fast version of the offline Velo tracking [6] is executed, followed by a primary vertex (PV) reconstruction. Next, the track candidates are filtered using a fast muon identification, which is discussed in section 5.1. Only Velo track candidates which have sufficient muon hits associated are then used as seeds for the forward track pattern recognition step [7]. The produced long tracks[1] are then fitted with a fast version of the offline Kalman track fitter and the offline muon ID based on the

[1] Definition of track types in LHCb: A long track has hits in the Velo and T-Stations (optionally

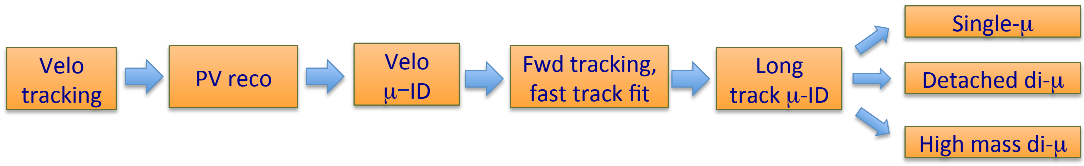


Figure 3: Scheme of the reconstruction and selection steps in the HLT1 muon trigger.

fitted long tracks (ISMUON, see [8]) is applied to reduce further background. The main differences of the HLT1 tracking sequence to offline are the following:

- **Velo track reconstruction:** The `FastVelo` tracking algorithm is divided in two steps. The second part (HLT2 Velo complement), which optimizes the performance for non-pointing Velo tracks, is not executed in HLT1 to reduce the algorithm execution time.

- **PV reconstruction:** A fast algorithm is used which approximates the track errors as the primary vertex is reconstructed on unfitted tracks. Furthermore, the primary vertex reconstruction used in HLT only uses Velo tracks, whereas offline also downstream and long tracks are included. Please note that the PV reconstruction is done once in the HLT at the beginning of HLT1.

- **Long track reconstruction:** In contrast to offline, where a redundant approach with two tracking algorithms is used, in the HLT only forward tracks are reconstructed. The configuration of the forward tracking algorithm used is identical to the one used offline, except for the requirement of a minimal transverse momentum of 0.5 GeV and a momentum above 6 GeV. This restriction significantly speeds up the forward track reconstruction. In HLT1, the forward track finding is only run on selected Velo tracks whereas offline all tracks are used, see [7] for details.

- **Track Fit:** The reconstructed long tracks are then fitted using a Kalman filter based track fit. The only difference to offline is the use of a simplified geometry description.

Using the identified muon candidates, selections for single muon candidates and dimuon vertices are performed, as discussed in section 5.2 and section 5.3 respectively.

5.1 Muon reconstruction in HLT1

A fast muon identification is performed to validate the Velo tracks as muon candidates. A combination of the low occupancy of the muon stations, the fact that the LHCb magnet does not bend tracks in the vertical plane and the requirement that a particle must have

in TT), i.e. it is traversing the whole spectrometer. A downstream track is missing the Velo and has hits only in TT and T-Stations. Long tracks can be reconstructed by two different algorithms: forward tracking and track matching.

at least 6 GeV of momentum to pass all muon stations provide the starting point for early selection of muon candidates from available Velo tracks. An algorithm has been designed to search for muon hits which match a Velo track. As a first step, a search window is defined in the M3 station, the centre of which is determined by extrapolating the Velo track to M3. Due to the large amounts of material present before and between the muon stations, multiple scattering might cause a muon track to deviate from the track obtained by extrapolating the VELO track in a straight line. The vertical size of the search window is chosen to be 20 cm, which is optimized empirically. For the horizontal size the maximum possible deflection of a 6 GeV track is calculated for a positive and negative particle. Any hits found inside the search window are combined with the Velo track to form candidate tracks for a search for additional muon hits in stations M2, M4 and M5. A candidate track is created by extrapolating the Velo track to the focal plane of the magnet and from that point on continuing to the position of the seed hit. By extrapolating the candidate track and using a fixed search window size, additional hits are searched for in M2, M4 and M5. To optimise the efficiency of the search, a candidate track is provisionally accepted if it contains at least one hit in addition to the seed hit. As the final step of the algorithm, a linear χ^2 fit in the horizontal plane is performed and this χ^2 is required to be less than 25. As soon as a single candidate is found, the algorithm stops and the Velo track is accepted.

To determine the efficiency of this algorithm, a sample of offline reconstructed and selected $J/\psi \to \mu^+\mu^-$ classified as TIS at all stages of the trigger is used. For both muons, the corresponding HLT1 Velo track is found before the matching algorithm is applied using this Velo track as a seed. The resulting efficiency of the algorithm as a function of momentum and transverse momentum is shown in Fig. 4. As can be seen from these plots, the efficiency if close to 1 for the full range of both p and p_T.

