PROCEEDINGS OF SCIENCE

Searches for long-lived particles with LHCb

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Many theories with physics beyond the Standard Model involve particles with a detectable decay length from the interaction point. This contribution summarises the LHCb approach to long-lived particle searches, with some highlights on specific studies performed with Run I data.

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1. Introduction

The LHCb experiment [1] is designed to detect long-lived hadrons, such as those containing b and c quarks. It is therefore naturally suited to search for Beyond the Standard Model Long-Lived Particles (LLP) in a similar range of mass and lifetime. LHCb is able to explore areas of the parameters space only partially covered by the other LHC experiments, due to the unique acceptance of $2 < \eta < 5$ and the loose requirements at the hardware level trigger, which allow the exploration of relatively small LLP masses. Such searches also take advantage of the low pile-up, the excellent mass resolution (0.5-2% in mass resolution for dimuons) and precise decay time resolution.
The tracking system and trigger play a crucial role in long-lived particle searches. The tracking system consists of the VErtex LOcator (VELO), which surrounds the proton-proton interaction point and is dedicated to the reconstruction of primary and secondary vertices, the Tracker Turicensis (TT) before the magnet and three tracking stations (T1, T2, T3) after the magnet. Among the tracks reconstructed in LHCb (Figure 1), long-lived particle searches up to this moment employed only long tracks which combine the information of all the tracking subdetectors and have excellent spatial resolution close to the primary vertex and excellent momentum resolution both in magnitude and direction. The online event selection proceeds through three trigger stages: the L0 trigger at the hardware level, the High Level Trigger 1 (HLT1) and High Level Trigger 2 (HLT2) at the software level which perform the full event reconstruction. As previously mentioned, the requirements at the L0 are quite loose, typically the muon transverse momentum must be greater than 1.5 GeV and the energy deposit in the calorimeter greater than 2.5 GeV for electrons. Topological triggers on detached vertices are available at the HLT level. Since the beginning of Run II, particle identification and jet reconstruction are performed at the trigger level. Future analyses using Run II data will also benefit from dedicated single and dijet trigger lines, which have been implemented with very loose p_{T} requirements. These dedicated lines additionally have the advantage that the jet is not required to point to any primary vertex.

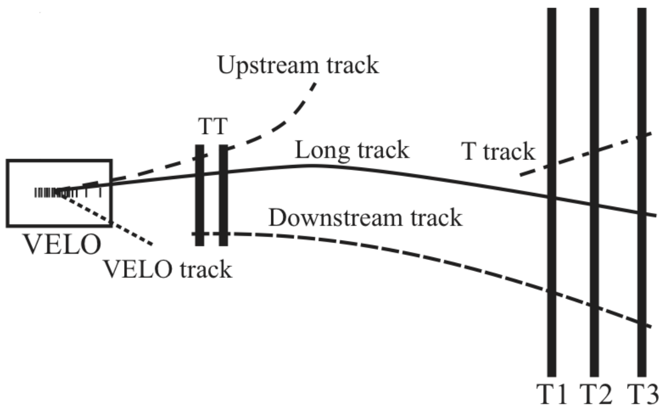

Figure 1: Tracks reconstructed in the LHCb detector [1].

The long-lived particle searches performed at LHCb so far can be classified in two groups: searches for LLP produced in the decay of B mesons or produced promptly in proton-proton collisions. The first type of searches is characterised by a displaced dilepton signature and low backgrounds, strongly reduced by requiring the mass of the decay particles to the B meson mass and by applying additional constraints on the vertices when possible. Typical signatures for the second family of searches are displaced jets and leptons. In this case there are two main backgrounds, depending on the distance from the beam axis: heavy flavour decays and material interactions. Heavy flavour decays are the dominant background before the VELO RF foil [2], a corrugated aluminum shield which is placed at ~ 5 mm from the beam axis and encloses the two VELO halves, in order to keep the vacuum of the machine and the one of the VELO separated. After the RF foil, the background is mainly due to the interaction with the material of the foil. While the first background is irreducible, the latter can be suppressed by having a detailed map describing the material distribution in the VELO.

