Impact of the high-level trigger for detecting long-lived particles at LHCb

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Abstract. Long-lived particles (LLPs) are very challenging to search for with current detectors and computing requirements due to their very displaced vertices. This study evaluates the ability of the trigger algorithms used in the Large Hadron Collider beauty (LHCb) experiment to detect long-lived particles and attempts to adapt them to enhance the sensitivity of this experiment to undiscovered long-lived particles. One of the challenges in the track reconstruction is to deal with the large amount of combinatorics of hits. A dedicated algorithm has been developed to cope with the large data output. When fully implemented, this algorithm would greatly increase the efficiency for any long-lived particle reconstruction in the forward region, for the Standard Model of particle physics and beyond.

1 Introduction

The LHCb is one of the experiments situated at CERN's Large Hadron Collider (LHC). Its primary objective is to probe the boundaries of the well-established Standard Model of particle physics. Several puzzles, such as the imbalance between matter and antimatter in the Universe, the nature of neutrino masses, and the origin of dark matter, remain unresolved. Models proposing physics Beyond the Standard Model (BSM) have been formulated to address these questions.

Long-lived particles (LLPs) represent a promising avenue to discover new physics. Recognizing their potential significance, efforts have recently been made to adapt the LHCb's capabilities for LLP detection. Although historically the LHCb lacked a dedicated first-level trigger for such processes, recent advancements are changing the landscape. This talk delves into one such advancement, focusing on the potential impact of a newly developed high-level trigger algorithm tailored for the detection of LLPs at the LHCb.

2 Upgraded LHCb detector

The LHCb forward spectrometer is one of the main detectors at the LHC accelerator at CERN, with the primary purpose of searching for new physics through studies of CP-violation and decays of heavy-flavour hadrons. It has been operating during its Run 1 and Run 2 periods with very high performance, producing numerous physics results and identifying new exotic particles.

Transitioning into the Run 3 phase, the upgraded LHCb detector results in a major transition in the experiment's approach. The detectors have been extensively upgraded to handle an instantaneous luminosity five times higher than in previous runs, enhanced by new readout systems. A key innovation of this is the implementation of full-software trigger using GPU, enabling real-time data processing and selection, which broadens the scope of LHCb experiments. A detailed discussion of the upgraded LHCb detector is presented in [6], summarized below

Contrasting with its predecessor [1], a significant upgrade is the new tracking system. LHCb now features a three-tiered tracking system comprising the Vertex Locator (Velo), Upstream Tracker (UT), and the Scintillating Fiber (SciFi) Tracker, hadronic and electromagnetic calorimeters, four muon chambers and a particle identification system which combines two Ring Imaging Cherenkov (RICH) detectors, hadronic and electromagnetic calorimeters, and four muon chambers.

The Velo uses pixelated-silicon sensors, crucial for accurately locating the decay vertices of b and c flavored hadrons. Following the Velo, the UT, with its vertically-segmented silicon strips, furthers the tracking process. It is particularly adept at calculating the momentum of charged particles with about 4% precision ($\Delta p/p \approx 4\%$). Importantly, the UT is effective at removing low-momentum fake tracks, significantly speeding up the software trigger.

Post-magnet tracking is performed by the SciFi detector. Particle identification is achieved through two RICH detectors: RICH1 focuses on lower momentum particles, while RICH2 is designed for higher momentum particles. The Electromagnetic Calorimeter (ECAL) efficiently identifies electrons and reconstructs photons and neutral pions. The Hadronic Calorimeter (HCAL) measures the energy deposits of hadrons. Muon chambers (M2-M5) are primarily used for muon identification.

