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Lifetime unbiased beauty and charm triggers at LHCb

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Abstract

This note describes the use of lifetime unbiased triggers in LHCb's High Level Trigger system, implemented during Run 2 of LHC data collection. This is the first time such a strategy has been employed to exclusively trigger on signal candidates in a lifetime unbiased way at a hadron collider. It provides samples of charm and beauty hadrons whose lifetime acceptance due to the trigger requirements is uniform. Consequently, these triggers are suitable for time-dependent measurements and calibration purposes.

1 Introduction

An effective way of triggering on heavy flavour signal candidates at LHCb is by requiring a large impact parameter (IP) between a signal track and the primary vertex (PV). Typically, signal B and D meson candidates will fly some distance before decaying. Therefore beauty or charm hadron candidates can be identified by requiring that their daughter tracks are inconsistent with originating from the PV. However, this means that signal candidates which don't fly very far, i.e. those with small decay times, are less likely to be selected by the trigger. This leads to highly non-trivial time acceptance effects which are challenging to accurately model in the simulation and consequently contribute substantial systematic effects to lifetime measurements.

This note describes a new set of trigger lines in the LHCb trigger [1] which reconstruct signal candidates in real time without the use of any IP cuts. The trigger rate is reduced by fully reconstructing signal candidates and requiring a good quality vertex, an invariant mass within an appropriate window and a requirement that the signal candidate is consistent with originating at the PV. Without the use of IP cuts the trigger rate is extremely high and the signal purity low. In order to improve this, a cut on the candidate decay time is also applied. This is fully lifetime biasing. However the acceptance of this cut is easy to model, taking the form of a pure step function, because the reconstruction algorithms used in the trigger are identical to the ones used offline. These lines can be used for lifetime analyses themselves and can also be used to accurately extract the lifetime acceptance for other trigger lines in a data driven way. Physics analyses which can benefit are those that measure the lifetime of B and D mesons via decays into hadronic final states, for example $B_s^0 \to \phi\phi$ and $D^0 \to K^{\mp}\pi^{\pm}$.

2 Method

For operations during LHC Run 2 (2015-2018) the LHCb High Level Trigger (HLT) is split into two stages. The first, HLT1, performs partial event reconstruction and selects events with dimuons or displaced tracks and vertices. These events are buffered to disk to allow for real time alignment and calibration on these events before the second stage, HLT2, is run. This performs a full offline event reconstruction and selects a mixture of inclusive and exclusive decay signatures. Before the software trigger, events are first selected by a hardware trigger (the L0 trigger) which reduces the LHC collision rate (up to 40 MHz) to about 1 MHz. This has to be reduced in HLT1 to around 160 kHz before HLT2 which writes out to storage at about 12.5 kHz. The LHCb online computing farm has the ability to run $\sim 50,000$ parallel processes which restricts the per event reconstruction time in HLT1 to about 50 ms. These performance requirements meant that for Run 1 (2010-2012) it was impossible to fully reconstruct signal candidates in HLT1 (i.e. convert tracks to particles, fit for a common vertex and construct mother particle candidates). In order to reduce the rate in HLT1 and select signal candidates without the use of lifetime biasing IP cuts this machinery had to be added to the HLT1 software. This new implementation has been possible because of vast improvements to the farm capacity and reconstruction algorithms. One significant difficulty is that there is no particle identification (PID) information available in HLT1. This means that for a given combination of hadronic particles in HLT1 each mass hypothesis must be separately included as there is no way of distinguishing between a kaon, pion and proton. Furthermore, sensible requirements on signal candidates and their decay products must be applied in order to reduce the number of combinations and consequently keep within the stringent timing requirements. In practice it was found that reducing the very high accept rate was of more concern than the timing, in order to keep the overall HLT1 rate within the required limits.