The analyses performed using Run I data, including those described in this document, apply a material veto based on the geometrical description of the detector elements. Recently, an alternative method has been developed, which is based on special runs where LHCb acquired data as a fixed gaseous (helium) target experiment [3]. Such study of the VELO material location has been performed for both Run I and Run II, to account for changes in the alignment of the detector. The beam-helium collisions produce hadrons along the full length of the VELO: their interaction with the material produces secondary hadrons which are detected and used to map the material. Combining the information of the map with other properties of the reconstructed displaced vertex, a p-value can be assigned to the hypothesis that the vertex is due to a material interaction. This method has already been employed in [4] and will be used for upcoming analyses in Run II.

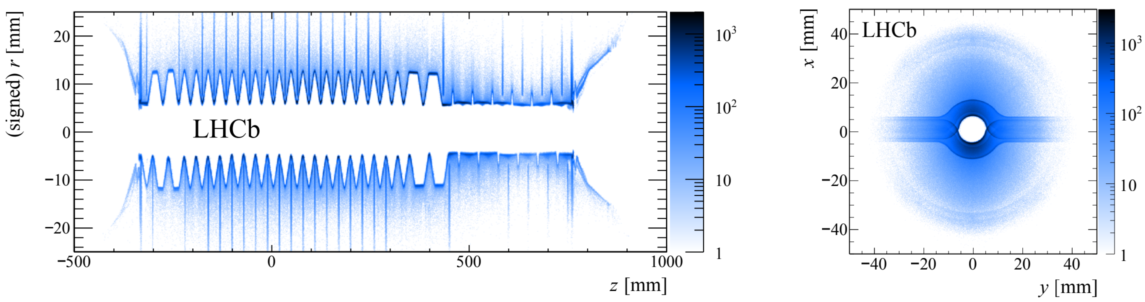

Figure 2: Reconstructed secondary vertices, showing (left) the corrugation of the RF foil and (right) the sensor modules [3].

Searches performed with Run I data collected by LHCb are presented for each of the two production modes in the following.

2. Long-lived particles from B decays

A search for a hidden sector boson χ is performed in decays mediated by a $b \to s$ transition, with a top loop at leading order. The sensitivity to χ arises from the coupling of the top to the hidden sector boson through a portal, for example a mixing with the Higgs sector. Two different decay modes have been studied:

- $B^0 \to K^{*0}\chi$ [5], with $K^{*0} \to K^+\pi^-$ and $\chi \to \mu\mu$,
- $B^+ \to K^+\chi$ [6], with $\chi \to \mu\mu$.

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Both searches cover a similar mass range, with the lower bound given by twice the muon mass and the upper bound by the difference between the B mass and the kaon mass. In the first decay mode, two different regions of dimuon lifetime are defined according to the lifetime resolution, which varies from 0.2 to 1 ps. The lifetime regions have been optimised in the second decay mode, leading to three samples, prompt ($\tau < 1$ ps), intermediate ($1 < \tau < 10$ ps) and very displaced ($\tau > 10$ ps). The B^0 decay search exploits the presence of a second vertex, which leads to a better decay time resolution and lower background. The B^+ decay has higher branching ratio, but also higher background; specifically, the Standard Model decay $B^+ \to K^+\mu\mu$ has the same final state as the signal, affecting the prompt decay time region. Both decay modes adopt similar strategies. The selection consists mainly of topological requirements and the dimuon vertex is allowed, but not required to be displaced. The main backgrounds consist of narrow resonances, which are explicitly vetoed, and combinatorial. The latter is reduced by a Boosted Decision Tree classifier, which in the case of the B^0 search is trained requiring the signal to be uniform in χ mass and lifetime [7]. A scan in the dimuon mass distribution is performed looking for an excess of signal over the expected backgrounds. No evidence of a signal is observed and model independent upper limits are set as a function of the mass for lifetimes between 0.1 and 1000 ps (Figure 3). The lifetime dependence in the long-lived sample is introduced by the detection efficiency, which drops at $\sim$ 100 ps due to the VELO acceptance, leading to a less stringent limit for longer lifetimes. Stringent constraints are also placed on a model with a light inflaton particle and a model with an axion particle, ruling out, in both cases, a large area of the theoretically allowed parameter space.