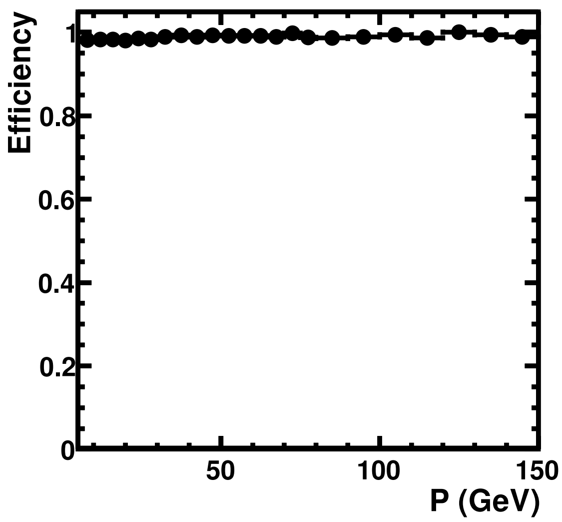
5.2 Single muon triggers

There are three main purposes for single muon triggers in HLT1:

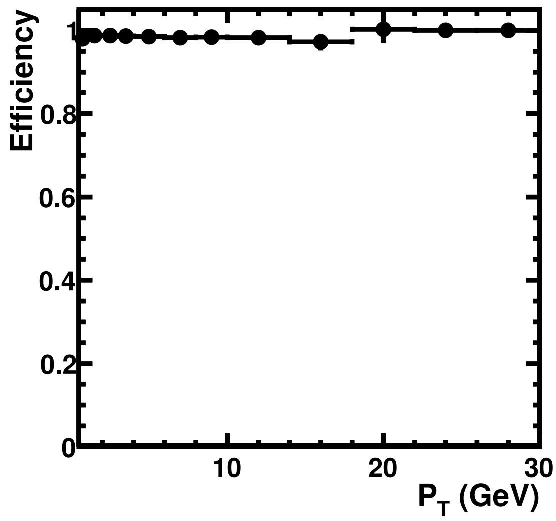
- **Inclusive signal trigger:** Inclusive signal trigger for B, D and τ decays with one or more muons in the final state, where the inclusive selection is based on only one of the muons. The trigger selection exploits the two main signatures to discriminate signal from background: p_T and χ^2(IP) in the displaced single muon trigger `Hlt1TrackMuon`.

- **Electroweak signal trigger:** The signal trigger for muons coming from $W^\pm$ and Z^0 decays needs to efficiently trigger prompt muons and exploits their very high p_T. It is implemented in the prompt high p_T single muon trigger `Hlt1SingleMuonHighPt`.

- **Calibration triggers:** For calibration and the determination of tracking and trigger efficiencies, a variety of single muon triggers is required. A popular method is the *tag&probe* method, where one muon of a resonance like the J/ψ is required to trigger the event leaving the second muon trigger unbiased. These prescaled prompt muon triggers are not discussed further in this note.



(a) p



(b) p_T

Figure 4: Efficiency of the HLT1 Velo to muon hit matching algorithm.

The signal trigger selections motivated above are discussed in the following and their performance is evaluated for the signal mode introduced in section 3.