Several new lines have been added to HLT1 which take advantage of this upgraded HLT1 functionality, including the `Hlt1TwoTrackMVA` line. This note concentrates mainly on new lines which are lifetime unbiased. Currently, these focus on exclusively reconstructing two body hadronic B and D decays from pairs of opposite charge tracks. The tracks are required to have transverse momentum, $p_{\mathrm{T}} > 600$ MeV/c, momentum $p > 4$ GeV/c and a track fit χ^2/ndf of less than two. Each of the four possible particle ID hypotheses, K^+K^-, $\pi^+\pi^-$, $K^+\pi^-$, π^+K^-, is considered, and at least one of them is required to fulfill the following requirements:

- vertex fit $\chi^2/\mathrm{ndf} < 10$,
- B or D signal candidate $p_{\mathrm{T}} > 1800$ MeV/c,
- distance of closest of approach between the two tracks of less than 0.1 mm,
- the cosine of the angle between the momentum vector of the B or D signal candidate and the line-of-flight between the primary and decay vertices should be larger than 0.99,
- at least one child with $p_{\mathrm{T}} > 900$ MeV/c,
- a lifetime of at least 0.25 ps,
- an invariant mass within a window of ± 60 MeV/c^2 around the true D^0 mass or within a window of ± 150 MeV/c^2 around the true B^0 or B^0_s mass (where all masses are taken from Ref. [2]).

These selections of $D^0 \to h^+h'^-$ and $B^0_{d(s)} \to h^+h'^-$ (where h is either a kaon or pion) are embodied in six exclusive lines whose invariant mass requirements are listed in Table 1. Furthermore, there are some other specific lines used to reconstruct $\phi \to K^+K^-$, $B^0_{d(s)} \to \phi\phi$ and $B^0_{d(s)} \to \phi\gamma$ decays whose selection requirements are listed in Table 2. All of these HLT1 lines are associated with corresponding lines in HLT2 which also remain lifetime unbiasing but make use of particle identification to correctly distinguish the flavour of the decay tracks and thus reject the considerable background.

Line Name	Mass Window
Hlt1CalibTrackingKPi Hlt1CalibTrackingKK Hlt1CalibTrackingPiPi	Within ± 60 MeV/c^2 of the true D^0 mass
Hlt1LTUB_B2KPi Hlt1LTUB_B2KK Hlt1LTUB_B2PiPi	Within ± 150 MeV/c^2 of either the true B^0 or B_s^0 mass

Table 1: Mass requirements for the six exclusive lines which reconstruct $D^0 \to h^+h'^-$ and $B^0_{d(s)} \to h^+h'^-$ decays

Line Name	Selection requirements
Hlt1IncPhi	As for $D^0 \to K^+K^-$ but with no lifetime cut and a mass window within ± 20 MeV/c^2 of the true ϕ mass
Hlt1B2PhiPhi	Construct a B candidate mother from two ϕ candidates with sum $p_{\mathrm{T}} > 3$ GeV/c and within ± 150 MeV of either the true B^0 or B_s^0 mass
Hlt1B2PhiGamma	Construct a B candidate mother from a ϕ candidate with $p_{\mathrm{T}} > 1800$ MeV/c and a photon candidate with $p_{\mathrm{T}} > 2000$ MeV/c within ± 150 MeV of either the true B^0 or B_s^0 mass
Hlt1CalibTrackingKPiDetached	As for $D^0 \to K^{\mp}\pi^{\pm}$ but with IP cuts applied to the child kaon and pion tracks. This is lifetime biasing but provides a clean sample of D^0 candidates which can be used for monitoring, alignment and calibration

Table 2: Selection requirements for an inclusive ϕ line and two further exclusive B decay lines containing at least one ϕ in the final state. The last line includes IP cuts to produce a high purity sample of D^0 candidates for calibration purposes.

3 Performance

Typically the requirements of these lines are quite inefficient for signal because they have tight requirements on the track fit, vertex fit and signal mother. This makes their use rather specific to lifetime measurements, or assessment of lifetime acceptance systematic uncertainties, for decays with high signal yields. The efficiency to trigger on the signal candidate (defined in Ref. [3]) for the lifetime unbiased `Hlt1CalibTrakingKPi` line is $(8.15 \pm 0.08)\%$, computed from Monte-Carlo (MC) simulation of $D^{*+} \to D^0\pi^+$ (with $D^0 \to K^-\pi^+$) decays. The signal efficiency for the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ lines is expected to be similar. The efficiency to trigger on the signal when adding the IP cuts of