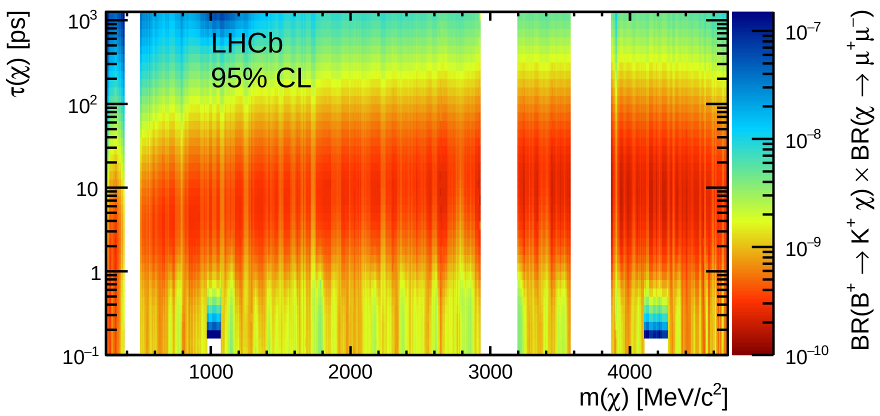

Figure 3: Upper limits on the branching ratio $\mathscr{B}\,(B^+ \to K^+\chi(\mu\mu))$ at 95% C.L. as a function of mass and lifetime [6].

Another long-lived particle from B decays searched at LHCb is an on-shell Majorana neutrino in the lepton number violating decay $B^- \to N\mu^-$, with $N \to \pi^+\mu^-$ [8], which is forbidden in the Standard Model. The analysis covers the mass range from 250 MeV to 5 GeV and extends the lifetime sensitivity with respect to previous LHCb analyses up to 1000 ps. Two samples are defined according to the neutrino lifetime: prompt ($\tau < 1$ ps) and displaced ($\tau > 1$ ps). The requirements of same-sign dileptons and on the B meson mass reduce greatly the background contamination. The main backgrounds in both samples are B meson decays to charmonium and combinatorial, which

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are fitted and compared to the total number of events. In the absence of signal, model independent upper limits are set as a function of the neutrino mass for different lifetimes (Figure 4). Upper limits are also set on the coupling between the muon and a fourth generation neutrino. The limits have been reinterpreted in the context of a different decay model in [9].

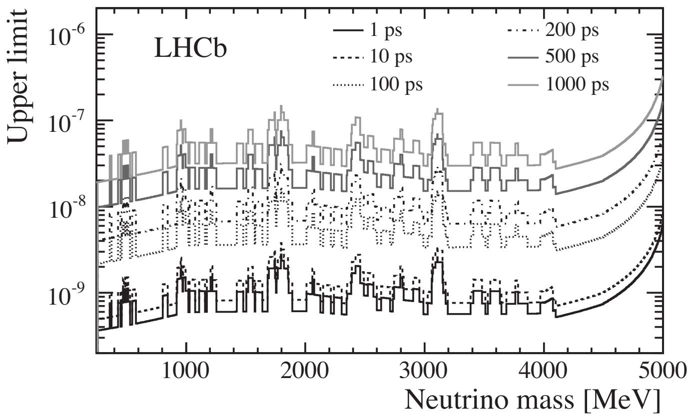

Figure 4: Upper limits on the $\mathscr{B}\,(B^- \to \pi^+\mu^-\mu^-)$ at 95% C.L. as a function of the neutrino mass for different lifetime values [8].

3. Long-lived particles from p-p collisions

LHCb has searched for a hidden sector LLP, denoted as π_v, in the context of hidden valley models [10], assuming that two π_v particles are produced in the decay of a SM Higgs boson. Each of the LLPs decays into a $b\bar{b}$ pair hadronising in two jets. Since in most cases only one of the two π_v is expected to decay within the LHCb acceptance, the signature of the decay is a single displaced vertex with two associated jets. The mass range investigated is from 25 to 50 GeV, where the lower bound is required in order to resolve two hadronic jets. The lifetime range covered extends from 2 ps, limited by the large prompt background at lower values, to 500 ps. In both cases the upper bounds are dictated by the VELO acceptance. The displaced vertex is used to trigger the event at the software level. Vertices within a veto region around the VELO are rejected to reduce the background due to material interactions and requirements are applied on the jet pointing to reduce the $b\bar{b}$ background. Standard Model dijet events, almost back-to-back in the transverse plane, are discarded by constraining the dijet opening angle. The background composition depends on the distance from the beam axis. Therefore, the number of signal candidates is obtained by fitting the dijet invariant mass in six bins of transverse distance. No signal excess has been observed above background, and upper limits are set on the SM Higgs branching ratio to dark pions, as shown in Figure 5.

