EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN Summer Student Programme
October 26, 2021

Searching for hidden signatures of physics beyond the Standard Model

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Abstract

A long-lived Higgs boson model produced in B meson decay is used to study the evolution of the LHCb trigger efficiency in a mass and lifetime region. Using the LHCb Simulation Software, the number of displaced vertex types has been estimated at generation and reconstructible level. The efficiency of the first stage of the LHCb trigger (HLT1) was directly computed from the reconstruction of Higgs samples and successfully compared to the prediction from the previous results. It is found that HLT1 efficiency is in general lower than 50% for lifetimes larger than 10 ps.

Contents

1 Introduction

The field of particle physics aims to observe the most elemental particles and understanding the fundamental interactions ruling their behaviour. The Standard Model of particle physics (SM) is the current dominant theory, being theoretically self-consistent and having predicted experimental results with high precision. It nevertheless has several limitations. For instance, the SM is unable to predict the existence of dark matter and the origin of neutrino masses. This has motivated theorists to propose New Physics (NP) extensions and alternative models involving beyond the Standard Model (BSM) particles that may be measurable in collider experiments. In general, these hypothetical new particles are assumed to decay promptly, which has impacted the design of detectors and reconstruction techniques over the last years. However, some theoretical mechanisms suggest that these particles may have large lifetimes. In these cases, they can fly a significant distance from the primary vertex[1] (PV), larger than the spatial resolution of the detector. The interest in long-lived particles (LLPs) is growing among BSM collider search programs, specially for high-luminosity and B-factory experiments [5], as it is the case for the LHCb experiment. Moreover, there is a substantial parameter region where these particles can be found. Figure 1 shows the a classification of unstable particles when they are compared to the spatial resolution of a detector. Long-lived particles whose flight distance is larger than the spatial resolution of the detector will leave a characteristic displaced vertex in their decay. In this scenario, detectors which are designed to

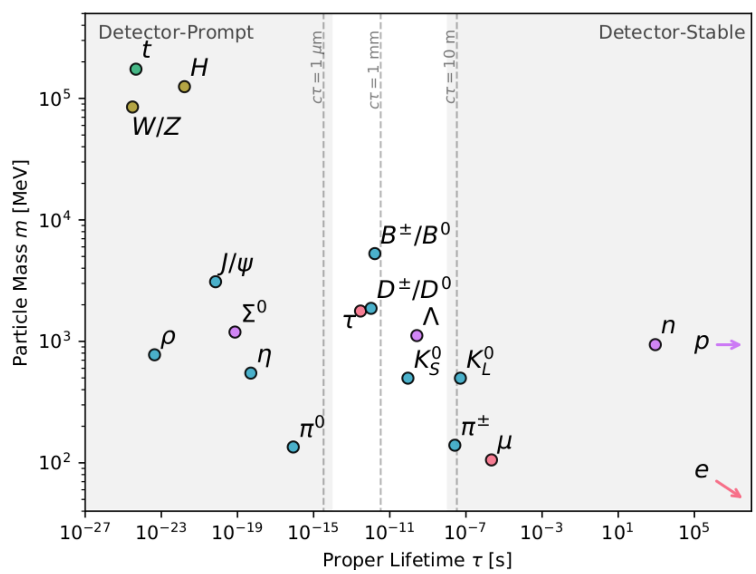

Figure 1: SM particles shown in function of their mass and lifetime. Image taken from [5]

measure prompt decaying particles may not be sensitive enough to measure experimental signatures of LLPs. Flight distances of LLPs can be larger than the spatial resolution of the detector, making the acquisition data system not reconstruct them . Therefore, these signals would be lost from useful data. The focus of this study is to determine the causes of this effect and quantify the efficiency to reconstruct signals of LLPs for the case of LHCb detector. Section 2 presents an overview of the detector setup and trigger performance for event reconstruction. The model of a potential long-lived Higgs boson working as mediator to the dark sector proposed in [6] is summarized in

[1] The primary vertex is the point where particles are produced by the proton-proton (pp) collision at the Large Hadron Collider (LHC)

Section 3. Monte Carlo (MC) samples of the Higgs model were generated from *pp* collisions and propagated inside the detector through the LHCb simulation framework. A comparison between two possible signals of a scalar and vector Higgs has been performed at MC generation level. Besides, the proportion of different track and displaced vertex types has been quantified in a large region of lifetime and mass of the dark Higgs boson. These results helps to understand and predict the LHCb trigger performance for the reconstruction of LLPs. Finally, the efficiency of the first stage of LHCb trigger[2] for the reconstruction of the MC samples of the long-lived Higgs is obtained. All these results are presented in Section 4. The report ends with the conclusion of the study and some proposals of future work in Section 5.

[2]HLT1 is the first stage of the LHCb trigger. It is presented in details in Section 2.2

2 LHCb performance

2.1 Detector setup

The LHCb detector is a single-arm spectrometer in the forward direction with an angular coverage from 15 mrad to 300 (250) mrad in the horizontal (vertical) plane, as shown in Figure 2. The beam pipe is located in the center, along the horizontal axis. The experiment is specifically dedicated to heavy flavour physics studies. It mainly aims to search for evidences of new physics through measurements of CP violation and rare decays of beauty and charm hadrons produced in a large variety of decay modes. At high energy, the $b\bar{b}$ or $c\bar{c}$ system is highly boosted in the longitudinal direction. Therefore, a large portion of them tend to be close to the horizontal axis. The choice of such geometry allows to get a large amount of pairs inside acceptance.

The LHCb detector is composed of subdetectors with different functions that can be moved out

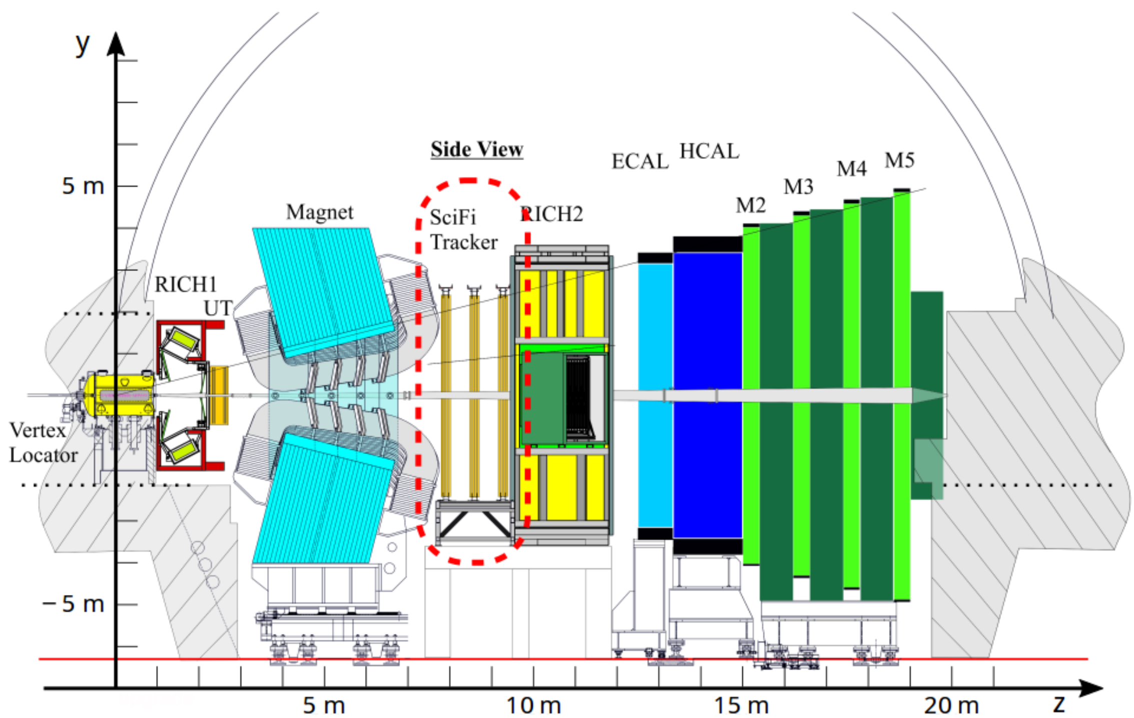

Figure 2: Side view of the Upgrade LHCb detector [4]

horizontally. They can be classified as follow for the upgraded detector:

- The spectrometer magnet deflects charged particles in the X-Z plane by generating an integrated field of about 4 Tm through a warm dipole magnet. This allows to measure the momentum of charged particles by comparing their trajectories before and after being deflected.
- The tracking system reconstructs trajectories of charged particles by matching hits in different subdetectors. A hit efficiency of 99% is generally achieved, resulting in efficient track reconstruction. The different trackers are
  - the VErtex LOcator (VELO). It is found around the interaction region and formed by

42 silicon modules. They provide a high spatial resolution measurement of the radial (r) and azimutal (ϕ) coordinates and therefore precise data flight directions and vertex positions[3].

- the Upstream Tracker (UT). It is formed by four planes of silicon strip sensors and located before the magnet. Due to the residual magnetic field in the region of this subdetector, it may provide a fast measurement of particle momentum. [1].
- the Scintillating Fibre Tracker (SciFi). A total of 12 detection planes of scintillating fibres are arranged in 3 stations. This subdetector is located after the magnet and will be able to measure the hit positions of particles. Doing so, it is possible to determine the deflection of particles going through the magnet and match hits in the previous components for tracking identification [3].

- Ring Imaging Cherenkov detectors (RICH1 and RICH2). These components are filled up with different gas radiators. They identify charged hadrons in the momentum range from 2 to 100 GeV/c
- The calorimeter system measures the energy of hadrons, electrons and photons, which helps to identify them. The calorimeters are: the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL).
- The muon detection system is composed of four stations (M2-M5). The minimum momentum necessary for a muon to cross all stations is around 6 GeV/c.

