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Reconstruction techniques and physics case for displaced tracks and vertices at LHC

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The primary focus of the LHC experiments was the observation of Standard Model particles and the search for unexplored signatures indicative of New Physics. Given the current discoveries and measurements done so far, the detectors and the trigger architecture are being changed to allow for the searches of long-lived particles. LHCb's trackers have excelled in the precise reconstruction of heavy flavour hadrons, and the experiment is now at the forefront of designing flexible trigger systems. Similarly, ATLAS and CMS, with their precise trackers, are also exploring new avenues by implementing innovative triggers to search for long-lived particles. The techniques of the reconstruction of displaced tracks and vertices in the upgraded LHCb detector, complementary with other general-purpose detectors at the LHC, are presented in this proceedings.

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1. Long-Lived Particles - a sign of New Physics?

The discovery of kaon in 1947 [1] can be considered a major step in the formulation of modern sub-atomic physics. Its time of life, longer than any of the known states at that era, introduced *strangeness* and led to the construction of the Quark Model and, eventually, the Standard Model (SM). Over the subsequent decades, the primary efforts of physicists, dedicated to the confirmation of SM predictions, were punctuated by unexpected discoveries of phenomena that instilled hopes for the discovery of New Physics effects. Measuring particle lifetimes nevertheless remained critical, in particular for b-tagging purposes, and later for several important searches initially carried out at LEP and continued further at hadron machines.

Precision tests of the SM required large particle accelerators, achieving higher center-of-mass energies and luminosities and tracking systems with excellent momentum resolution. The LHCb experiment, with the spectrometer-like acceptance, reported observation of the vast amount of SM heavy hadrons along with precise measurement of their lifetime (see Fig.1a) which is crucial to show the combined charge-parity violation. The primary program of general-purpose LHC experiments like ATLAS and CMS for the searches of long-lived particles (LLPs) included signals of supersymmetry and other processes that manifested their presence in a rather hard interaction. However nowadays, following the models proposed from theory, searches of bound states with low masses and long lifetimes are more promising [2].

Since theorists cannot predict the lifetime of particles, how can experimentalists design a proper setup to measure them? The only reasonable solution is to design a flexible system that would precisely reconstruct displaced tracks and vertices, whose possible patterns are depicted in Fig.1b. The design should filter out the SM background at the same time. Since the start of the LHC, the ATLAS, CMS and LHCb collaborations have risen to this challenge and have produced an impressive set of new analyses aiming at the LLP discovery, often relying on highly innovative strategies.

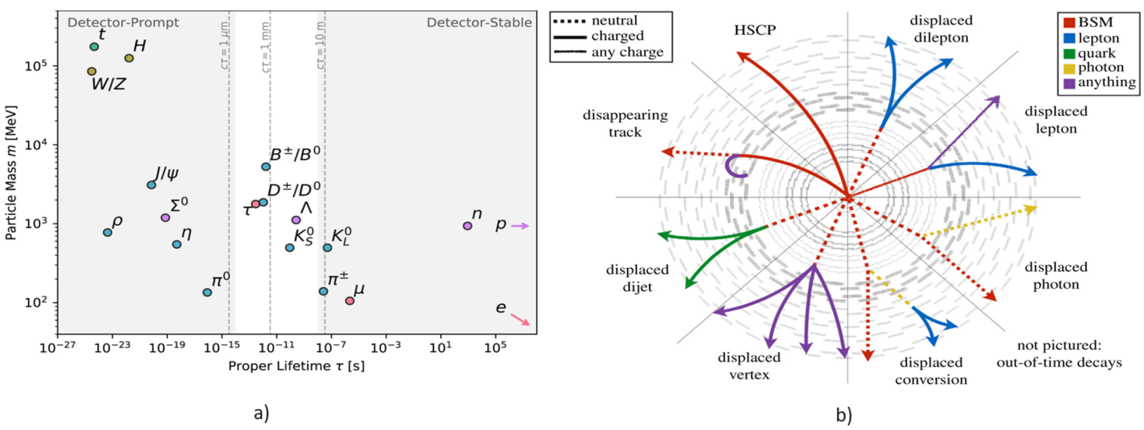

Figure 1: a) Standard Model particles mean lifetime τ. The white band indicates particles whose decay vertex is reconstructed in the LHCb spectrometer. b) Collection of displaced tracks and vertices as signatures of physics Beyond the Standard Model (BSM) [2].