Line	Inclusive Rate (kHz)	Exclusive Rate (kHz)
`Hlt1 All`	209.0 ± 4.1	–
`Hlt1TrackMVA`	95.1 ± 2.9	56.1 ± 0.7
`Hlt1TwoTrackMVA`	48.5 ± 2.1	13.9 ± 0.4
`Hlt1TrackMuon`	22.2 ± 1.5	8.1 ± 0.3
`Hlt1CalibTrackingKPi`	14.8 ± 1.2	6.2 ± 0.2
`Hlt1CalibTrackingKK`	10.7 ± 1.0	5.0 ± 0.2
`Hlt1CalibTrackingPiPi`	6.9 ± 0.8	2.4 ± 0.2
`Hlt1B2HH_LTUNB_KPi`	2.7 ± 0.5	0.12 ± 0.03
`Hlt1B2HH_LTUNB_KK`	2.4 ± 0.5	0.4 ± 0.1
`Hlt1B2HH_LTUNB_PiPi`	2.2 ± 0.5	0.14 ± 0.03

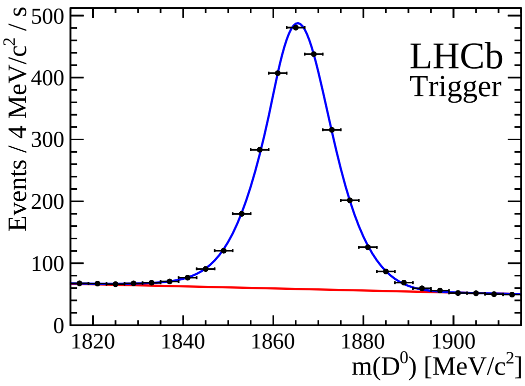
Table 3: Comparison of inclusive and exclusive rates for data in *pp* physics collisions at LHCb in 2015. The total rate is higher than the 160 kHz quoted in the Sec. 1. This is because the L0 thresholds used in 2015 were slightly looser than they will be for the remainder of Run 2.

the `Hlt1CalibTrackingKPiDetached` line is $(3.54 \pm 0.05)\%$.

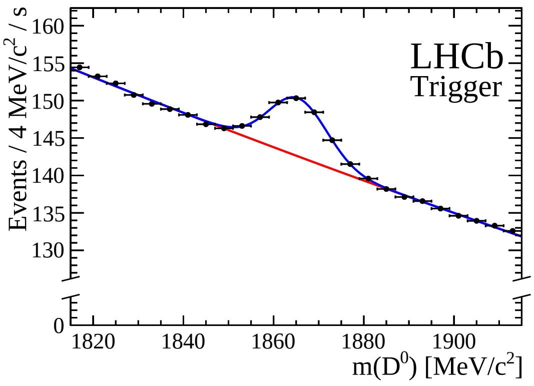
The inclusive and exclusive trigger rates for these lines (compared to some others) in 2015 *pp* collision data are shown in Table 3. These rates and the plots below are produced using data from Run 164433 which was taken on 29 September 2015 and corresponds to a trigger configuration (`0x010600A2`) with which the majority of the 2015 data was collected.

The invariant mass of signal candidates selected by some of these lines in 2015 *pp* collisions is shown in Fig. 1 for data taken during a single one hour run (Run 164433) which corresponds to an integrated luminosity of $0.78\ \text{pb}^{-1}$. The signal rates (after background subtraction) are given in Table 4. These candidates are the direct output from HLT1 with no further cuts applied. It can be seen that the `Detached` line provides a large sample of relatively clean D^0 meson signal candidates although includes lifetime biasing cuts on the daughter track IP χ^2. The size of the background is considerably larger for the lifetime unbiased lines which contain no IP cuts (note the cutoff in the y-axis). However, the signal purity is considerably improved by the D^0 candidate decay time cut. The large background can be reduced in HLT2 by using particle identification on the daughter tracks. Figure 2 shows the invariant mass of $D^0 \to K^{\mp}\pi^{\pm}$ and $\phi \to K^+K^-$ candidates when full offline quality event reconstruction is applied in HLT2, making use of the "Turbo" stream [4].