2.2 The LHCb trigger and track classification

The trigger system selects useful data for B meson reconstruction from other decays and background produced in *pp* collision. In Run 3, the LHC will be producing p-p collision at $\sqrt{s} = 14\,\text{TeV}$ with an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1}. A full software trigger is implemented in the LHCb Upgrade to handle such a large flow of data, removing the Level-0 hardware trigger where the largest inefficiencies were occurring. It is essentially formed by two High Level Trigger (HLT) steps. A basic scheme of the LHCb trigger is shown in Figure 4.

The trigger decision depends on, among other variables, the track type of the particle involved in the event. It uses a fast identification algorithm in order to determine the track type when doing real time analysis in the first level of the trigger (HLT1). This forms part of the tracking system explained in the previous section. It classifies tracks depending on their origin point and direction inside the LHCb detector:

- Long tracks. They are associated to particles whose origin point is inside VELO and they can cross the entire LHCb detector. They can interact with all sub-detectors, but their identification is assured by matching VELO and SciFi hits. This helps the identification algorithm to save time.
- Upstream tracks. They refer to particles created inside the VELO and deflected away by the magnet before reaching the SciFi. They can also leave hits in UT.

[3]Particles of interest involving b and c quarks generally decay promptly due to their short lifetime. This can occur inside VELO, enabling the measurement of this decay point, called vertex.

- Downstream tracks. Their origin point is after VELO, so these particles do not leave hits on it. They cross UT and SciFi, which allow to reconstruct them although this is more time consuming for the identification algorithm.
- Velo tracks. They only leave signals inside VELO, corresponding to particles that are produced outside the LHCb angle acceptance and do not reach other sub-detectors.
- T tracks. They are associated to particles that only leave hits in SciFi. Their reconstruction is very time consuming and inefficient for the identification algorithm.

Some of these tracks are used in the different trigger steps, providing information in order to take a decision on the event reconstruction. They can be visualized in Figure 3.

The first stage of the trigger system is HLT1. It receives bits from the detector at 30 MHz and

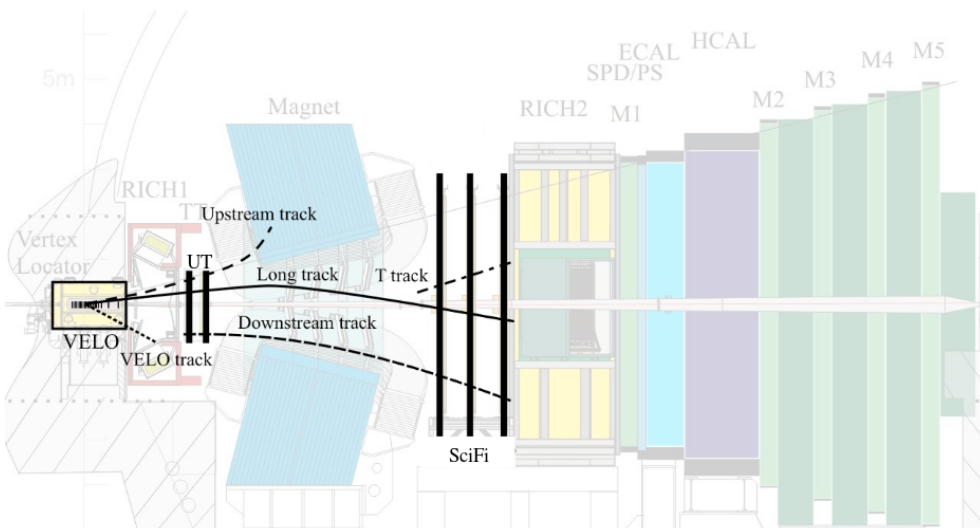

Figure 3: Track types in LHCb detector

performs event reconstructions using information from the tracking system. Variables related to primary vertices, long tracks, muon tags or Particle Identification (PID) allow HLT1 to perform a fast selection on the events of interest and a real-time calibration and alignment of the detector for the next trigger step. Two categories contribute to HLT1 efficiency for any specific decay channel of the type $B \to KX(\to f\bar{f})$[4], X being our particle of interest and K a kaon:

- Trigger independent of the signal (TIS). The trigger decision on the event reconstruction does not depend on the variables of the signal considered. The decision relies for instance on the other b quark produced in the p-p collision.
- Trigger on signal (TOS). The trigger decision depends on the decay products of the signal B meson produced in the collision. However, both K and X can influence differently on the decision to save the event:

[4] In section 3, this decay will be proposed for the model to analyze in this study.

- Triggering on the kaon. The decision depends on the kaon kinematics, related to some variables of X as its mass. For instance, the X lifetime would not have any impact on the trigger decision in this case.
- Triggering on X. It now depends solely on the X variables, the lifetime being a key variable in the decision.

The next stage in the trigger system is HLT2. It receives a data flow of 1 MHz from HLT1 and performs a selection of the events using more variables. The decision made does not need to be as fast as in HLT1. For instance, downstream and T tracks are reconstructed, although only downstream tracks are used in the selection. However, lines can be saved as 'Turbo', where HLT2 only saves to disk the objects used in the selection or close to the trigger candidate; or they can be saved as 'Fullstream' and HLT2 stores all bits from the line [2]. In this last case, it is possible to re-reconstruct T tracks and access other information.

For the signal considered before ($B \to KX(\to f\bar{f})$), the TIS efficiency in HLT1 is expected to have a constant value for different properties of X. The TOS on the kaon efficiency will vary for different X properties. Nevertheless, the main evolution of HLT1 efficiency is TOS on X. It will have a strong dependence on the type of tracks produced in the decay considered. Inspecting the X parameter region can give useful information about the total HLT1 efficiency. For instance, related to particles that decay promptly (short lifetime), a large amount of long tracks will be produced from the displaced vertices, giving as result a good HLT1 efficiency. On the contrary, the longer a particle lives, the more Downstream and T tracks they produce in decay, which are not considered at present in HLT1 TOS on X. Therefore, the efficiency of HLT1 would be reduced for these type of signals. As the information is passed from HLT1 to HLT2, the events not selected in HLT1 are lost.

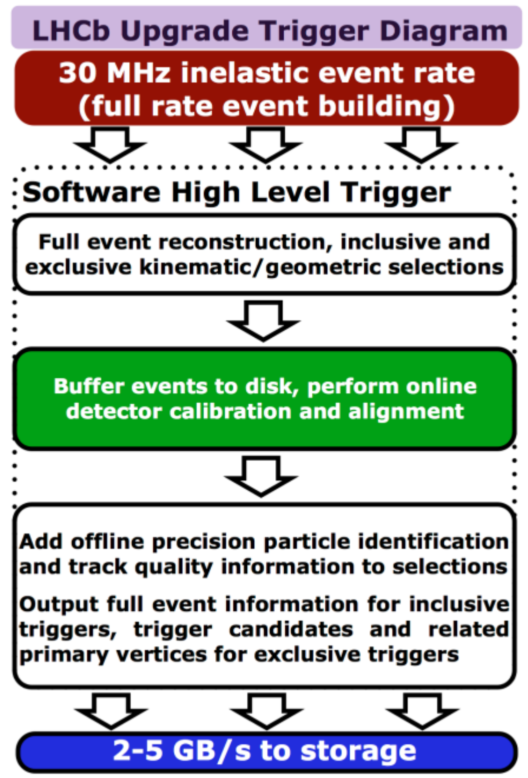

Figure 4: Basic scheme of LHCb trigger stages, taken from [8]

3 Dark boson model

Some extensions of the SM involve the concept of hidden sectors, which would be linked to the SM through feeble interactions, generally modeled by a single new field. This is still restricted by the gauge and Lorentz symmetries of the SM and characterized by the mediating particle involved, also known as portal. A viable scenario consists of a gauge singlet Higgs field, which lightly mixes with the SM Higgs field, serving as a mediator to the dark sector. The resulting state (h) is a dominant $125\,\mathrm{GeV/c^2}$ Higgs boson (H) mixed with an additional one of unknown mass ($\mathrm{H_0}$)

$$h = Hcos\theta - H_0 sin\theta \tag{1}$$

where θ is the mixing angle. The state could be reached through a $\mathrm{b} \to \mathrm{sH_0}$ vertex. Several one-loop diagrams that can contribute to this vertex are shown in Figure 5.