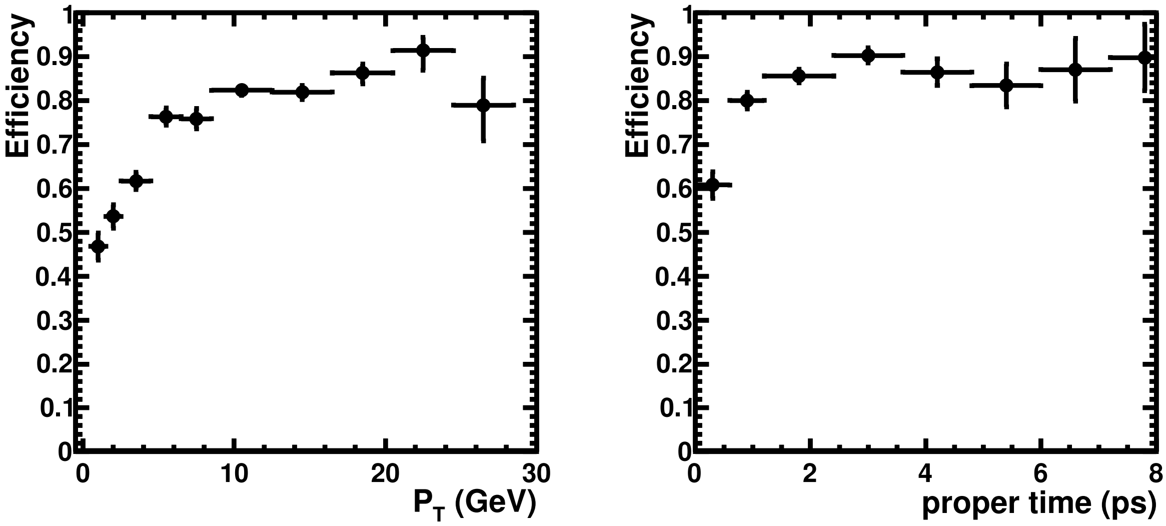
5.2.1 Displaced single muon

Displaced single muons are selected by the `Hlt1TrackMuon` trigger, which is described in detail in [9]. As a first step, the Velo tracks are validated as muon candidates by the selection described above. Then, after a set of track quality requirements (most importantly a track $\chi^2/ndf < 2$), a minimal p_T of 1 GeV and an χ^2(IP) of larger than 16 are required.

The signal efficiency of the single muon trigger is analysed using the TISTOS method, as described in section 1.1 for $B^+ \to J/\psi K^+$ decays, as introduced in section 3. The turn on curves as a function of the B transverse momentum and the B candidate lifetime are shown in Fig. 5. The trigger has a reduced efficiency for low lifetimes and low transverse momenta. The turn on in p_T (B) is dominated by the p_T dependence of the muon identification efficiency and to the p_T requirements in the decision. The lifetime turn on is a consequence of the χ^2(IP) requirement in the trigger selection. At higher lifetimes and p_T, the efficiency becomes flat at a plateau value of about 85%.

5.2.2 Prompt single muon

High p_T muons originating from decays of $W^\pm$ and Z^0 bosons are selected by the `Hlt1SingleMuonHighPT` trigger which is based on a good quality track (track $\chi^2/ndf < 4$) identified as a muon with a relatively large transverse momentum of $p_T > 4.8$ GeV. While



(a) p_T (b) τ

Figure 5: Turn on curves of $B^+ \to J/\psi K^+$ candidates for the line Hlt1TrackMuon.

this trigger selects $W^{\pm}$ and Z^0 bosons decaying into muons with a high efficiency, it contributes only marginally to the selection of B and D decay products.

5.3 Dimuon triggers

The HLT1 dimuon triggers serve as signal trigger for many analyses with two or more muons in the final state, *i.e.* $B \to J/\psi X$. The trigger decisions are based on the mass of the dimuon candidate and the separation of the dimuon vertex, which is selected via the χ^2(IP) of the muons.

The HLT1 dimuon triggers require, like single muon triggers, the logical OR of `L0Muon` and `L0DiMuon`. They are separated in two selections:

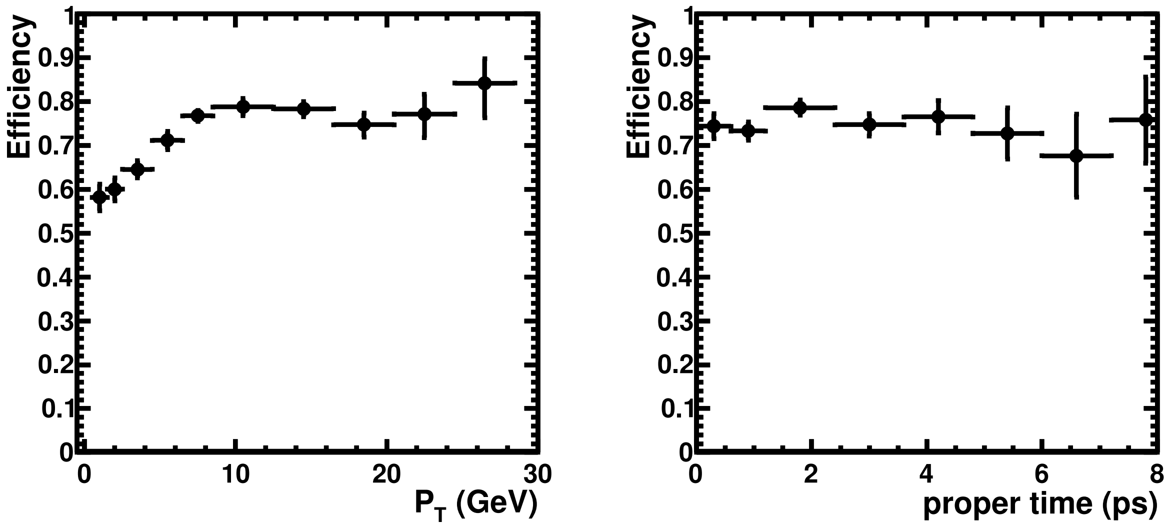
- **High mass dimuons:** Dimuon vertexes with an invariant mass at or above the J/ψ mass can be selected without requiring any vertex separation in the trigger line `Hlt1DiMuonHighMass`.
- **Detached dimuons:** Combinations of muons with lower masses are selected in the trigger line `Hlt1DiMuonLowMass`. Additionally it is required that the muon tracks have a significant χ^2(IP) with respect to their best primary vertex.