A search for a massive LLP decaying semileptonically into Standard Model particles [11] has been performed in two different scenarios. It is interpreted in the context of neutralino production in different R-parity violating mSUGRA models, covering the mass range from 23 to 198 GeV, and in terms of four different simplified topologies, less model dependent, spanning the mass range from 25 to 50 GeV and the lifetime range from 5 to 100 ps. The distinctive signature of a single

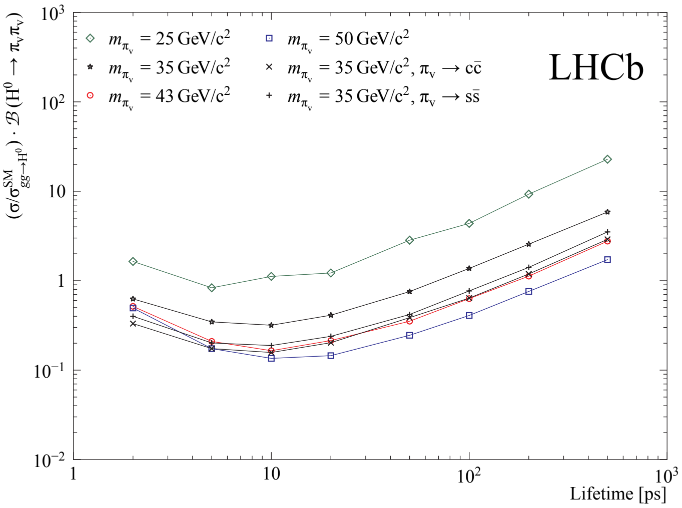

Figure 5: Upper limits set on the SM branching ratio do dark pions at 95% C.L. as a function of lifetime for different masses [10].

displaced high multiplicity vertex with an associated high transverse momentum muon, is exploited by triggering on the muon at the hardware level and the displaced vertex at the software level. After applying the material veto, the background is dominated by $b\bar{b}$, suppressed with a dedicated multivariate classifier. The muon is expected to be harder and more isolated than a muon coming from a heavy quark decay due to the heavy mass of the neutralino. Therefore, a signal region and a control region enhanced in background are defined according to the muon isolation and are fitted simultaneously to extract the number of candidates. No significant excess is observed and upper limits on the production cross section times the branching ratio are set as a function of neutralino mass and lifetime for each of the models previously mentioned. Figure 6 shows the regions of the parameter space excluded at 95% confidence level for different branching ratios in the context of double LLP production from a SM Higgs-like particle simplified topology.

4. Summary

LHCb proves to be a general purpose detector in the forward region. It has a unique coverage compared to the other LHC experiments, being able to explore relatively low long-lived particle masses and lifetimes. Different search strategies have been adopted, exploiting the capabilities and the knowledge of the detector in suppressing the backgrounds. A selection of various studies has been presented here, demonstrating a growing interest for direct searches involving long-lived particles at LHCb.

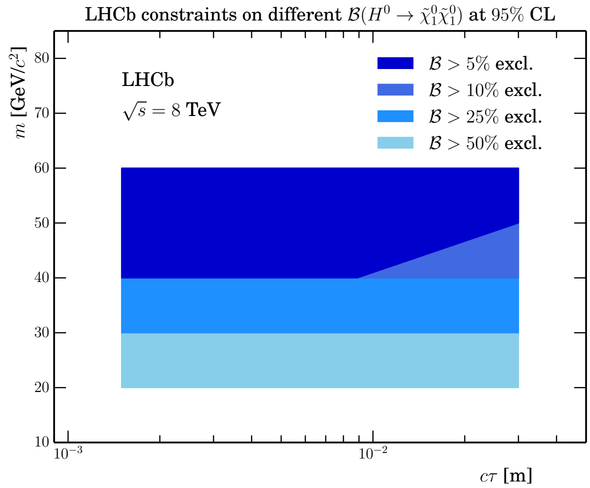

Figure 6: Areas of the parameter space excluded by LHCb at 95% confidence level for different branching ratios in the context of double neutralino production from SM Higgs-like boson [11].

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