The study the Higgs portal to dark sector on rare B meson decays is possible in experiments such as LHCb and Belle II. The signatures proposed for this aim correspond to scalar and vector[5] dark Higgs:

- $\mathrm{B^+} \to \mathrm{K^+H_0}[\to f\bar{f}]$,
- $\mathrm{B^0} \to \mathrm{K^*(894)H_0}[\to f\bar{f}]$

[5]Scalar means a Higgs produced with a secondary particle of zero spin while vector refers to one produced with a secondary of non-zero spin

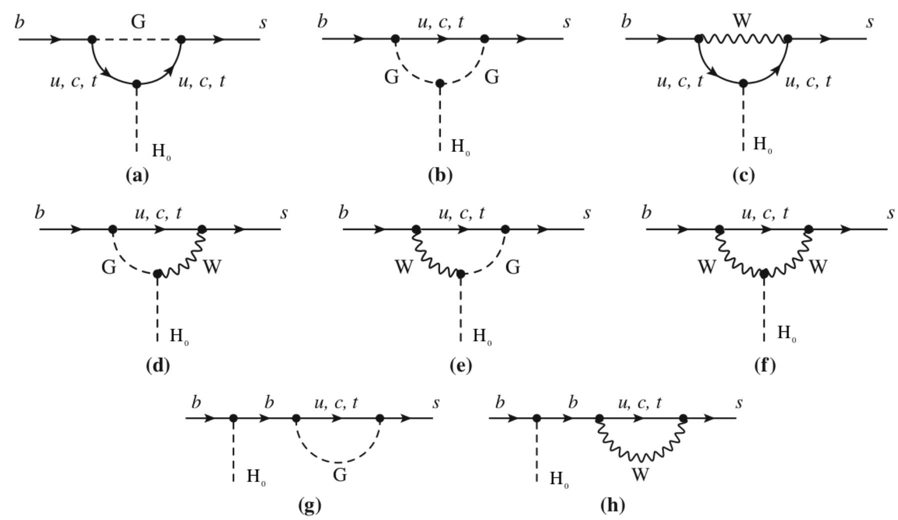

Figure 5: One-loop diagrams contributing to b $\rightarrow$ $\mathrm{sH_0}$

where f refers to fermions produced in the Higgs decay. Experimentally, these signals are notably characterized by a displaced vertex (decay point of the Higgs) from where the two lepton tracks emerge. By measuring the decay kinematics, the Higgs mass can be trivially computed. Moreover, the kaon and B tracks allow to determine the b $\rightarrow$ $\mathrm{sH_0}$ vertex (origin point of the Higgs). Measuring the flight distance of the Higgs and using its momentum, the Higgs lifetime can be measured. The experimental measurement of the B $\rightarrow$ $\mathrm{KH_0}$ branching ratio is also useful to obtain the mixing angle θ.
This model is experimentally attractive as key properties of the Higgs boson can be measured. In the following, we will restrict ourselves to the final state $\mu^+\mu^-$. This bounds the Higgs mass to be $m_{H_0} > 2m_\mu \approx 212\,\mathrm{MeV/c^2}$. From above, if the first channel involving B^+ is considered, the Higgs mass must satisfy $m_{H_0} < m_{\mathbb{B}^+} - m_{k^+} \approx 4700\,\mathrm{MeV/c^2}$. The leptonic decay rate is given by the following equation

$$\Gamma\left(H_0 \rightarrow \ell\ell\right) = \sin^2\theta \frac{G_F m_{H_0} m_\ell^2}{4\sqrt{2}\pi}\left(1 - \frac{4m_\ell^2}{m_{H_0}^2}\right)^{3/2}, \tag{2}$$

where G_F is the Fermi constant and m_l the lepton mass. Considering only two muons in the final state, the Higgs lifetime is computed below.

$$\tau_{H_0} = \frac{1}{\Gamma\left(H_0 \rightarrow \mu^+\mu^-\right)} \tag{3}$$

Authors in [6] have performed a sensitivity study of the Belle II experiment for the proposed model. Considering different potential final states, the mass and lifetime (or mixing angle) region is scanned to analyze where this detector is sensitive enough to measure such displaced vertex signals. Furthermore, a sensitivity comparison with other experiments such as LHCb is performed for this model. Both cases are shown in Figures 6 and 7.

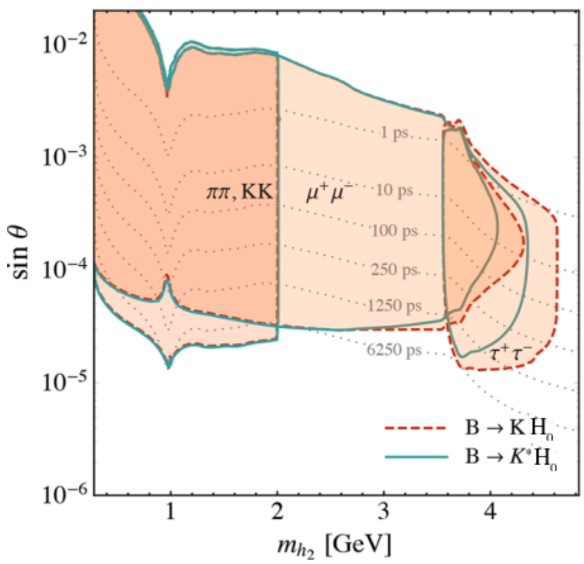

Figure 6: Parameter region for the signal $B \to KH_0(\to f)$ and $B \to K^*H_0(\to f)$, $f = (\pi\pi + KK), \mu^+\mu^-, \tau^+\tau^-$ for Belle II experiment

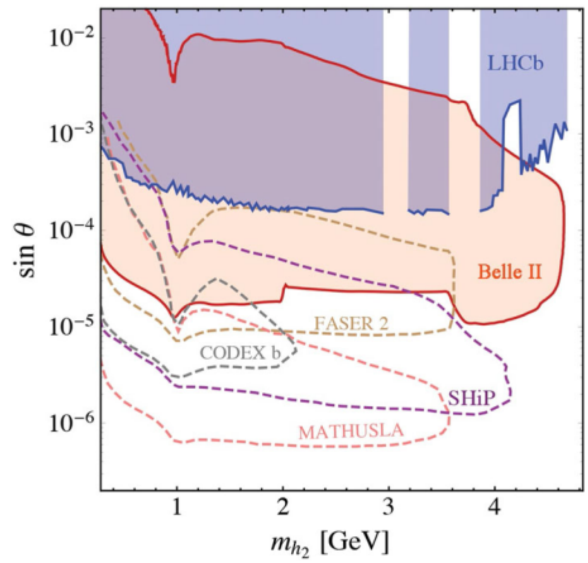

Figure 7: Sensitivity comparison for displaced vertices of H_0 between Belle II, LHCb and other experiments

Although the search for displaced vertices signatures from rare B meson decays seems possible at LHCb, the sensitivity study suggests that it would be limited to a small region in the parameter space. This region is shown in Figure 7 and it is restricted to small values of the Higgs lifetime where its flight distance is not large. Considering the trigger discussion done in Section 2.2, this is directly correlated to the amount of different track types that appear in these decays. These track types have some influence on the trigger efficiency. For small values of the Higgs lifetime, it decays inside VELO and produces a dominant amount of long tracks which are used in HLT1 to reconstruct these events, making the detector sensitive in this region. Nevertheless, when the lifetime increases, a relevant amount of downstream and T tracks appear as it is more probable that the Higgs decays outside the VELO. These tracks are not used in HLT1 reconstruction, making the detector sensitivity decrease. Consequently, the current LHCb trigger performance would be inefficient to search for potential signatures of LLPs, as this dark Higgs may be. This fact is the motivation for the present study. We aim to study the gain in the reconstruction of LLPs when including other tracks in HLT1. To do so, we quantified the proportion of different tracks for an extensive parameter region of a dark Higgs model and computed the HLT1 efficiency. This can give information about LHCb sensitivity limits and be compared with the previous study of the dark boson model.

4 Simulation and results

4.1 Comparison scalar and vector models at generation level

A theoretical model of Higgs dark boson serving as mediator between the SM and the dark sector has been proposed in Section 3. Two possible signals are studied, involving either a scalar or vector dark boson. Both were used to produce 13 MC samples of 7000 events each from proton-proton collision simulations. At this stage, no interaction with the detector was implemented in the simulations ("true" events). The Higgs variables generated are:

- Lifetime $\tau = 100\,\mathrm{ps}$ and mass M from 500 to $4500\,\mathrm{MeV/c^2}$, by $500\,\mathrm{MeV/c^2}$ step
- Mass $\mathrm{M} = 2500\,\mathrm{MeV/c^2}$ and lifetime $\tau = 1, 10, 100$ and $1000\,\mathrm{ps}$

After generating collisions, reconstruction and selection of events are performed in order to separate the decay channels from background and other signals. Therefore, all properties at MC level of particles involved in the decay mode are available. An analysis of some relevant properties is done in Appendix A to validate the simulation. As explained in Section 3, these decays leave very characteristic displaced vertices signals. At "true" generation level, these vertices are classified depending on their Z coordinate, as shown in Figure 8. These displaced vertices produce two tracks of the same type: Long, Downstream or T tracks.

- Vertices produced between the PV and right part of VELO are called "LL" vertices.
- Those produced between VELO and UT are "DD" vertices
- Vertices generated between UT and SciFi are classified as "TT" vertices

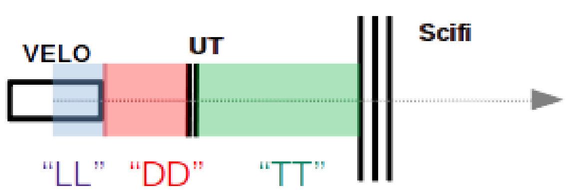

Figure 8: Displaced vertices classification depending on their Z coordinate

In principle, the amount of types of displaced vertices at true level generation should not depend on the spin of the secondary particle generated from the B meson. Therefore, a similar distribution of displaced vertices type is expected for the scalar and dark boson when they have same values of lifetime and mass. This comparison is shown in Figure 9 for the generated samples. Both models are in agreement with the previous hypothesis as they produce very similar proportions[6] of vertices types. For large values of mass and short lifetime, "LL" vertices dominate. This corresponds to small flight distances for the Higgs, making most of them decay inside VELO. However, going to smaller masses, where the boost of the Higgs is greater, or higher lifetimes, "DD" and "TT"

[6] The displaced vertex proportion is computed by normalizing the amount of this type of vertices with the total number of displaced vertices for a value of lifetime and mass

vertex proportions substantially increase. There exist regions where they can even become more numerous than "LL" vertices. This reduction may affect the trigger efficiency (in particular HLT1 efficiency) as explained in Section 2.2. In order to study this hypothesis, it would be helpful to scan a larger parameter space in Higgs lifetime and mass to identify such regions and quantify the vertex proportions. This will be done in the following sections.