5.3.1 High mass dimuon

The track reconstruction for the trigger line `Hlt1DiMuonHighMass` follows the same algorithm flow as described in Fig. 3. Both muons are required to pass the pattern recognition and muon ID steps and are then combined, if their distance of closest approach (DOCA) is below 0.2 mm. The dimuon vertex is fitted and required to have a reasonable fit quality ($\chi^2 < 25$).

Dimuon candidate vertexes with an invariant mass above 2.7 GeV are then accepted by the HLT1 trigger. No vertex separation related quantity is cut on to allow a precise analysis of trigger acceptance. This is, *e.g.*, one of the key inputs of the analysis of the CP violating phase β_s [4].

The turn on curves for the `Hlt1DiMuonHighMass` trigger are shown in Fig. 6. The reduced efficiency in the low p_T region originates in the p_T dependence of the muon ID efficiency, as discussed in section 5.1. For transverse momenta above 10 GeV, the TOS efficiency plateaus at about 80%. The turn on curve shows no dependence on proper time.



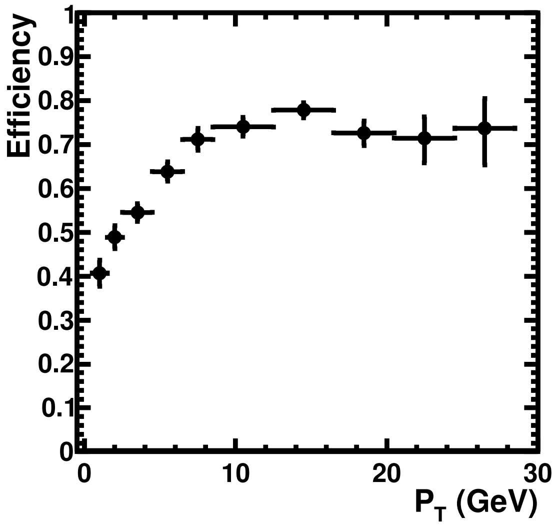
(a) p_T (b) τ

Figure 6: Turn on curves for the line `Hlt1DiMuonHeavy`.

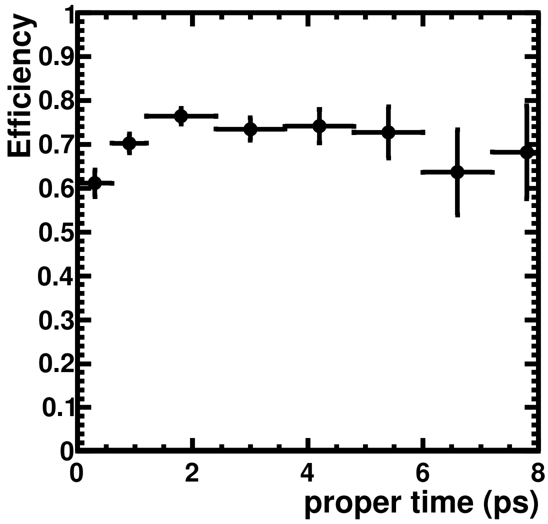
5.3.2 Detached dimuon

The trigger selection for detached dimuons in HLT1 is designed analogously to the high mass selection, it differs only in the final selection criteria. The trigger line `Hlt1DiMuonLowMass` accepts dimuon vertexes with a mass above 1 GeV where both tracks have a significant χ^2(IP) to the PV which minimizes the IP ($\chi^2(\mathrm{IP}) > 3$).

The performance of the HLT1 displaced dimuon selection is shown in Fig. 7. The p_T dependence follows a comparable curve as the high mass selection with a slightly lower plateau efficiency (about 75%). The lifetime dependence shows an inefficiency for low lifetimes which is introduced by the χ^2(IP) requirements.



(a) p_T



(b) τ

Figure 7: Turn on curves for the line `Hlt1DiMuonLowMass`.

5.4 Performance of HLT1 muon triggers

The rates of the HLT1 muon triggers are shown in Tab.4. They are taken from the online monitoring during a run taken with the trigger configuration `TCK_0x00760037`, at a luminosity of $3.5 \times 10^{32}\, cm^{-2}s^{-1}$. This trigger configuration does not apply prescales to the HLT1 muon triggers and due to the high quality of the muon identification, their combined rate amounted to only a small fraction of the full HLT1 output rate of 48 kHz.