Long-lived particles (LLPs) show up in many extensions of the Standard Model, but they are challenging to search for with current detectors, due to their very displaced vertices. This study evaluated the ability of the trigger algorithms used in the Large Hadron Collider beauty (LHCb) experiment to detect long-lived particles and attempted to adapt them to enhance the sensitivity of this experiment to undiscovered long-lived particles. A model with a Higgs portal to a dark sector is tested, and the sensitivity reach is discussed. One of the challenges in the track reconstruction is to deal with the large amount of and combinatorics of hits in the LHCb detector. A dedicated algorithm has been developed in Run 3 to reconstruct the decay products of these LLPs, and the corresponding impact is studied in this article. The LHCb detectors span an angular coverage of $2 < \eta < 5$. Figure 1 provides a visual representation of the upgraded LHCb detector.

3 Tracking system and track types

The LHCb experiment's tracking system consists of three main subsystems: VELO, UT, and SciFi, responsible for reconstructing charged particles. A key component is a 4 Tm magnet that curves the particles, aiding in momentum (p) determination. Notably, the magnet's reversible polarity helps counteract systematic errors due to detector inefficiencies.

Track types are classified according to the subsystems that contribute to particle reconstruction. Each track type is defined by its interaction with the corresponding detectors, as illustrated in Fig. 2.

Three primary track types are integral to physics analyses:

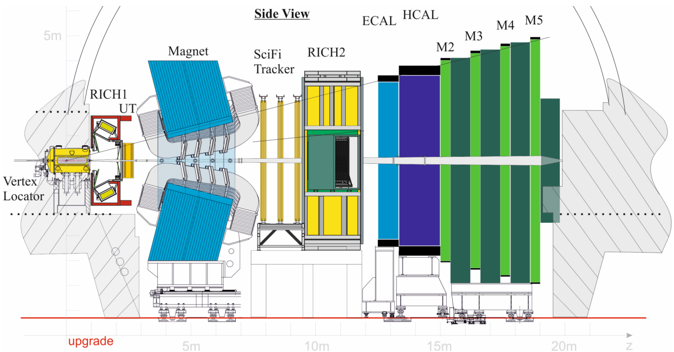

Figure 1. The LHCb detector operating during the Run 3 [6].

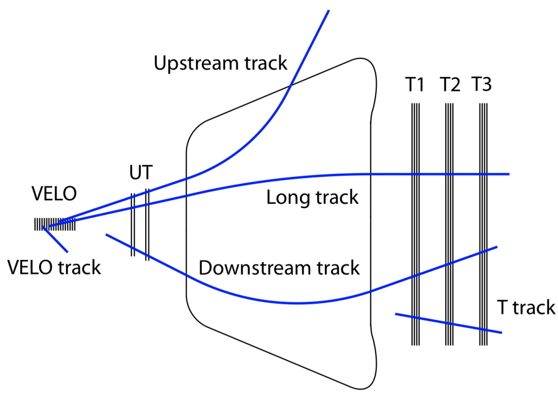

Figure 2. Definition of the track types in the LHCb detector, according to which detectors are hit. The different tracker layers and the magnet, in the centre, are sketched.

- Long tracks: these primarily utilize data from the Velo and SciFi, with occasional input from the UT. Essential for physics analyses, they are included in all trigger stages;
- Downstream tracks: relying on UT and SciFi data but excluding Velo, these tracks often represent decay products from K_s^0 and Λ^0 hadrons;
- T tracks: solely based on SciFi hits, T tracks are typically excluded from triggers and standard analyses. Recent research, however, indicates their potential significance in physics [9].

In simulations of collision data, "reconstructible" tracks are those that fulfill specific criteria based on the capability to reconstruct them in the relevant subdetector. This capability is determined by the presence of reconstructed detector digits or clusters in the simulated detector, which must correspond with the simulated particles through accurate matching of originating detector hits [10]. The criteria for reconstructibility, parsed by subdetector, are:

- **Velo**: requires at least three pixel sensors, each housing a minimum of one digit;

∘ **SciFi**: demands a minimum of one 'x' cluster coupled with a 'stereo' cluster across the three SciFi stations.

Track types are distinguished by specific reconstructibility requirements: *long* tracks must exhibit signals in both Velo and SciFi, *downstream* tracks are identified by signals in UT and SciFi, whereas T-tracks only necessitate signals in SciFi.