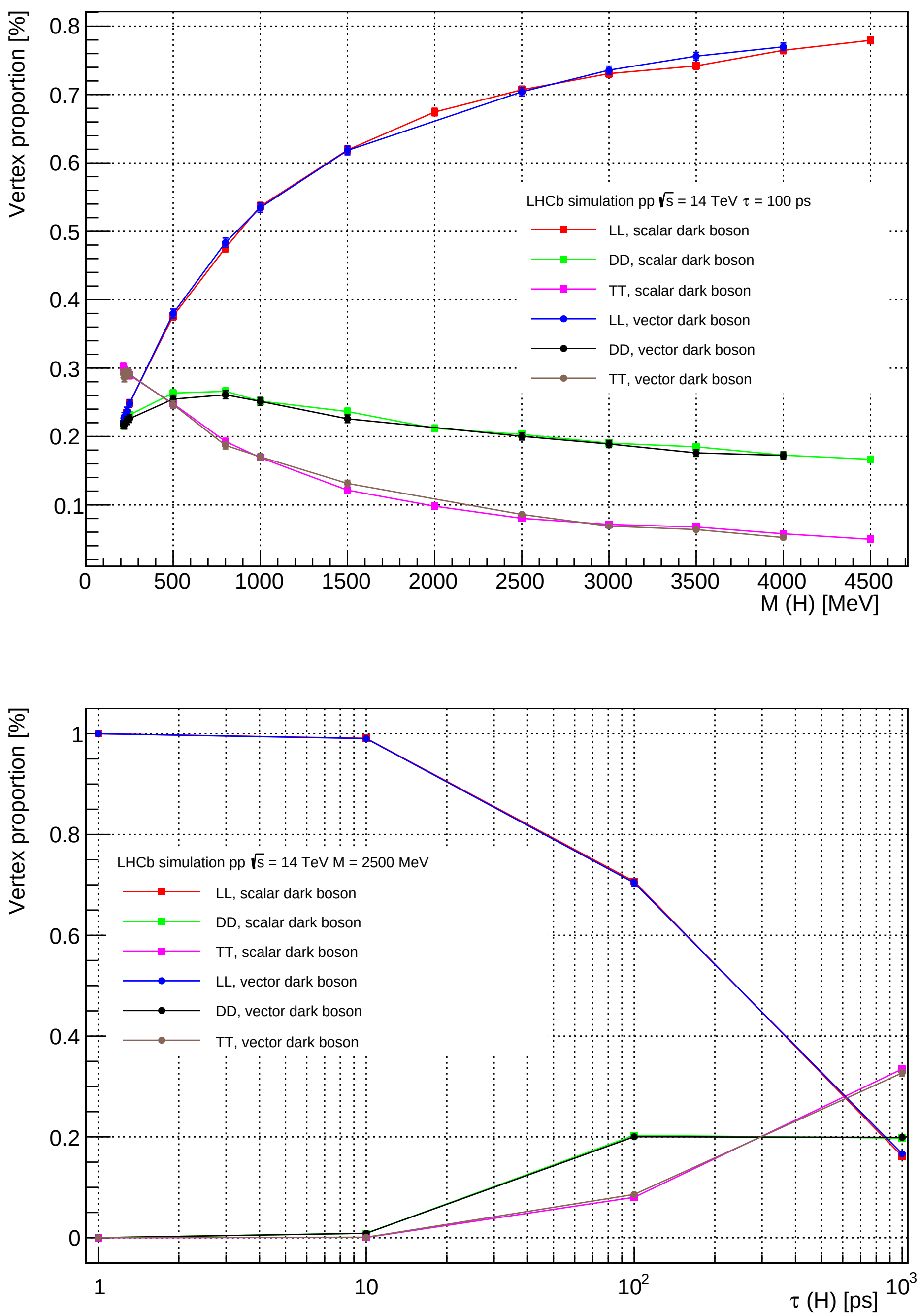

Figure 9: Comparison of the propagation of displaced vertices between the scalar and vector dark Higgs for fixed lifetime (above) and mass (below)

4.2 Number of displaced vertex types at generation level

Previous results indicate some specific regions where the importance of “LL” vertices decrease. The aim now is to scan a larger parameter region where the Higgs decay is probable to happen. More MC samples were generated at “true” level by manually adding new decay files not available in the DecFiles Package provided for Gauss. The final parameter region studied varies from 1 ps to 2000 ps in lifetime and from 500 MeV to 4500 MeV in mass. The generation is done now for only the scalar Higgs. Further details about generation and interpolation of data are presented in Appendix C

The estimation of displaced vertex proportions is shown in Figures 10 and 11. For “LL” vertices, the proportion is close to one for small values of lifetime. In this region, the Higgs mean flight distance is short enough that it decays inside VELO, producing Long tracks. When τ is larger than 10 ps, a transition region appears and the proportion significantly decreases as the particle is more likely to decay beyond VELO. It reduces to 10% for the largest lifetime values. There is also a weak dependence on the Higgs mass, as the proportion is reduced for small masses. Results for "DD" and “TT” vertices are quite different from the previous. Their contribution is negligible for small lifetime and it increases when lifetime gets larger, being both around 30 % of the total vertex proportion as maximum. For "DD" vertices, the proportion has a maximum for lifetimes between 100 and 500 ps. After this limit, it decreases as the mean flight distance of the Higgs gets larger than the UT position. For “TT” vertices, the maximum is reached for the largest lifetime.

These result are quantitatively informative to understand how the LHCb trigger performance can behave to identify LLPs in this region. “DD” and “TT” contribution can only be negligible for very low lifetimes. In this region, there is no significant impact on HLT1 efficiency. However, the reduction of “LL” vertices and the increase of “DD” and “TT”, which are not used at present in HLT1, makes us expect a significant reduction of HLT1 efficiency and therefore LHCb trigger efficiency for LLPs.

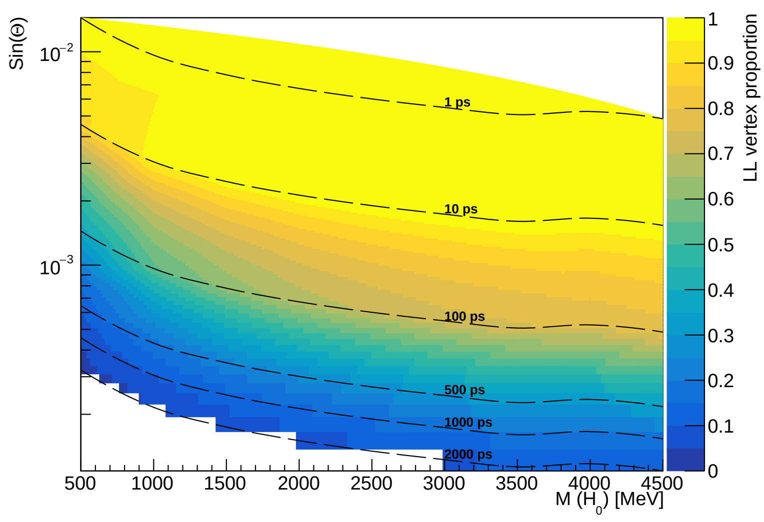

Figure 10: Proportions of “LL” displaced vertex for the scalar Higgs at “true” level of generation

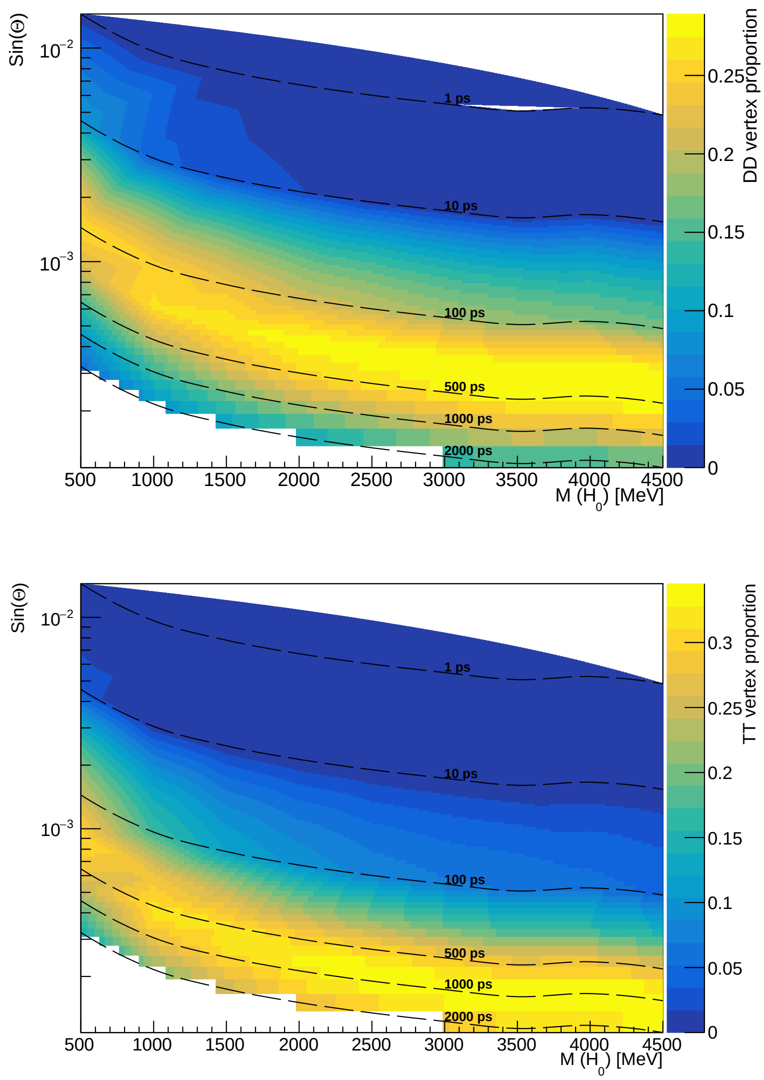

Figure 11: Proportions of “DD” (top) and “TT” (bottom) displaced vertex types for the scalar Higgs at “true” level of generation