Table 4: Rates of the HLT1 muon trigger lines, taken with `TCK_0x00760037`.

line	prescale	rate [Hz]	$\epsilon(B^+ \to J/\psi K^+)$
`Hlt1Physics`	1	36 000	$95.1 \pm 0.6\%$
`Hlt1TrackMuon`	1	5000	$80.5 \pm 1.0\%$
`Hlt1SingleMuonHighPT`	1	700	$23.9 \pm 1\%$
`Hlt1DiMuonHeavy`	1	1200	$75.5 \pm 1.0\%$
`Hlt1DiMuonLowMass`	1	1300	$71.2 \pm 1.1\%$

5.5 Outlook

Since HLT1 processes events at the full L0 rate, any improvements in computing time in HLT1 give large gains. Possible improvements on the HLT1 muon trigger lines are as follows: Once the matching algorithm has found a seed hit in M3 for a given Velo track, the charge and momentum of the candidate can be estimated using the so-called p_T-kick method [10]. This momentum estimate can be used in two possible ways:

- The first option is to improve the efficiency of the matching tool for low momentum tracks by using momentum dependent search windows in the matching algorithm. This approach is also taken when the ISMUON criterion is applied.

- The second option is to store the charge and momentum estimate on accepted tracks so they can be used by the subsequent pattern recognition step, yielding a significant reduction in computing time; knowledge of the charge alone reduces the number of hits which the pattern recognition initially considers by a factor of two.

These improvements reduce the execution time of the pattern recognition algorithms significantly. This would immediately translate in a reduction of the full HLT1 execution time, as the CPU time spent in HLT1 is currently evenly split between the HLT1 hadron and muon lines.

6 Muon triggers in HLT2

The second level of the software trigger, HLT2, performs a full reconstruction of the event at the output rate of HLT1: 40 kHz. The track reconstruction sequence of HLT2 is sketched in Fig. 8. It was designed to be as close as possible to the offline sequence, see [1]. All differences are due to the limited time budged in HLT2, a detailed discussion is given in [11]. The track reconstruction sequence is analogue to the HLT1 sequence as described in section 5. The following items are different in HLT2 with respect to HLT1 and offline:

- **Velo reconstruction:** In HLT2, the non-pointing Velo tracks are also reconstructed. This makes the HLT2 Velo tracking identical to the configuration used offline.

- **Long Track reconstruction and fit:** The long track reconstruction is configured identically to HLT1. However, in HLT2, the tracks are reconstructed globally, which makes the HLT2 reconstruction close to offline.

These differences in combined yield to a tracking efficiency which is reduced by $1-2\%$ per track with respect to offline. The mass resolution in HLT2 differs to the full offline mass resolution by less than 10%. In HLT2, most signals are selected by a few inclusive trigger selections; the single muon and dimuon selections are discussed in more detail below.

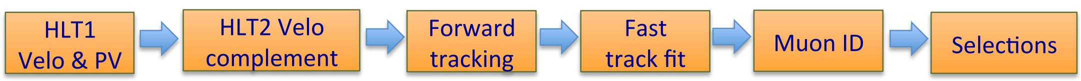


Figure 8: Scheme of the reconstruction steps in HLT2. Note that before the Hlt2 Velo complement, the Velo tracks and the primary vertices of HLT1 are reused.

6.1 Single muon triggers

Due to the high rate of single muons in the LHCb experiment, single muons are not feasible as main signal trigger for B or D decays. Trigger selections combining one identified muon with one or more additional tracks can be used to select semileptonic decays efficiently. These triggers are discussed elsewhere [9].

The single muon triggers in HLT2 serve the following purposes:

- **Semileptonic signal trigger:** Semileptonic decays of B and D mesons can be triggered with a detached single muon trigger without imposing a bias on the hadronic part of the event. This is one of the purposes of the trigger `Hlt2SingleMuon`.
- **Calibration trigger:** Many calibration and efficiency methods use J/ψ ($\mu^+\mu^-$) decays in *tag&probe* methods. For this, the detached single muon trigger `Hlt2SingleMuon` provides reasonable efficiency. To measure the trigger efficiency of electroweak decays, a set of prescaled prompt single muon triggers is run. They are not discussed further.
- **Electroweak signal trigger:** The decays of $W^\pm$ and Z^0 to one or two muons can be triggered effectively, based on the high p_T of the tracks by the prompt single muon trigger line `Hlt2SingleMuonHighPt`.