4 High Level Trigger in LHCb upgrade

The trigger system of the LHCb detector, starting from Run 3, adopts a fully software-based approach. This system consists of two sequential levels: High Level Trigger 1 (HLT1) and High Level Trigger 2 (HLT2), as outlined in Ref. [5]. Notably, HLT1 stands out for its requirement to operate at a rate of 30 MHz. This demanding pace imposes stringent time constraints on the event reconstruction process.

HLT1 acts as the initial trigger stage, conducting partial event reconstruction and selecting events of interest to decrease the data rate. Tracking algorithms play a crucial role in this rapid selection process, with parallel processing capabilities offering potential improvements in trigger performance. To leverage this, the HLT1 framework is designed to operate on a GPU cluster provided by the Allen project [4]. This configuration can handle an impressive 4 TB/s and reduces the data rate by a factor of 30. Following this initial data reduction, the selected events are directed to a buffer system. This buffering period allows time for real-time calibration and alignment of the detector, facilitating more detailed event reconstruction by HLT2.

Persistent time constraints prompt LHCb's trigger approach to rely on partial reconstructions, focusing particularly on *long* tracks, notably those with hits in the Velo. However, this focus poses challenges for identifying long-lived particles (LLPs), especially those decay over a meter away from the interaction point beyond the Velo's coverage. To address this limitation and broaden the scope of LLP identification, a new algorithm has been developed to trigger *downstream* tracks. This innovative addition enhances the HLT1 system's capability to capture a wider range of particle lifetimes.

5 Long-living Particles in SM

Certain particles within the Standard Model (SM), such as K_s^0 and Λ^0 baryons, are known for their significantly extended lifetimes, typically around 100 ps. These particles frequently appear in various physics analyses aimed at uncovering potential signatures of novel physics models. For example, the rare decay $\Lambda_b \to \Lambda^0\gamma$ is of particular interest, where the Λ^0 baryon decays into a proton-pion pair. Investigating the branching fraction and angular distribution of these decay products may provide insights into non-standard right-handed currents [7]. Another possibility is the yet-to-be-observed decay $K_s^0 \to \mu^+\mu^-$, which is highly suppressed within the SM framework. The detection of this decay mode could signal alternative Beyond Standard Model (BSM) scenarios such as Supersymmetry (SUSY) [12] or the presence of leptoquarks [2].

The next phase involved a detailed analysis of 10,000 simulated events to understand the influence of the HLT1 trigger on the decay channels involving Λ^0 and K_s^0 particles. Figure (4) shows the distribution of reconstructible events across the *long-long (LL)*, *downstream-downstream (DD)*, and *TT* track categories for both decay particles as a function of their respective end decay vertices of both Λ^0 and K_s^0.

These categorisations are essential for understanding how particles are tracked and identified within the detector setup.

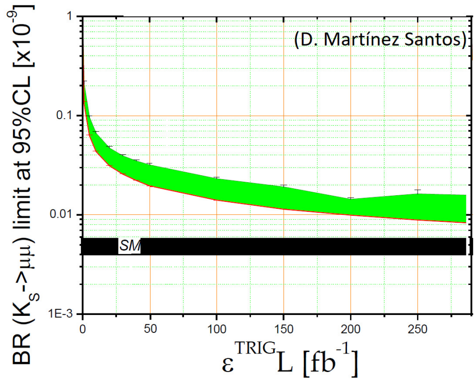

Figure 3. The sensitivity (illustrated by the green band) to the $K_s^0 \rightarrow \mu^+\mu^-$ branching fraction as function of the trigger efficiency × luminosity. The black line demarcates the SM's predictions [11].

The proportions of track types for the $\Lambda_b \rightarrow \Lambda^0\gamma$ decay are determined as 12% (*LL*), 51% (*DD*), and 37% (*TT*). For prompt K_s^0, the distribution of reconstructible tracks stands at 46% (*LL*), 38% (*DD*), and 16% (*TT*). It's worth noting that a significant portion of decays occur at the Velo's extremity, yielding insufficient hits for categorization as *long* tracks. Consequently, these decays are predominantly classified under the *DD* category. Thus, the *DD*+*TT* track combination constitutes approximately 88% for the $\Lambda_b \rightarrow \Lambda^0\gamma$ decay and 54% for prompt K_s^0.