4.3 Number of displaced vertex types at reconstructible level

The next step in the study consists of reproducing the previous analysis for MC samples where the interaction with the LHCb detector is simulated. This can give a more realistic estimation of the vertices proportions as the z coordinate of the Higgs decay point is not the only variable involved. The LHCb angle acceptance and interaction with different subdetectors are now considered. The tracking system and identification algorithm are used when tracks are identified from signals in the detector, as explained in Section 2.2. However, the LHCb trigger is not applied at this level. Candidates (particles) that satisfy different conditions are proposed to be reconstructed as tracks of type Long, Downstream, T... but reconstruction is not performed yet. This enables to identify potential displaced vertices and classify them of type “LL”, “DD” and “TT” at “reconstructible” level. Figures 12 and 13 show the results in the same region studied previously and for MC samples of 1000 events each. Displaced vertex proportions slightly decrease on average due to tracking efficiency[7]. The general behaviour of "LL" and "DD" vertex proportions is the same as described in the previous section. However, results for "TT" vertices present a problem. A reduction was expected, but there is no explanation for losing all vertices at "reconstructible" level. An official discussion about these

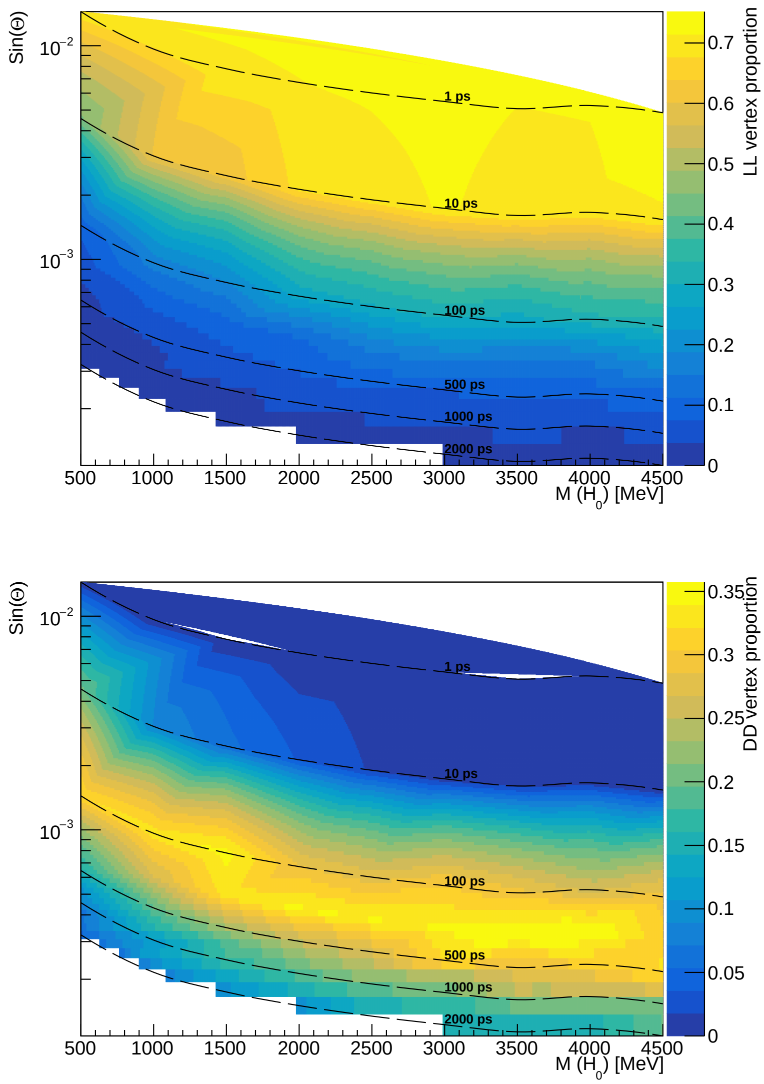

Figure 12: Proportions of "LL" (top) and "DD" (bottom) displaced vertex types for the scalar Higgs at "reconstructible" level.

results for "TT" vertices is done in Appendix B. We conclude that the reconstruction code presents a problem when identifying T tracks at "reconstructible" level. An alternative program was used with the same MC samples for track identification in order to compare its results with the previous ones. They are shown in Figures 14 and 15. New results for "LL" and "DD" vertices are in complete

[7]Some tracks may not leave signal in LHCb components or be outside LHCb acceptance. Therefore, some are not reconstructed.

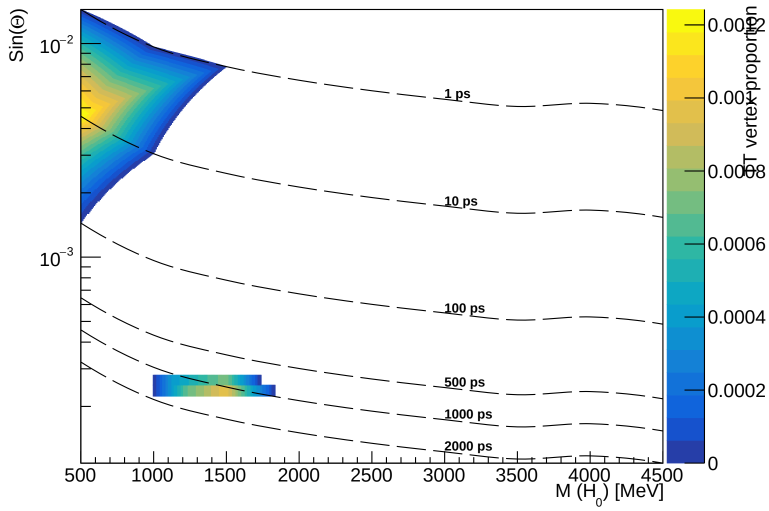

Figure 13: Proportions of “TT” displaced vertex types for the scalar Higgs at “reconstructible” level.

agreement with the previous ones. Nevertheless, “TT” vertex results seem more reasonable using the alternative code, so it will be used in the rest of the study.

After studying the vertex proportions at “reconstructible” level, the conclusion done in the previous section is reaffirmed. The effect of using only Long tracks in HLT1 can be negligible for low lifetime regions but not for the whole parameter space. The importance of Downstream and T tracks is essential to discover signal from a potential LLP. The sum of vertex proportion can get to values around 60% of the total vertex proportion for these MC samples. Therefore, we expect an important effect in HLT1 efficiency when triggering these type of signals.

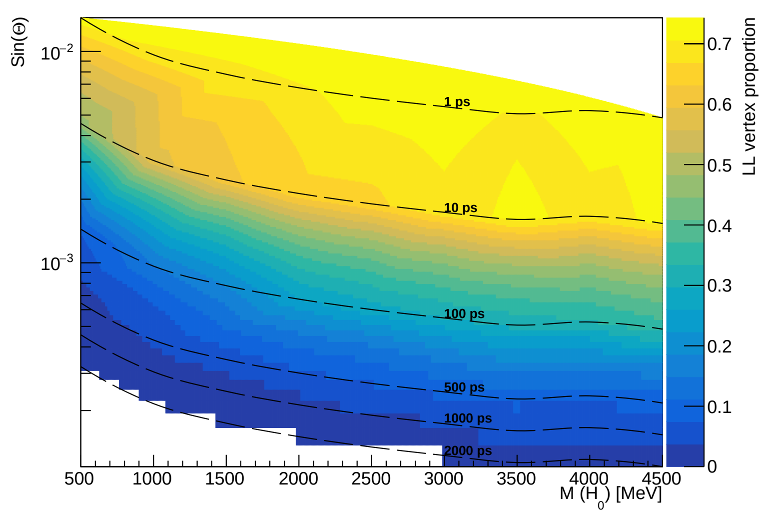

Figure 14: Proportions of “LL” displaced vertex types for the scalar Higgs at “reconstructible” level. Use of the proposed alternative code.

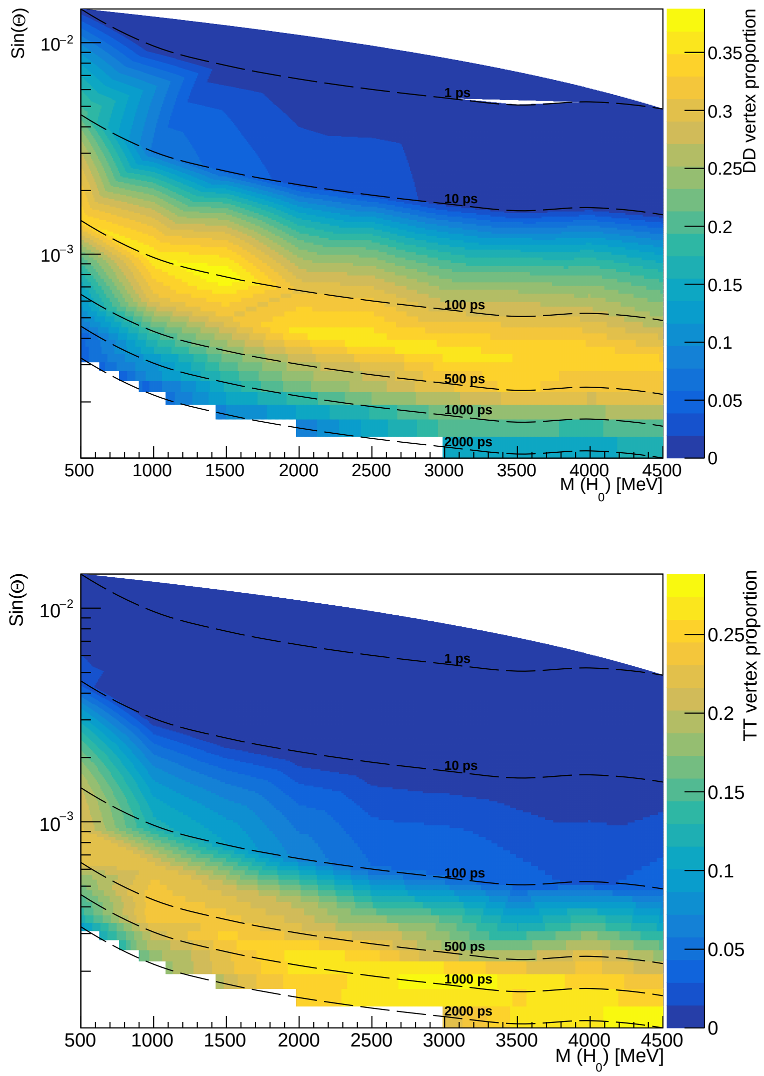

Figure 15: Proportions of "DD" (top) and "TT" (bottom) displaced vertex types for the scalar Higgs at "reconstructible" level. Use of the proposed alternative code.