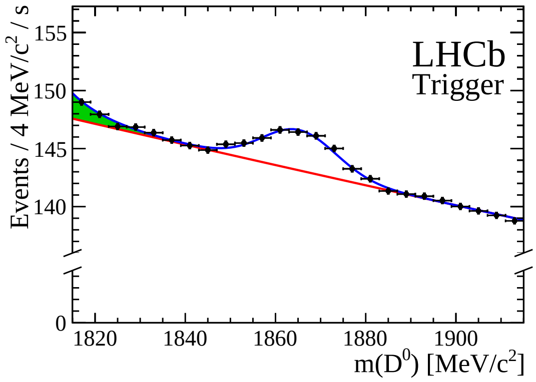
In order to measure the lifetime of the D^0 meson with these lifetime unbiased lines the large combinatorial background has to be reduced. This is done for demonstrative purposes by selecting candidates consistent with $D^{*+} \to D^0\pi^+$ where $D^0 \to K^-\pi^+$ (charge conjugation is implied). A particle identification variable, PIDK, as defined in Ref. [3] is used to select kaon and pion candidates respectively. The selection requires PIDK> 10 for the kaon and PIDK< -10 for both the pions, an IP $\chi^2 < 9$ for the D^0, D^0 transverse momentum $p_{\text{T}} > 2000\ \text{MeV}/c$ and a mass difference between the D^0 and D^{*+} candidates consistent with the expectation from Ref. [2]. This very effectively isolates a clean sample



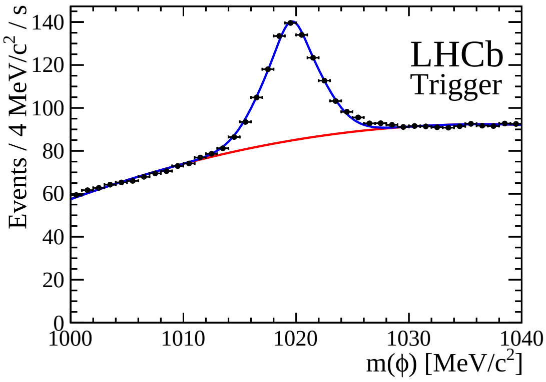
(a) `CalibTrackingKPiDetached`



(b) `CalibTrackingKK`



(c) `CalibTrackingPiPi`



(d) `IncPhi`

Figure 1: The invariant mass of signal candidates in data taken during 2015 which have fired the `Hlt1CalibTrackingKPiDetached` (top left), `Hlt1CalibTrackingKK` (top right), `Hlt1CalibTrackingPiPi` (bottom left) and `Hlt1IncPhi` (bottom right) lines. Shown in terms of the rate; number of events collected per second. The combinatorial background is represented by the solid red line. In the bottom left plot the shaded green area represents the contribution from $D^0 \to K^{\mp}\pi^{\pm}$. The total distribution is represented by the solid blue line. The signal rates are shown in Table 4.

of D^0 events and removes the majority of secondary charm decays. The invariant mass of selected signal D^0 and D^{*+} candidates in a subset of the 2015 data are shown in Fig. 3. The decay time distribution of the D^0 candidates is shown in Fig. 4. The expected distribution from the world average value of $\tau = 410$ fs is overlaid on the plots to guide the eye and demonstrate consistency with a single exponential particle decay distribution. A robust analysis of the D^0 lifetime using the full 2015 dataset is ongoing at LHCb.

Name	Signal Rate (Hz)
`Hlt1CalibTrackingKPiDetached`	2100
`Hlt1CalibTrackingKK`	35
`Hlt1CalibTrackingPiPi`	35
`Hlt1IncPhi`	320

Table 4: The signal rates for candidates which have fired the `Hlt1CalibTrackingKPiDetached`, `Hlt1CalibTrackingKK`, `Hlt1CalibTrackingPiPi` and `Hlt1IncPhi` lines