When applying HLT1 criteria to these reconstructible events, the actual selection efficiency can be evaluated. Trigger lines such as "OneTrackMVA" or "TwoTrackMVA", which require tracks to possess minimal transverse momentum and minimal Impact Parameter (IP) significance relative to the Primary Vertex (PV), yield varying efficiencies. In the case of the $\Lambda_b \rightarrow \Lambda^0\gamma$ decay, the HLT1 efficiency for detecting the proton and pion from Λ^0 is below 10%. For K_s^0 candidates, despite inclusive muon lines and specialized selection pathways, the efficiency barely reaches 25%. These efficiency figures are compared against the sum of reconstructible *LL*, *DD*, and *TT* events. If K_s^0 candidates originate from b or c-hadron decays, the number of reconstructible *LL* candidates is expected to decrease, rendering HLT1 less efficient.

6 Long-living BSM Particles

Some BSM theories propose that the SM Higgs field serves as a portal to a dark sector, possibly housing candidates for dark matter [8]. One prominent model in this framework predicts a mixed state between a new scalar low-mass boson (denoted as H') and the SM Higgs (H). This mixing is characterized by the parameter θ:

$$h = H\cos\theta - H'\sin\theta \tag{1}$$

In this model, H' can be considered a mediator to a dark sector with an unknown mass and lifetime. Experimental validation could be achieved through the signature decay $B \rightarrow H'K$, where H' subsequently decays into $\pi^+\pi^-$, K^+K^-, $\mu^+\mu^-$, or $\tau^+\tau^-$, depending on its mass. A displaced vertex could then be identified, enabling the reconstruction of the H' mass based on the kinematics and identification of the two decay particles. However, the sensitivity to

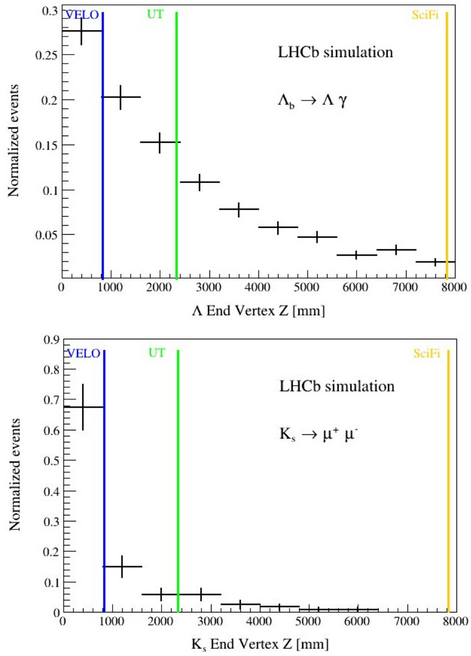

Figure 4. Λ^0 (top) and K_s^0 (bottom) reconstructible candidates charted against the decay vertex position. The candidates of Λ^0 disintegrate into a proton-pion pair, whereas the K_s^0 candidates devolve into two charge muons. The vertical colored demarcations denote the placements of the Velo, UT, and SciFi detectors on the Z-axis [3].

this model depends on the mass and lifetime of H', which may lead to its decay occurring outside the detector's fiducial volume. Especially if H' has a long lifetime, the two final decay particles may not be selected by the first level of the LHCb trigger, potentially escaping detection.