4.4 HLT1 efficiency on LLPs

Previously, the number of displaced vertex types was computed in a large parameter space of a long-lived dark Higgs decay mode. Although the possible effect of these results in HLT1 performance was discussed, no real estimation of the LHCb trigger efficiency for LLPs was carried out. In this Section, the HLT1 efficiency is directly computed when events from the studied MC samples are reconstructed. The aim is to understand the dependence of the efficiency on the amount of tracks for each value in the parameter space.

Firstly, the total HLT1 efficiency was obtained when reconstructing the generated MC samples.

The three HLT1 contributions (TIS and TOS on K^+ and H_0) explained in Section 2.2 provide these results. Figures 16 and 17 show the total HLT1 efficiency when using *onetrackMVA, twotrackMVA*[8] and all trigger lines in the reconstruction. The efficiency increases when using all lines in the trigger. The maximum value obtained is greater than 60 % (HLT1 reconstruct 60 of 100 events for the Higgs decay channel) for low lifetime regions. The efficiency decreases for higher values of the Higgs lifetime. It gets to values around 20 % as minimum. This shows a relevant decrease of the efficiency related to the amount of Long tracks generated in the Higgs decay.

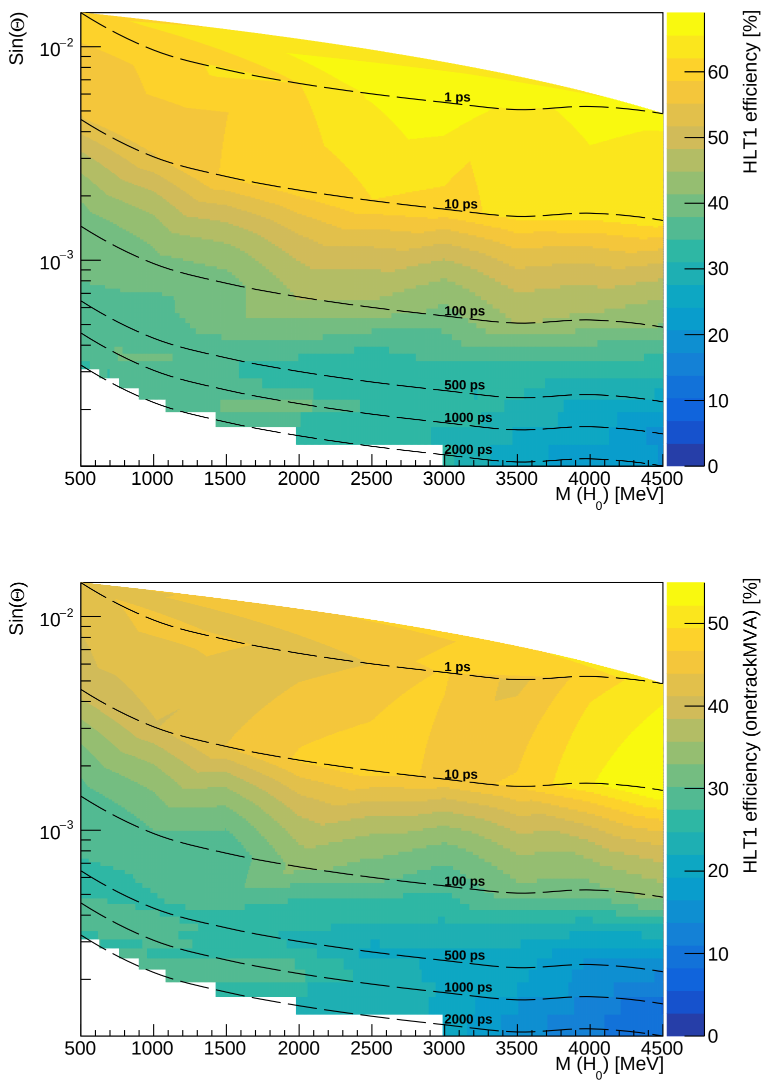

Figure 16: Total HLT1 efficiency in the parameter space for all lines and onetrackMVA.

[8] OnetrackMVA is a line for which the trigger looks for a track that is consistent with being originated from a B meson decay. TwotrackMVA searches for a pair of tracks of the same characteristics.

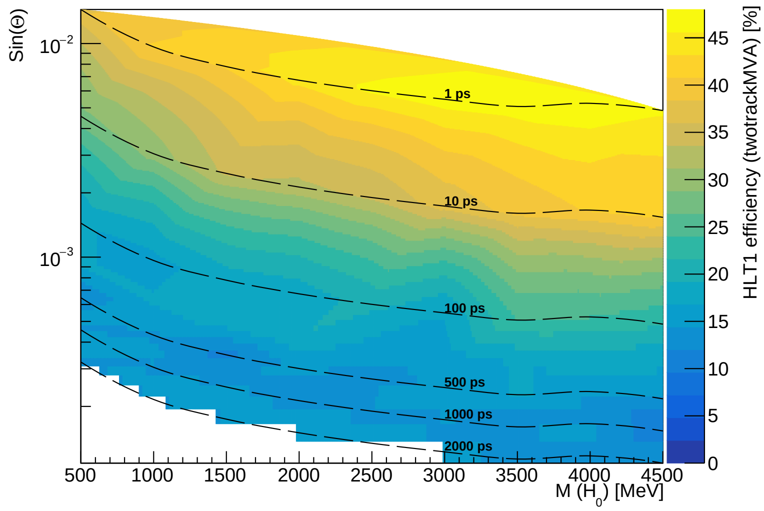

Figure 17: Total HLT1 efficiency in the parameter space for twotrackMVA line.

These results are outstanding for the purpose of this study. They demonstrate that HLT1 efficiency significantly decreases when lifetime values larger than 10 ps are considered. This constitutes a large region of the parameter space simulated for a probable LLP decay. Regardless the evidence of the results, the three contributions of HLT1 are still mixed. It is unknown how much each one contributes and what is the effect of the Higgs lifetime and mass on them. It would be beneficial for the analysis to distinguish the HLT1 efficiency of each contribution separately. This can be done using MooreAnalysis package (see Appendix C for more details).

Figure 18 shows the results of HLT1 efficiency for TIS and TOS on K^+ and H_0 contributions. From TOS on K^+, the contribution to HLT1 efficiency has a strong dependence on the Higgs mass but not on its lifetime (as was anticipated in Section 2.2). The maximum contribution to HLT1 efficiency is around 25% and it happens for low masses of the Higgs. However, this efficiency decreases to almost zero for the largest masses of H_0. The reason of this behaviour is due to the energy that each particle gets when the meson B^+ decays. The Higgs gets more energetic from the decay when its mass is larger. Therefore, kaons are less likely to trigger the decision when their energy is low. TOS on H_0 contribution is the main contribution to HLT1 efficiency. Its dependence on Higgs lifetime and mass is directly related[9] to the amount of track types produced in the Higgs decay. Results from previous sections demonstrate that HLT1 TOS on H_0 is only efficient in those regions where Long tracks (coming from "LL" displaced vertices) are dominant. Finally, TIS contribution to HLT1 efficiency was expected to have a flat shape as the other b quark does not depend on the Higgs properties. However, it can be possible that the event is also reconstructed as TOS. The result shows only those events that can only be reconstructed as TIS, so a dependence on the Higgs properties appears. It can be seen how the efficiency plotted decreases for small lifetimes, where both TOS contributions are more efficient.

