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Prospects for searches for long-lived particles after the LHCb detector upgrades

LHCb collaboration[†]

Abstract

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, initially designed for the study of particles containing b or c quarks. As such, it is naturally suited for the search of beyond SM long-lived particles in a range of mass and lifetime not too dissimilar to heavy-flavour hadrons, as it has been demonstrated in several publications. Prospects for these searches in regard of future LHC upgrades, where challenging conditions are foreseen, are presented in this conference note with the goal to serve as an input for the HL-LHC and HE-LHC Yellow Report.

[†]Conference report prepared to serve as an input for the HL-LHC Yellow Report. Contact authors: Xabier Cid Vidal, xabier.cid.vidal@cern.ch; Carlos Vázquez Sierra, carlos.vazquez@cern.ch, and Aurelio Bay, aurelio.bay@epfl.ch.

1 Introduction

The LHCb detector, a single-arm spectrometer [1, 2], is the only LHC experiment to be fully instrumented in the forward region $2 < \eta < 5$, where decays of hadrons with b and c quarks are abundant and for which the decay length is enhanced due to their Lorentz boost. In the forward region, the detector occupancy is extremely high and therefore during LHC Run 1 and Run 2, the LHCb experiment has been run at reduced luminosities compared to those delivered to ATLAS and CMS experiments [3]. Originally designed for heavy-flavour physics, the LHCb experiment has proved to be also highly competitive in the regard of direct searches for Beyond Standard Model (BSM) long-lived particles (LLPs) [4–8].

An upgraded detector is foreseen to run at a luminosities five times larger ($2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$) in LHC Run 3 (starting in 2021) compared to those in Runs 1 and 2, while maintaining or improving the current detector performance. This first upgrade phase (named Upgrade I) will exploit a novel trigger concept where all subdetectors are read out in real time and the first level trigger is fully software implemented [9]. This new trigger scheme is extremely flexible and offers a great opportunity for searches of striking signatures, like those of LLPs with softer final state particles, compared to the hardware-based first level trigger used in Runs 1 and 2 which would entail a bottleneck in terms of kinematic reach (*i.e.* LLPs decaying into leptons or hadrons with low transverse momentum). In addition to improvements to the LHCb trigger system, improvements to the tracking and vertexing subdetectors are also foreseen: optimised track reconstruction algorithms plus the addition of new elements to the tracking stations are part of the LHCb Upgrade I [10]; and the complete replacement of the current LHCb Vertex Locator (VELO) — built with integrated silicon strips — by a new one entirely based on a silicon pixels pattern, which will lead to improved impact parameter (IP) and vertex resolutions, and a reduction in the background contribution due to material interactions [11]. This upgrade comes earlier than the ATLAS and CMS upgrades planned for the HL-LHC phase (starting in 2026) and will be followed by the so-called Upgrade II phase (planned for 2031) to run at an even more challenging luminosity of $\sim 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ [12].

The goal of this document is to provide prospects for searches of LLPs decaying either hadronically [5] or semileptonically [6] in the LHCb detector, during data-taking periods with LHCb Upgrade I (Runs 3 and 4) and LHCb Upgrade II (Run 5 onwards), and to serve as an input for the HL-LHC and HE-LHC Yellow Report document, being prepared for the Particle Physics European Strategy Update. This note focuses on the HL-LHC upgrade. The total integrated luminosities used for the projections in this document are summarised in Table 1. They follow the general assumptions for the LHCb experiment included in Ref. [12]. The energy of the pp collisions is assumed to be $\sqrt{s} = 14$ TeV.

Table 1: Assumptions for the integrated luminosity used in this document.