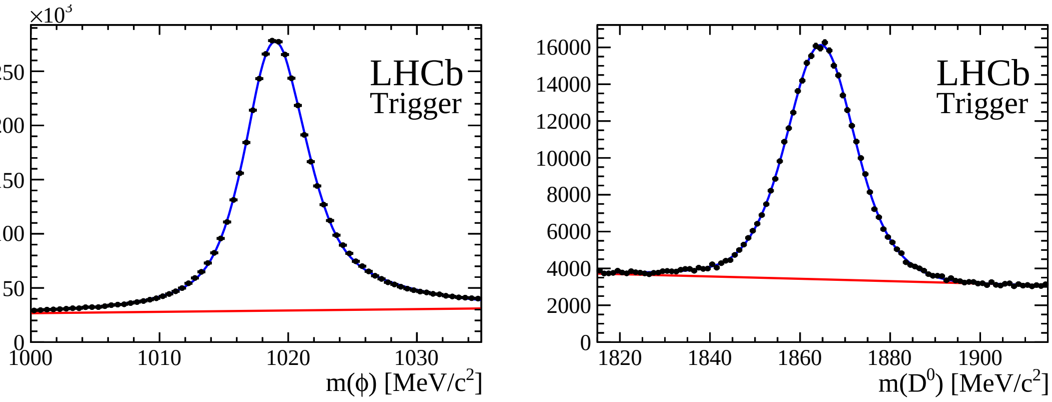
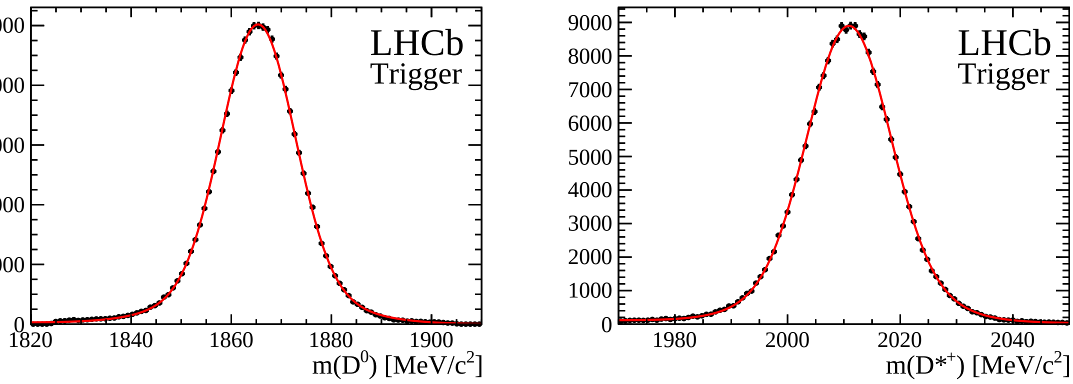


Figure 2: Invariant mass of $\phi \to K^+K^-$ (left) and $D^0 \to K^\mp\pi^\pm$ candidates after PID requirements in HLT2.



(a) D^0 candidates

(b) D^{*+} candidates

Figure 3: The invariant mass of D^0 and D^{*+} signal candidates in data after the D^{*+} selection where the D^0 is required to have fired the `Hlt1CalibTrackingKPi` line.

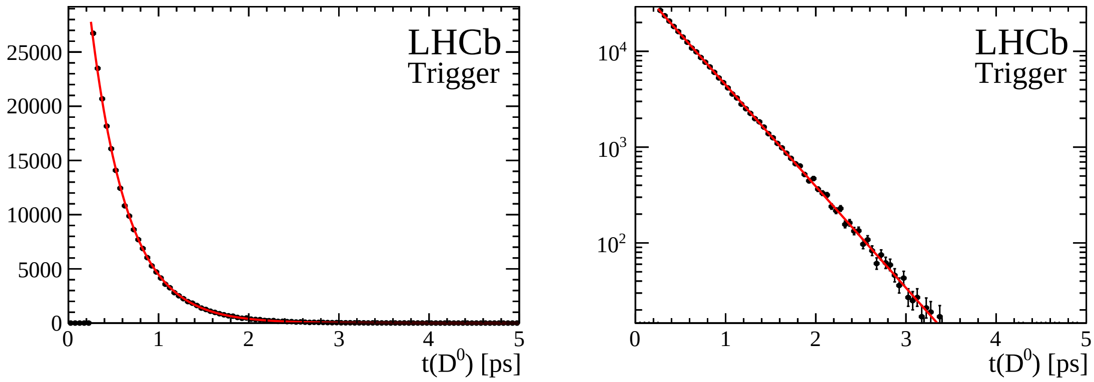


Figure 4: The lifetime of D^0 signal candidates in data after the D^{*+} selection where the D^0 is required to have fired the `Hlt1CalibTrackingKPi` line (left) also shown with a logarithmic scale (right). The red line is not fitted to the data but simply the world average value overlaid.

4 Conclusion

The machinery to fully reconstruct particle decay chains has been added to the LHCb HLT1 software, enabling decays of charm and beauty hadrons to be triggered without any lifetime-biasing requirements. A set of HLT1 lines have been written to select events in this way and have been shown to perform well in data with a signal efficiency in simulation of around 10% for $D^{*+} \to D^0\pi^+$ decays. The timing and rate of these lines is within the requirements of the LHCb trigger system. The combinatoric framework in HLT1 allows for more complex decay chain reconstruction and in the future further lifetime unbiased exclusive lines can be developed.

References

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