[9]There exists other variables that play an important role in the dependence. For instance, if the Higgs is not very energetic, the muons produced in its decay may not be energetic enough to be triggered

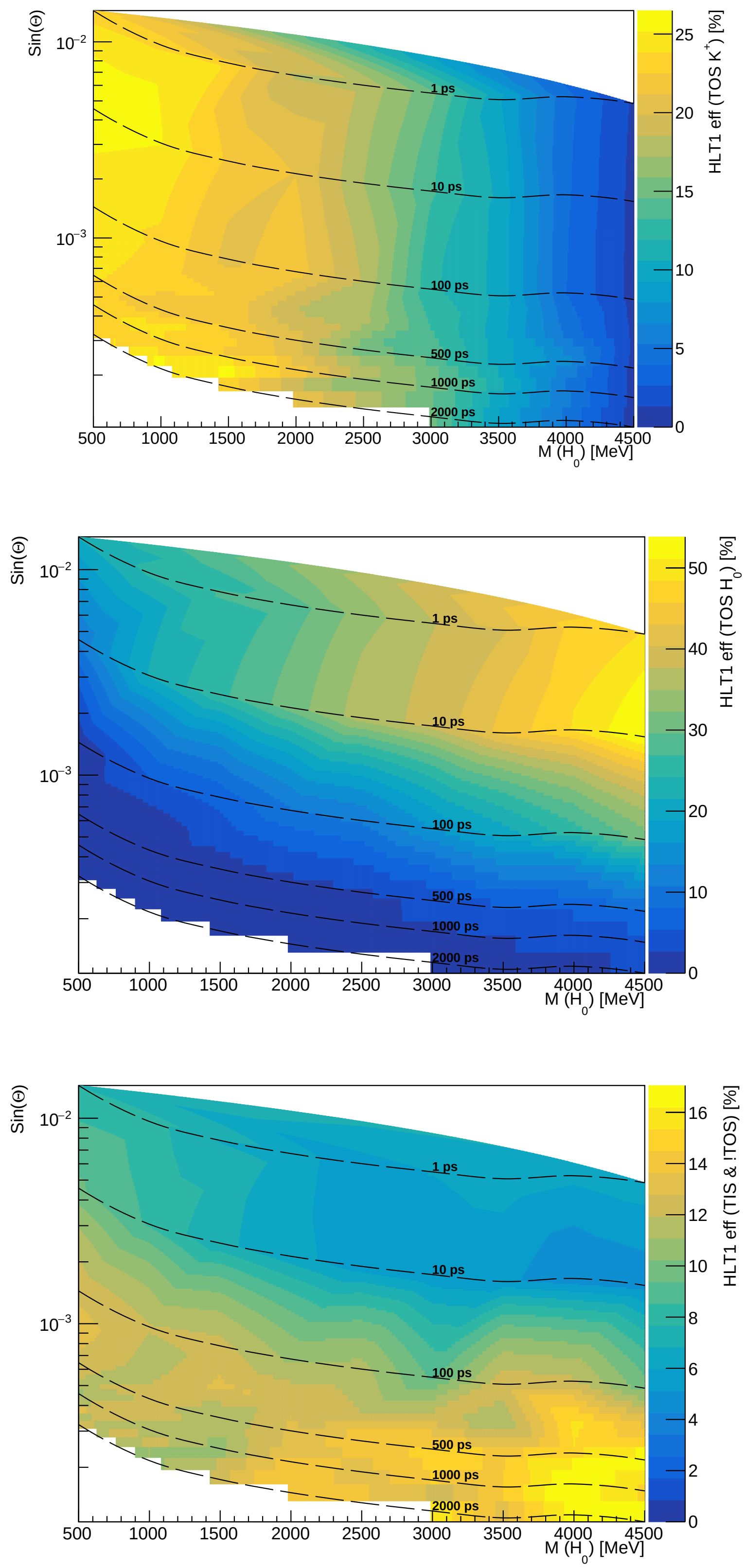

Figure 18: Contributions to HLT1 efficiency in the parameter space using all trigger lines: TOS on K (top), TOS on H_0 (middle), TIS and not TOS (bottom).

5 Conclusion and future work

In this study, a general analysis of the sensitivity to a long-lived Higgs boson in the scope of the LHCb detector has been proposed by making use of the LHCb Simulation Software. Firstly, MC samples of the proposed model were generated for a wide region of lifetime and mass values in order to quantify the number of displaced vertex types at generation level. Secondly, propagation and interaction with the detector was considered in the simulation to estimate more realistic results. These help understanding the projected performance of the first stage of the LHCb trigger system (HLT1) when reconstructing LLPs. The final part of the study has consisted of obtaining the HLT1 efficiency when reconstructing the long-lived Higgs MC samples. This result has been obtained for different lines and for the different contributions of HLT1 depending on the particle that it selects to reconstruct the event. As a result, the study shows that the current HLT1 efficiency could be significantly improved for measurements of LLPs by adding other types of tracks in HLT1.

While these results seem promising at this level, this study can be improved in several aspects and a large amount of work is still needed. For example, these result might be used to perform a sensitivity study of the LHCb detector. As it directly depends on the trigger efficiency, one could investigate the gain in sensitivity by improving the trigger efficiency. This could serve as motivation to design new experiments or push for ealir reconstruction of Downstream and T tracks. Moreover, it would be interesting to study the HLT1 efficiency for the long-lived Higgs using other different lines or even developing a own line for this purpose. Such an extension has already started, using a line designed to trigger on K^0_S mesons that decay to long tracks. This method has successfully shown small improvements to the HLT1 efficiency. As final objective, adding Downstream in HLT1 selection could hugely improve its efficiency and be a relevant step in for BSM research involving LLPs at LHCb.

6 Acknowledgements

This report has been written as result of my participation in the 2021 Online Summer Student Program at CERN. I would like to thank the Summer Student team, professors and organizers that have made possible participate in all lectures, seminars and meetings. The experience gained has been incredible.

Among everyone involved, I could not be more lucky of having been tutored by Louis and Arantza. They have motivated me since the first moment, until the point of doing a work that I never thought I could do at this moment. I really thank them for all the opportunities given.

Appendices

A Physic variables of MC samples

In this appendix, some variables of the particles generated in p-p collision simulations are shown at the generation level. The aim is to validate that MC samples were generated as it was wished. The decay channel used was: $B^+ \to K^+ H_0[\mu^+\mu^-]$. Figure 19 shows how the B^+ decay length is short for all samples. It was expected, due to its small lifetime, $(1.641 \pm 0.008) \times 10^{-12}$ s [7].

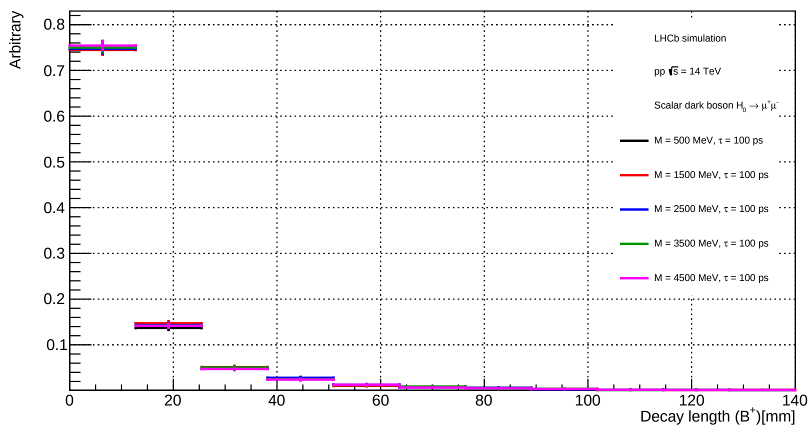

Figure 19: Normalized histogram representing the B^+ decay length from MC samples

However, Figure 20 shows the Higgs decay length for some MC samples. For small masses, where the Higgs velocity is high, it flights a larger distances than when the Higgs is heavy. This results is in agreement with the hypothesis.

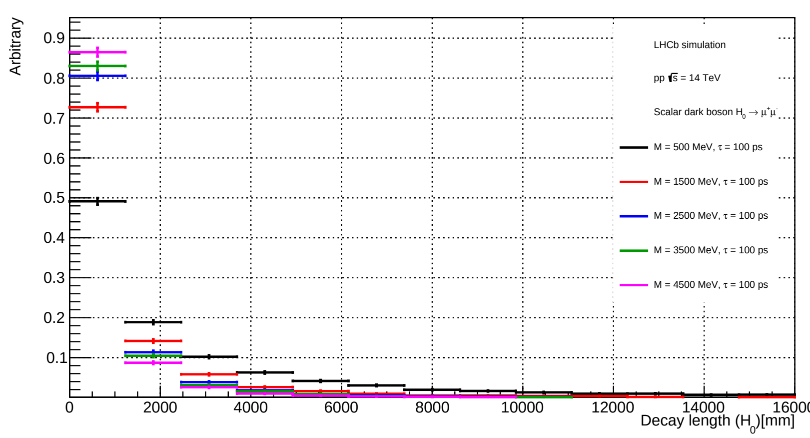

Figure 20: Normalized histogram representing the H_0 decay length from MC samples

Figures 21 and 22 respectively show the transverse momentum of K^+ and the total momentum of the Higgs.

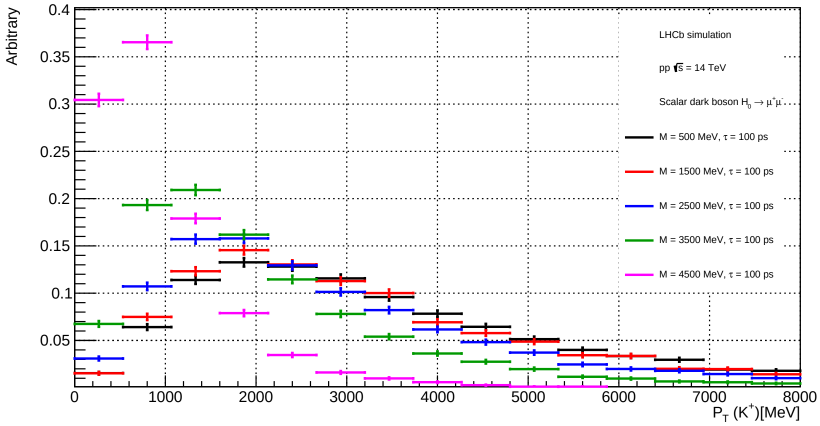

Figure 21: Normalized histogram representing the K^+ transverse momentum from MC samples

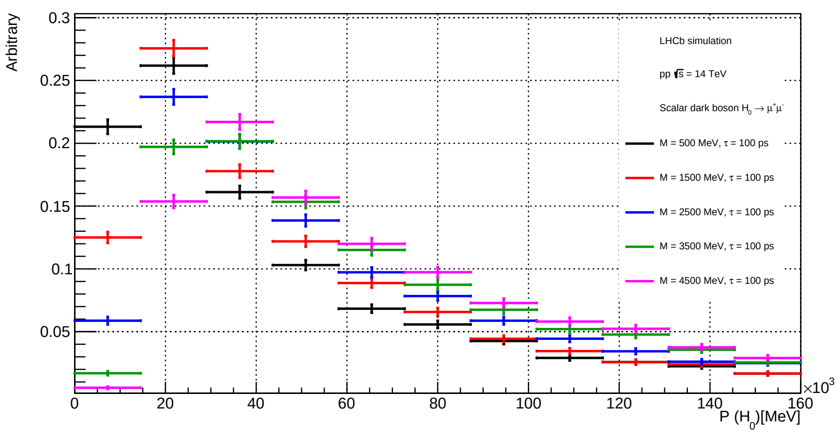

Figure 22: Normalized histogram representing the H_0 total momentum from MC samples

Finally, Figure 23 shows the angle between the muons produced in the Higgs decay. It is seen how the lighter the Higgs is, the smaller the angle becomes as the boost is higher.