2. LHCB Upgrade 1

The LHCb detector at the LHC is a general-purpose detector in the forward region with a focus on studying decays of c- and b-hadrons [3]. The spectrometer covers the pseudorapidity region $2 < \eta < 5$ and during LHC Run 1 and 2 (2011-2012 and 2015-2018) allowed for the reconstruction of particles' momentum with resolution 0.5-1% in the range from 2 to 200 GeV/c. Excellent time resolution, 50 ps, along with the efficient hadron identification system enabled the attainment of the most significant results in heavy-flavor physics [4]. The schematic view of the LHCb experiment is shown in Fig. 2 (left).

The tracking system of LHCb spectrometer consists of three subdetectors: pixel Vertex Locator (VELO), silicon strip Upstream Tracker (UT)[1] and three stations of scintillating fibres (SciFi) which are placed almost 8 m from the proton-proton interaction point (IP) see Fig.2 [5]. Due to this geometry, traversing particles may not be reconstructed in every tracking station. So-called *long tracks* pass through all tracking stations: VELO, UT, and SciFi and since they traverse the full magnetic field, they have the most precise estimation of momentum and provide the majority of heavy flavour results. The SM long-lived particles, like K^0_S and Λ, may decay outside VELO, thus their decay products leave tracks called *downstream tracks*. Tracks reconstructed in SciFi are called *T tracks*. Three types of tracks reconstructed in the LHCb are schematically shown in Fig.2 (right).

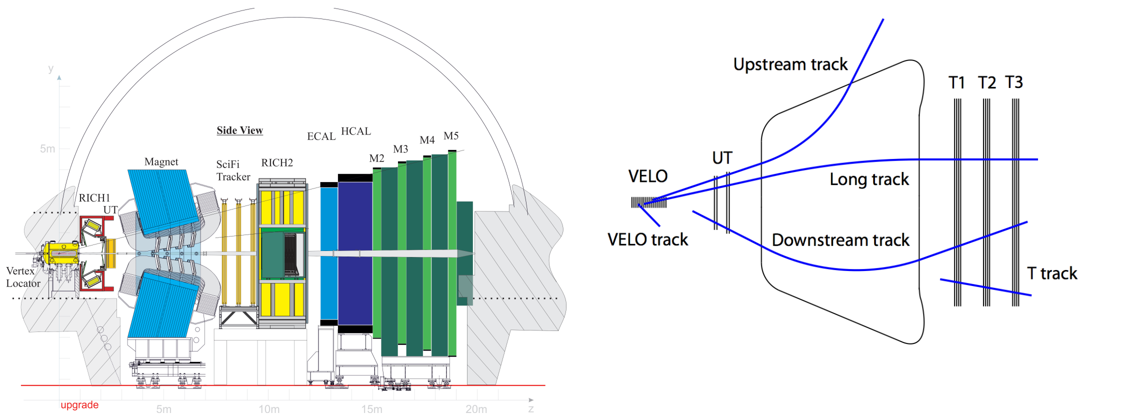

Figure 2: Schematic view of the LHCb spectrometer (left) [5]. Types of tracks reconstructed in the detector (right).

During the current Run 3 LHC data-taking period, LHCb will take data at an instantaneous luminosity of $2{\times}10^{33}$ cm^{-2}s^{-1}, five times higher than in Run 2 [6]. From 2022 the LHCb experiment uses a triggerless readout system that collects data at an event rate of 30 MHz and a data rate of 4 TB/s, see Fig. 3.