6.1.1 Detached single muon

The line `Hlt2SingleMuon` selects one clean muon serving the needs discussed above. To reduce the enormous rate of single muon events, it requires that the trigger candidate itself has triggered `Hlt1TrackMuon` selection (TOS required). Additionally, a very good track quality (track $\chi^2 < 2$), a reasonably high PT ($p_T > 1.3\,\mathrm{GeV}$) and very large IP and χ^2(IP) are required (IP$>$ 0.5 mm and χ^2(IP) > 200). The p_T requirement is kept relatively low not to introduce a bias on the hadronic part of semileptonic decays. The trigger efficiency for $B^+ \to J/\psi K^+$ events is measured to be $34.1 \pm 1.5\%$. As the rate of the single muon selection is approximately 1 kHz, it is prescaled by a factor of two in the current trigger configuration (this prescale is corrected for in the above efficiency figure).

6.1.2 Prompt single muon

The prompt single muon trigger `Hlt2SingleMuonHighPT`, which serves as signal trigger for some electroweak decay modes, is set up analogously to its HLT1 counterpart. However, the p_T cuts are higher ($p_T > 10\,\mathrm{GeV}$) as the rate budget in HLT2 is much tighter than in HLT1.

6.2 Dimuon triggers

The inclusive dimuon triggers are consist of prompt trigger selections, where the mass and muon ID are the dominant discriminants used to distinguish between signal and background, and detached dimuon triggers, where the selections are based on the *decay length significance* of the dimuon vertex (DLS). As long as the HLT2 output rate allows, LHCb runs with the prompt dimuon triggers as main $B \to J/\psi X$ signal trigger, but to allow running at higher luminosities, these triggers will eventually be prescaled and the detached dimuon selections take over.

6.2.1 Prompt dimuon

The prompt dimuon triggers are organized in tree lines with mass windows of 120 MeV around the J/ψ and $\psi(2S)$ mass whereas the third line accepts all dimuons with a mass above 4.7 GeV (line names: `Hlt2DiMuonJPsi`, `Hlt2DiMuonPsi2S` and `Hlt2DiMuonB`). As the rates would be too high, no prompt trigger selection for dimuon vertices below the J/ψ mass are implemented. In these lines, explicit p_T requirements on the tracks are avoided as the lines serve as main signal trigger for $B_s^0 \to J/\psi\phi$, where each p_T requirement in excess of the signal selection would bias the angular distribution of the final state muons. All lines discussed above require a good track quality (track $\chi^2/ndf < 5$) and a reasonable vertex quality (vertex $\chi^2 < 25$, $\chi^2 < 10$ for `Hlt2DiMuonB`).

Dedicated, partially prescaled trigger lines for Drell-Yan studies exist but will not be discussed here.

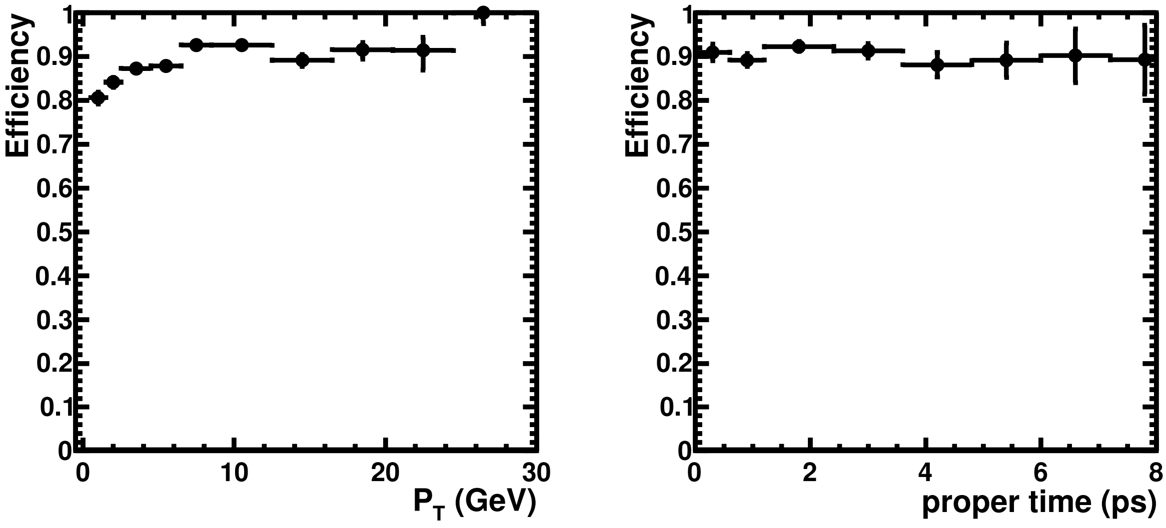
Additional to the prompt dimuon selections which minimize requirements on the transverse momentum of any kind, a set of high p_T lines exist which apply a requirement on the dimuon resonance p_T ($p_T(\mu\mu) > 2$ GeV for the J/ψ and $p_T(\mu\mu) > 3.5$ GeV for the $\psi(2S)$). The lines are called `Hlt2DiMuonJPsiHighPT` and `Hlt2DiMuonPsi2SHighPT` respectively. In case the prompt dimuon selections are not prescaled, all events selected by the high p_T lines are also included in the prompt lines.