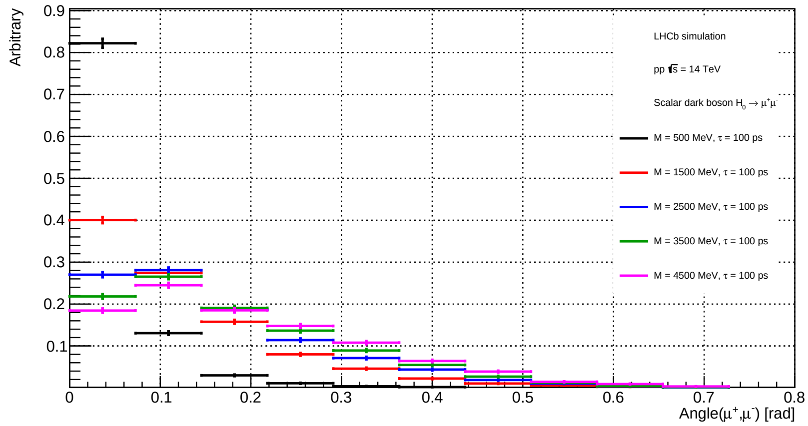

Figure 23: Normalized histogram representing the angle between the muons generated in the Higgs decay.

B Analysis of T track results

Results obtained at "reconstructible" level in Section 4.3 show that the program is not working properly to detect T tracks. Therefore, all are lost from data and the proportion of displaced vertices of type TT dramatically decreases to zero. A study of the possible causes for this problem and intermediate variables has been done. A first step is to inspect how the code classifies potential "TT" vertices (generated by tracks whose origin point is between UT and SciFi, Figure 3). Figure 24 shows the total number of potential "TT" vertices for all MC samples generated. Almost all of them are classified at "reconstructible" level as "outside acceptance" (0 value), meaning that they get out of the detector. However, a small proportion is classified as "DD" vertices (value 3). This is clearly a sign of bug for the code as tracks that are originated further some sub-detectors cannot be reconstructed as if they were originated before.

The fact that almost all potential "TT" vertices are outside acceptance does not seem very reliable. Then, a study of the X-Y track position of both muons that form these displaced vertices is done in the first and last SciFi layer. Figure 25 shows these results. They confirm that the large majority of muon tracks are crossing SciFi inside LHCb angle acceptance in both layers. The hit efficiency is very high in these trackers, as explained in Section 2.1. Therefore, there is no expectation why all T tracks are lost from data as they should leave signals in SciFi. The most probable explanation for this problem is that there exist a problem in LCHb code at this specific point.

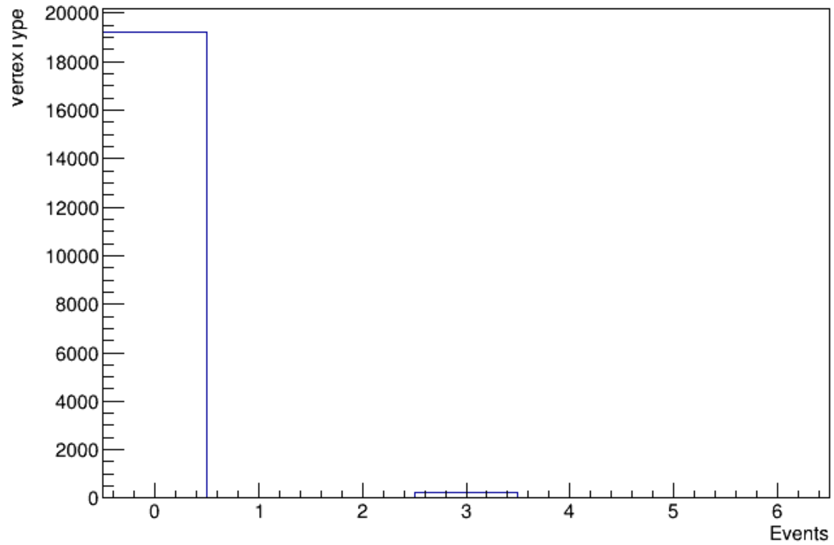

Figure 24: Classification of potential "TT" tracks (generated between UT and SciFI). The code classifies them depending on the angle acceptance and hits that tracks leave in the detector

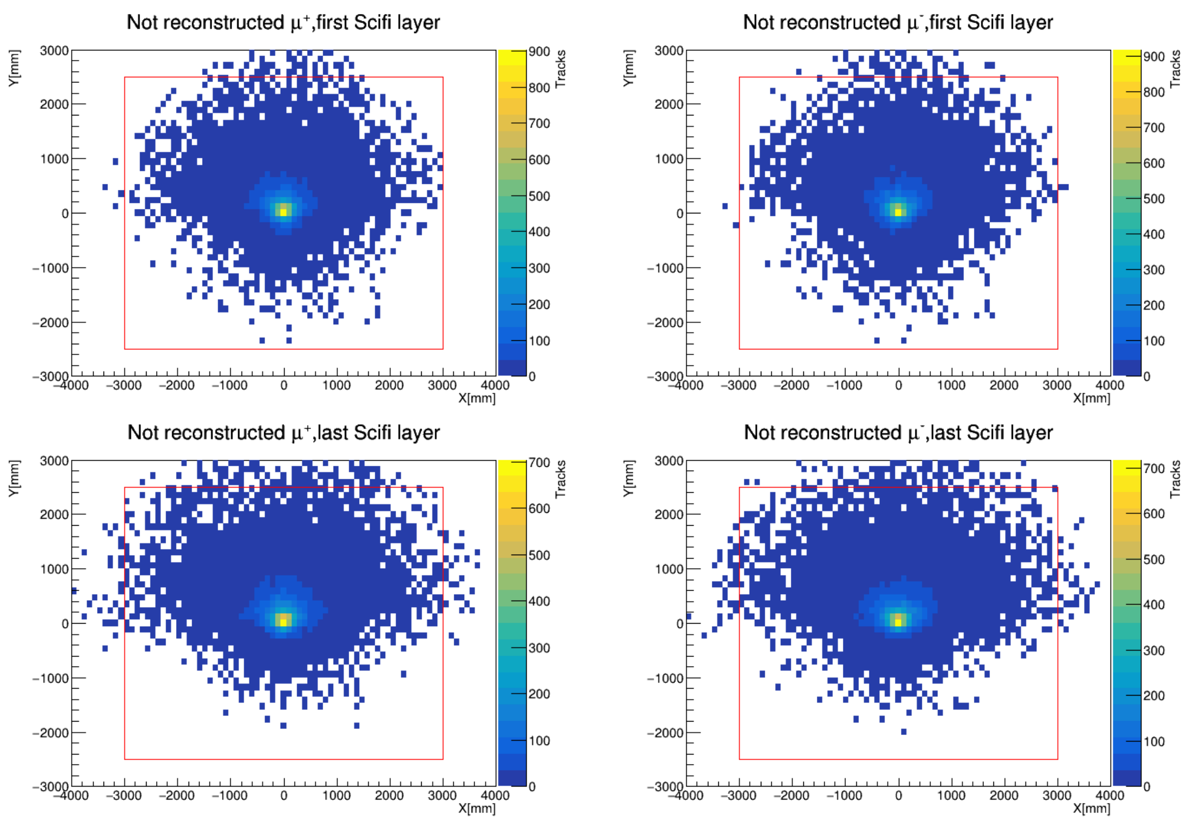

Figure 25: Track position at first and last SciFi layer for both muons that give displaced vertices originated bewteen UT and SciFI and are classified as "outside acceptance" by the code.

C Details about the simulations

All simulations performed in this study have been done making use of the official LHCb Simulation Software. The different programs used are:

- Gauss. It is the LHCb simulation framework for creation of simulated events. It interfaces other external applications as Pythia, EvtGen or Geant4 for different purposes. The Dec-File Package provides the decay files for the generation of different particles. For the case of the Higgs, a manual modification of such files to generate values of lifetime and mass not available was done. Version: v55r0 Generator phase: PYTHIA 8, pp collision at 14 TeV, $\nu = 7.6 andEvtGenforb-decays.Geant4forparticleinteractionwiththedetector.Magnetconfiguration : down$

- Moore. It is the application for the LHCb high level trigger (HLT).
- DaVinci. It is the application to perform physics analysis. It stores information into ROOT files
- MooreAnalysis. Application that allows to use Moore and Analysis in the same time. It is used to measure physics performance and the analysis of the output of such jobs. It has been used for the last part of the study.

Events are generated following the previous method for next parameters:

- Lifetime values (ps): [1,10,100,250,500,750,1000,1250,1500,1750,2000]
- Mass values (MeV/c^2): [500,1000,1500,2000,2500,3000,3500,4000,4500]

A total of 11 x 9 = 99 samples are obtained for the study in the mass and lifetime region. To generate the continuous plots, a TGraph is filled with the desired information (i.e. LL vertex proportion). From the Tgraph, 2D Delunay interpolation to create a 2D histogram of desired binning

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