Considering the leptonic decay mode $H' \to \mu^+\mu^-$, the decay rate is given by:

$$\Gamma(H' \to \ell\ell) = \sin^2\theta \frac{G_F m_{H'} m_\ell^2}{4\sqrt{2}\pi}\left(1 - \frac{4m_\ell^2}{m_{H'}^2}\right)^{3/2}, \tag{2}$$

Where G_F is the Fermi constant and m_l is the lepton mass. The Higgs' lifetime is then:

$$\tau_{H'} = \frac{1}{\Gamma(H' \to \mu^+\mu^-)}. \tag{3}$$

In the Run3 LHCb simulation, a sensitivity study is conducted to explore the reconstructible efficiencies of the H' decay into the $\mu^+\mu^-$ final state. This analysis confines the Higgs mass to $m_H > 2m_\mu \approx 212$ MeV/c^2. Furthermore, the H' mass is constrained to $m_{H'} < m_{B^+} - m_{K^+} \approx 4700$ MeV/c^2. For this study, 55 Monte Carlo (MC) samples of 7000 events each are simulated from proton-proton collisions. These samples are generated using Pythia8 under Run 3 beam conditions. Specifically, the $B \to H'(\to \mu^+\mu^-)K$ decay channel is produced, considering H' masses ranging from 500 to 4500 MeV and lifetimes from 1 to 2000 ps [3].

Figure 6 illustrates the reconstructibility of the H' particle's decay vertex concerning its mass and lifetime. For lifetimes under 10 ps, a substantial proportion of *LL* vertex topologies

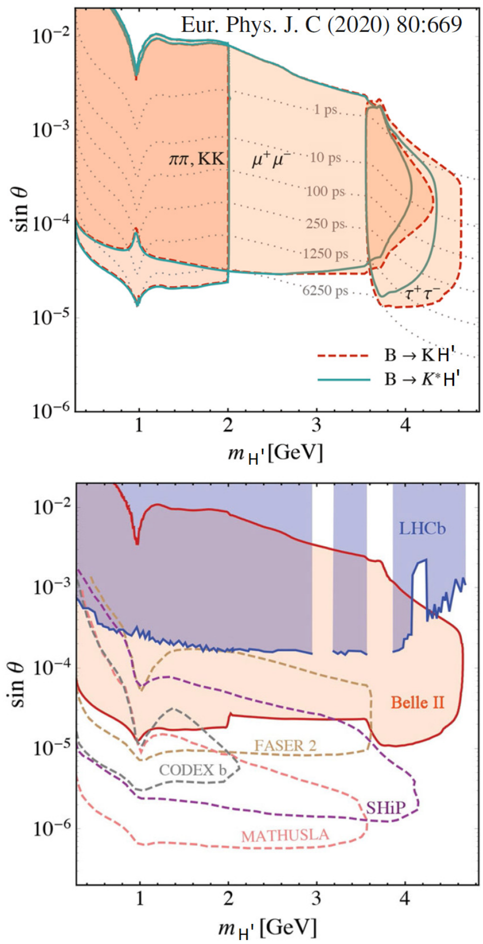

Figure 5. Parameter space regions for the $B \to H'K$ and $B \to H'K^*$ decay channels (top) and sensitivity to the H' displaced vertex by different present and future experiments (bottom), (Figs. adapted from [8]).

are observed, as expected, since the H' decays within the VELO acceptance, allowing both muons to be identified as Long tracks. However, for H' lifetimes exceeding 100 ps (and a small mixing angle), the majority of decays occur downstream of the VELO, resulting in a higher proportion of the *DD* and *TT* topologies. It's noteworthy that these fractions remain quite similar when H' decays into two hadrons, considering that track reconstruction at this stage does not include particle identification.

Figure 7 shows the response of the LHCb HLT1 when triggering on the H' decay products, denoted as Trigger on Signal (TOS). Since only Long tracks are reconstructed at the HLT1 level, a significant inefficiency is evident for extended H' lifetimes, decreasing to 10% for lifetimes exceeding 500 ps. Additionally, there is a noticeable reduction in sensitivity for lower H' masses. This reduction occurs because, with larger boosts experienced by the H', muons are more likely to escape detection in the VELO.