The performance of the prompt dimuon triggers is analyzed in Fig. 9 for the line `Hlt2DiMuonJPsi`. The trigger efficiency shows no dependence on the B candidate proper time and has an average efficiency of 90%.

6.2.2 Detached dimuon

The detached dimuons in HLT2 are organized in three inclusive lines, where the trigger rate is controlled by the decay length significance (DLS):

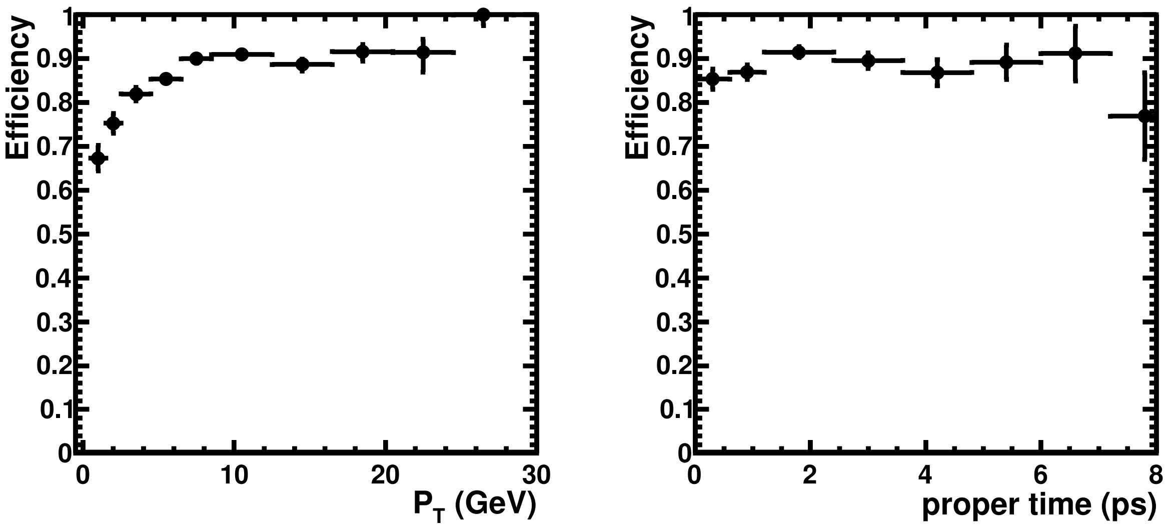
- `Hlt2DiMuonDetached` is the main detached dimuon trigger for low masses (below J/ψ). The candidate is required to have a mass above 1 GeV, a significant χ^2(IP) of the muons and a vertex separation with respect to its closest PV ($\chi^2(\mathrm{IP}) > 9$ and $DLS > 7$) and a minimum resonance p_T of 1.5 GeV.



(a) p_T

(b) τ

Figure 9: Turn on curves for the line `Hlt2DiMuonJPsi`.



(a) p_T

(b) τ

Figure 10: Turn on curves for the line `Hlt2DiMuonDetachedJPsi`.

- Hlt2DiMuonDetachedHeavy is an analogue line for J/ψ and heavier resonances with the non-mass cuts reduced with respect to the low mass line (mass$>$ 2.95 GeV, $DLS > 5$ and no selection based on χ^2(IP) and resonance p_T).
- Hlt2DiMuonDetachedJPsi is a special line to enhance the efficiency inside the relatively small J/ψ mass window ($\Delta m < 120$ MeV) where the vertex separation requirement is reduced compared to the line Hlt2DiMuonDetachedJPsi ($DLS > 3$).

In addition to the selections discussed above, all detached dimuon selections are require a reasonable vertex quality (vertex $\chi^2 < 25$) and a good track quality (track $\chi^2/ndf < 5$), while the requirement of a minimal transverse momentum of 0.5 GeV is implicit in the track reconstruction used in HLT2.

The performance of the detached dimuon triggers is evaluated on the Hlt2DiMuonDetachedJPsi trigger line. The efficiencies dependent on B candidate p_T and lifetime are shown in Fig. 10. They show the usual turn on vs. p_T and only a small efficiency reduction at low lifetimes, as the detachment cut is very loose.

Additionally a set of exclusive selection of decays with one or two muons exist which is not discussed in further detail here. Also, an inclusive selection for detached trimuon events (not necessarily from the same vertex) exists, Hlt2TriMuonDetached. A line to enhance the efficiency for lepton flavor violating decays of $\tau^\pm \to \mu^+\mu^-\mu^\pm$ exist, Hlt2TriMuonTau.