The software trigger at LHCb is composed of two stages: in the first stage the selection is based on a fast and simplified event reconstruction, while in the second stage a full event reconstruction is used. This gives room to perform a real-time alignment and calibration after the first trigger stage, allowing an offline-quality detector alignment in the second stage of the trigger.

[1]The UT commissioning took place at the end of 2023 data taking, therefore, it has not been used for reconstruction so far

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The detector alignment is an essential ingredient to have the best detector performance in the full event reconstruction. The alignment of the whole tracking system of LHCb is evaluated in real-time by an automatic iterative procedure. This is particularly important for the vertex detector, which is retracted for LHC beam injection and centered around the primary vertex position with stable beam conditions in each fill. Hence it is sensitive to position changes on a fill-by-fill basis. LHCb's second

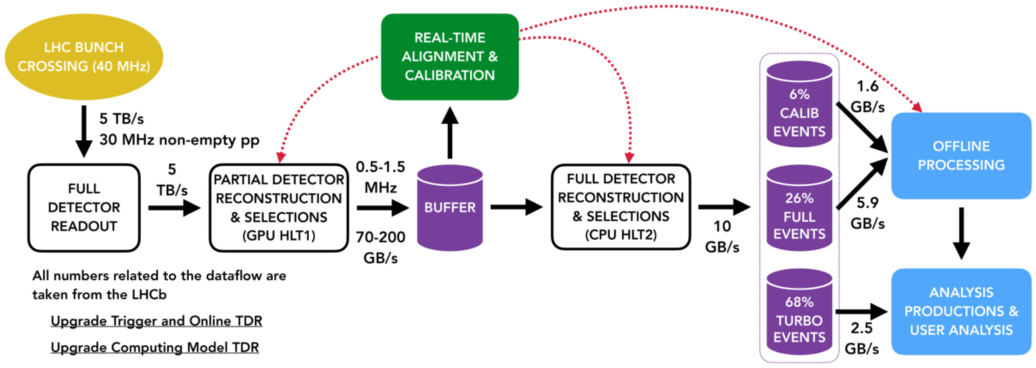

Figure 3: Online data processing chain of the LHCb Upgrade I. A software-only High-Level Trigger (HLT) reduces the LHC rate to 10 GB/s that are stored on a disk. The first stage (HLT1) performs partial reconstruction with simple criteria, reduces the event rate to 1 MHz, and sends data to a buffer. After calibration and alignment, full event reconstruction is performed [7].

level trigger, deployed on a CPU server farm, not only selects events but performs an offline-quality alignment and calibration of the detector and uses this information to allow physics analysts to deploy essentially their full offline analysis level selections (including computing isolation, flavour tagging, etc) at the trigger level. This "real-time analysis" concept has also allowed LHCb to fully unify its online and offline algorithms and selections.

The system was successfully tested during Run 2 and in May 2022 the first selection in real-time at LHC was performed. Due to the timing requirements, in the current trigger implementation, long tracks are currently considered only, with secondary vertices reconstructed inside VELO. The first results obtained by the LHCb experiment in this new trigger system are presented in Fig. 4.

3. Displaced Tracks and Vertices in the Upgraded LHCb experiment

During Run 1 and 2 displaced vertices of K_s^0 and Λ decays were reconstructed in the silicon Trigger Tracker which was replaced by the UT in Run 3. However, the UT, which is the major detector for downstream tracking, has not been fully operating so far, and the idea arose that SciFi hits can be used for searches of particles with longer lifetimes. SciFi hits were initially used in HLT1 for the reconstruction of tracks that passed through both VELO and UT and in HLT2 for full reconstruction as a stand-alone pattern recognition algorithm, called *Hybrid Seeding*. This allowed for fast and efficient reconstruction of charged particles, with the perspective for the usage of long-lived ones as well.