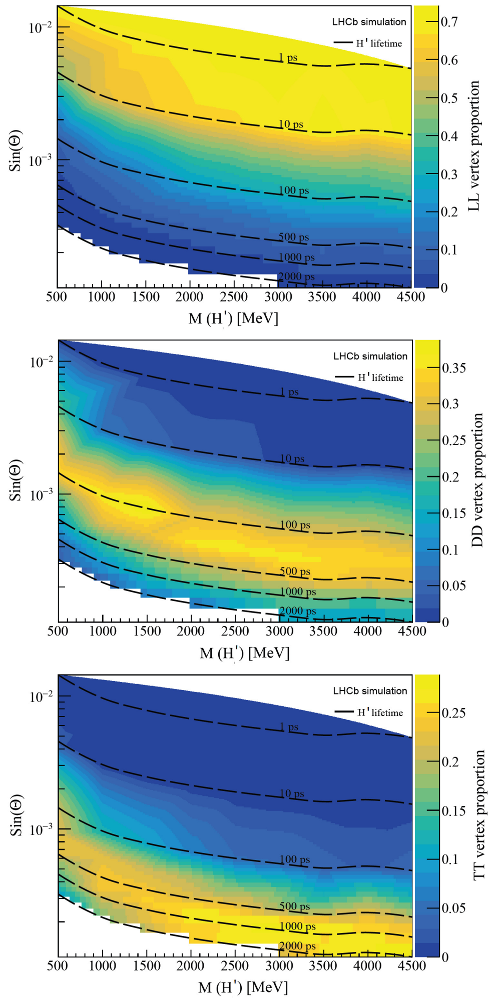

Figure 6. Reconstructibility of the decay vertex of the H' particle as a function of its mass and lifetime. Decay topologies are shown, from top to bottom, in the order: *LL*, *DD*, *TT*, corresponding to the track types of the two muons. [3]

7 Summary

In summary, the upgrades to the LHCb detector for Run 3 are significant, yet they bring challenges in tracking reconstruction due to the increasing data output. Particularly complex is the task of reconstructing particle trajectories that bypass the first tracker (VELO) and interact only with the UT and SciFi detectors. These larger detectors, with their extensive occupancy, present unique complexities. While the focus has traditionally been on reconstructing particles from b- and c-hadron decays, primarily *long* tracks, there is a growing recognition of the importance of *downstream* and *T*-tracks in the initial stages of the trigger.

The current trigger efficiency for long-lived particles is suboptimal, impacting both Standard Model and beyond Standard Model scenarios. In this study, we investigated the effect of HLT1 on a model proposing a Higgs portal to a dark sector, revealing significant inefficiencies for Higgs particles with extended lifetimes and low masses. The implications of

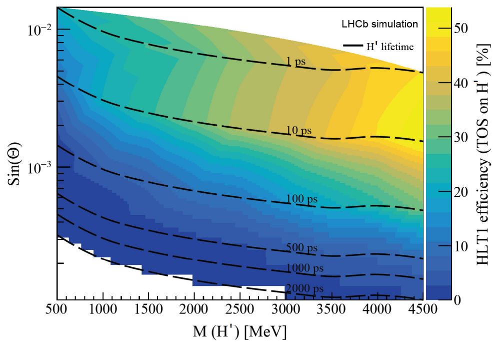

Figure 7. Proportion of events triggered by the HLT1 decision on the H' decay products (Trigger on Signal (TOS)) [3]

HLT1 decisions on decays, particularly for particles like Λ^0 and K_s^0, are substantial, with a significant portion of potentially reconstructible candidates going unselected.

The introduction of the new HLT1 *downstream* track trigger within the LHCb experiment is expected to be transformative. It is anticipated to enhance efficiency not only for standard particles such as Λ^0 and K_s^0, but also to expand the research horizons for particles beyond the Standard Model. By harnessing the power of the SciFi seeds for reconstructing trajectories of long-lived particles, this innovative algorithm signifies a new era of precision and possibility for the LHCb experiment. The significance of this inclusion cannot be overstated, promising to have a profound impact on particle physics research.

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