6.3 Performance of HLT2 muon triggers

Table 5: Rates of the HLT2 muon trigger lines, taken with TCK_0x00760037 at an HLT2 input rate of 36 kHz. Only rates of the lines discussed in the text are given.

line	prescale	rate [Hz]	$\epsilon(B^+ \to J/\psi K^+)$
Hlt2Physics	-	3200	$96.5 \pm 0.5\%$
Hlt2SingleMuon	0.5	483	$34.0 \pm 1.5\%$
Hlt2SingleMuonHighPT	1	45	$4.7 \pm 0.5\%$
Hlt2DiMuonJPsi	0.2	51	$91.0 \pm 0.7\%$
Hlt2DiMuonJPsiHighPT	1	113	$59.4 \pm 1.2\%$
Hlt2DiMuonDetached	1	71	$69.2 \pm 1.1\%$
Hlt2DiMuonDetachedHeavy	1	75	$87.6 \pm 0.8\%$
Hlt2DiMuonDetachedJPsi	1	36	$88.9 \pm 0.8\%$
Hlt2DiMuonPsi2S	1	4	-
Hlt2DiMuonPsi2SHighPT	1	15	-
Hlt2DiMuonB	1	81	-
Hlt2TriMuonDetached	1	2	-
Hlt2TriMuonTau	1	1	-

The rates of the HLT2 muon triggers are shown in Tab.5. They are taken from a summary of the recorded rates taken with the trigger configuration `TCK_0x00760037`, which has been run at a luminosity of $3.5 \times 10^{32}\, cm^{-2}s^{-1}$. The prescales given in the table are included in the rates.

6.4 Summary and outlook

The J/ψ line `Hlt2DiMuonJPsi` runs as main signal trigger for luminosities around $1{-}2{\times}10^{32}\, cm^{-2}s^{-1}$. Above these luminosities its role as main signal trigger for $B \to J/\psi X$ decays is taken over by the high p_T lines (`Hlt2DiMuonJPsiHighPT`) and the detached dimuon lines (`Hlt2DiMuonDetachedJPsi`). The $\psi(2S)$ signal triggers are designed analogously.

Dimuon resonances with masses below the J/ψ are triggered by the displaced dimuon selection `Hlt2DiMuonDetached` and heavy dimuon resonances (*e.g.*, $B^0_{(s)} \to \mu^+\mu^-$, but also heavier resonances) are selected without requiring vertex separation by the line `Hlt2DiMuonB`.

7 Conclusions

The algorithms and selections used to trigger events containing muons in the software trigger have been presented and their performance has been discussed. Offline reconstructed $B^+ \to J/\psi K^+$ candidates are selected by the muon triggers with a total trigger efficiency of $83.9 \pm 1.0\%$ (only HLT: $91.6 \pm 0.8\%$), while only a small fraction of the 3.2 kHz trigger output rate is used.

The described trigger selections have been used successfully to collect the vast majority of LHCb data in 2010 and 2011 with luminosities up to $3.5 \times 10^{32} cm^2 s^{-1}$. With slight adjustments of the prescales they can also trigger events at higher luminosities.

References

[1] The LHCb Collaboration, "The LHCb Detector at the LHC", *JINST* **3** (2008) S08005.

[2] J.A. Hernando Morata et al., "Measurement of trigger efficiencies and biases", LHCb-2008-073.

[3] The LHCb Colalboration,"Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$", Phys Lett B 699(2011), 330-340

[4] The LHCb Collaboration, "Tagged time-dependent angular analysis of $B_s^0 \to J/\psi\phi$ decays with the 2010 LHCb data", LHCb-ANA-2011-006

[5] Y. Xie, "sFit: a method for background subtraction in maximum likelihood fit", arXiv:0905.0724, May 2009

[6] O. Callot, "FastVelo, a fast and efficient pattern recognition package for the Velo", LHCb-PUB-2011-001

[7] S. Hansmann-Menzemer, O. Callot, "The Forward Tracking: Algorithm and Performance Studies", CERN-LHCb-2007-015

[8] A. Sarti, S. Furcas, G. Lanfranchi and M. Palutan, "Calibration Strategy and Efficiency measurement of the Muon Identification procedure at LHCb", LHCb-PUB-2010-002

[9] V. Gligorov, C. Thomas, M. Williams, "The HLT inclusive B triggers", LHCb-PUB-2011-016

[10] J Van Tilburg, "Track simulation and reconstruction in LHCb.", CERN-THESIS-2005-40

[11] J. Albrecht, "Fast Track Reconstruction for the High Level Trigger of the LHCb Experiment", CERN-THESIS-2009-120