The *SciFi Seeding* algorithm is an adaptation of the *Hybrid Seeding* algorithm, designed as a fast program to be used at the first stage of data processing (HLT1) with access to downstream and T tracks. This is an iterative reconstruction procedure that uses information from the three

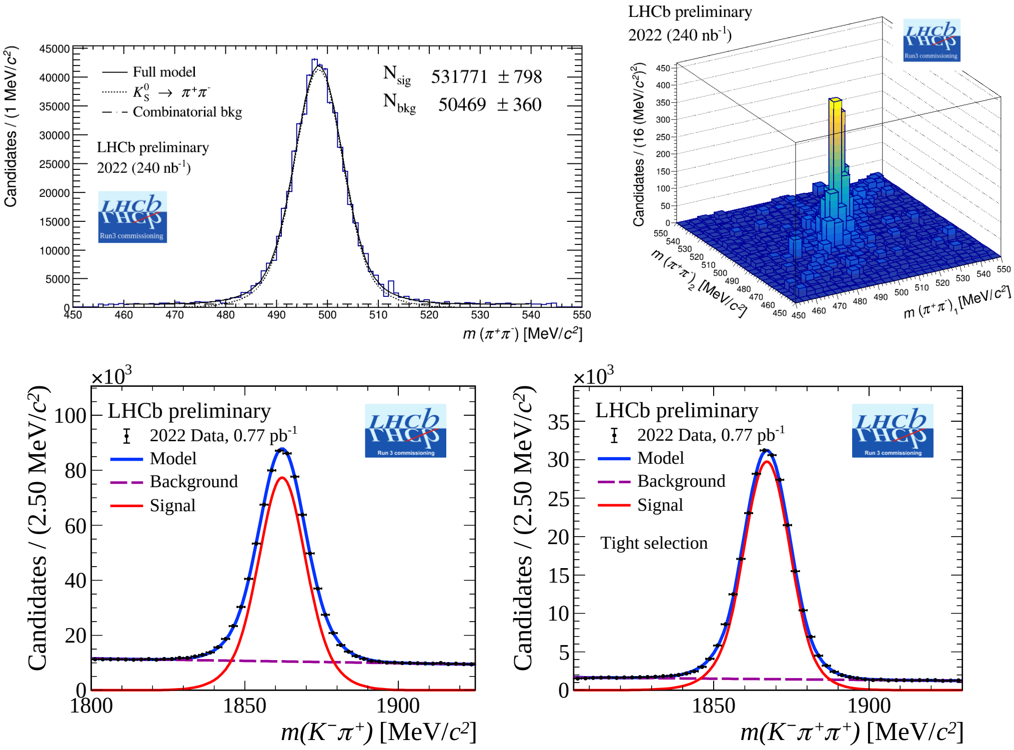

Figure 4: First hadrons reconstructed with a full software trigger of the LHCb experiment: $K_s^0 \to \pi^+\pi^-$ and K_s^0 pairs candidates (top), [9]. D^+ in decay $K^-\pi^-\pi^+$ (bottom) [8].

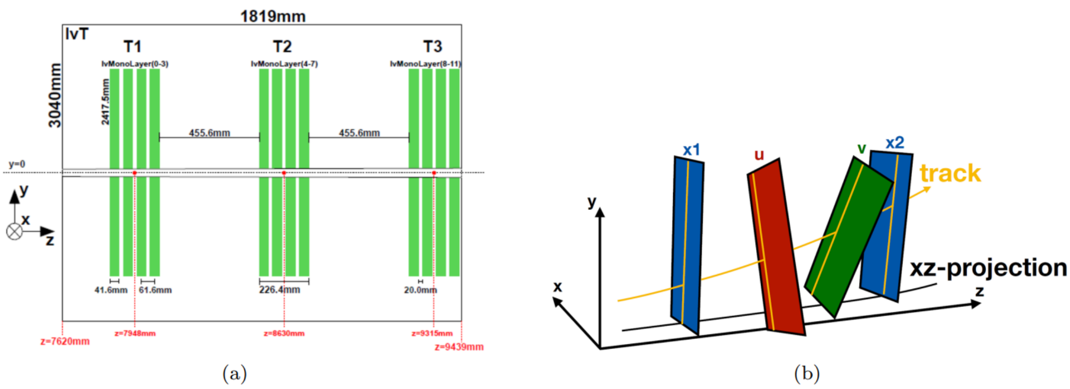

Figure 5: Schematic of (a) The SciFi detector layout (b) Position of SciFi layers in each station with a track traversing a station in xyz coordinates [11].

stations of the scintillating fiber tracker. Each station is composed of four layers, the outer ones, x_1, x_2, and u, v - the inner layers, tilted by 5° with respect to the outer ones, see Fig.5. In the first stage, the algorithm takes xz hits as seed candidates. Then the hits from uv layers are added. The final output of the algorithm is a 3-dimensional track segment that in the next step can be combined with information from other detectors [10]. In the procedure called *VELO-SciFi Matching*, the seeds reconstructed by the *SciFi* are matched with VELO tracks to form a long track. Finally, a

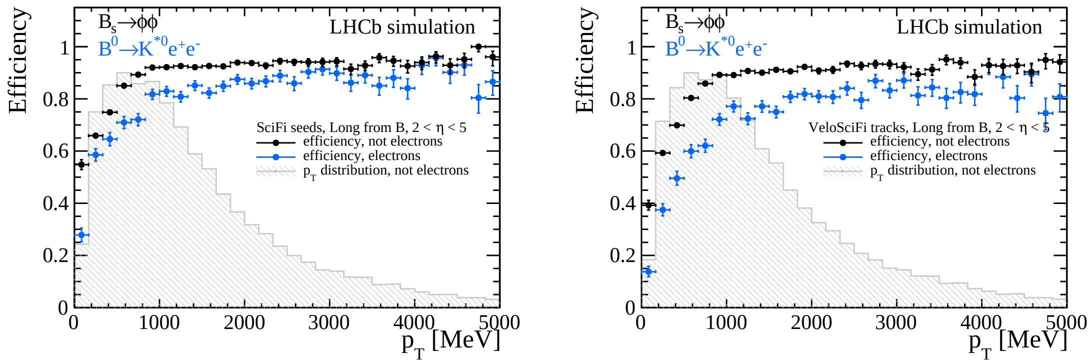

Figure 6: Tracking efficiencies for HLT1 electron (blue) and non-electron (black) SciFi seeds (left) and VeloSciFi tracks formed after matching SciFi tracks segments with VELO hits. (right) from B decays as a function of transverse momentum p_T [12].

clone removal procedure is applied which checks on tracks with shared hits. In another available algorithm, T tracks can be also extrapolated to UT to make downstream tracks. This task currently tested in simulation, is postponed till real data from UT are available.

The performance of *SciFi Seeding* and *VELO-SciFi* Matching fully fits HLT1 requirements. Both are within the timing limit and allow for GPU implementation. Efficiency on long tracks from B meson decays is above 80% and for electrons from B decays is around 70% with a ghost rate below 9% for all reconstructed tracks. These efficiencies, as a function of transverse momentum p_T are depicted in Fig. 6 [12]. Currently, at the beginning of Run 3, *SciFi Seeding* is implemented in HLT1 and is the basic block for downstream tracking.

4. Summary

Even though LHC delivers an unprecedented amount of data, there is still no significant observation of effects originating from Physics Beyond the Standard Model. New physics models including long-lived particles provide an interesting perspective for the searches on new states. LLPs have characteristic experimental signatures that leave them undetected unless special methods for trigger and data-acquisition systems are implemented. The LHCb experiment began the era of full software trigger and showed heavy hardons reconstructed online with offline quality. Other LHC experiments made a huge effort to upgrade the tracking system mainly to extend the physics program for LLPs searches. In general, reconstruction of LLPs at the LHC is now feasible due to the progress in reconstruction algorithms.

Acknowledgments

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