Run 3	Run 4	HL-LHC total
23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

2 General assumptions and projected sensitivities

Several BSM scenarios predict the existence of LLPs coupling to Standard Model (SM) particles via different mechanisms. One interesting type of mechanism is the one involving exotic decays of the SM Higgs boson. In the context of this production mode, and depending on the decay of the LLP itself, different signatures may be considered: using Run 1 data, the LHCb collaboration has searched for R-Parity Violating (RPV) supersymmetric neutralinos decaying semileptonically into a high-p_{T} muon and two jets [6]; and for Hidden Valley (HV) [13,14] pions (π_v) decaying hadronically into a pair of jets [5]. These analyses have shown the potential of the LHCb experiment to search for such signatures, especially in the low mass (few GeV/c^2) and low lifetime (few picoseconds) region, for which the detector has the best sensitivity. In general, excellent reconstruction of displaced vertices and of the associated tracks is crucial, as is the need to keep under control the dominant background contributions and effects from pile-up.

Projections of the search for a LLP decaying semileptonically or hadronically, and produced through the exotic decay of the SM Higgs boson, are presented in the following paragraphs. The excluded parameter space, in terms of lifetime and mass of the LLP, with different integrated luminosities, is compared for different branching fractions of the Higgs boson decay to the LLP. It should be noted that, apart from the exclusion of the signal considered here, the performed searches will also have the potential for a new physics discovery in similar parameter space regions.

Several samples of simulated events are used to compute the efficiencies considered for the interpolation of the limits presented in this document. The production of Higgs bosons in proton-proton collisions, with a mass of 125 GeV/c^2 and through the gluon-gluon fusion process, is simulated with the Pythia 8 generator [15] and with a specific LHCb configuration [16], using the CTEQ6 leading-order set of parton density functions [17]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [18, 19] as described in Ref. [20]. For the particular case of supersymmetric neutralinos, where proton-proton collisions are simulated at a centre-of-mass energy of 13 TeV, the signal is represented by the lightest neutralino $\tilde{\chi}^0_1$ allowed to decay into two quarks and a muon, and is produced in pairs from the decay of a Higgs boson. Decays to all quark pairs are assumed to have identical branching fractions except for those involving a top quark, which are neglected. For the production of HV pions through the Higgs portal, the model is fully specified by the mass and the lifetime of the π_v particles allowed to decay exclusively as $\pi_v \to b\bar{b}$, since this decay mode is generally preferred in this model. However, here, proton-proton collisions are simulated at a centre-of-mass-energy of 8 TeV, and then the production cross-section is re-scaled to account for a centre-of-mass-energy increase to 14 TeV.

The removal of the hardware level trigger [21] will be very beneficial for the reconstruction of jets. In this regard, by assuming a 100% efficient first level trigger, the overall trigger efficiency could improve by a factor of $2-3$. Similarly, for material interactions, the use of the detailed mapping of the VELO material recently reported in Ref. [22] can be very useful to tackle this background. Moreover, improved jet reconstruction techniques are foreseen to disentangle low mass jets merged into a single jet. However, conservative assumptions are made (namely the same values as those from Run 1 or Run 2 are taken) where the expected improvements discussed in the previous lines are ignored.

Regarding pile-up effects, the considered assumptions are optimistic (no effects at all or moderate effects are considered for these calculations), so the impact of pile-up has to be studied in more detail (especially concerning jet reconstruction). However, previous experience from ATLAS and CMS collaborations [23, 24], together with potential improvements expected in the jet reconstruction, makes this assumption reasonable. For instance, the effect from pile-up can be mitigated by using a jet reconstruction without neutral particles or by using machine-learning techniques. In the same regard, this can be also useful to compensate the removal of the Hadronic Calorimeter, foreseen between Run 3 and Run 4.

For projections of searches for LLPs decaying both semileptonically and hadronically, the results are interpolated for different masses and lifetimes not considered in simulation. The interpolation is linear and two-dimensional. Furthermore, in the cases when statistical fluctuations due to the low statistics available make the limits look irregular, the sensitivities are modified in a conservative way, always towards worse limits, to make the display more smooth.

2.1 Projected sensitivities for LLPs decaying semileptonically

This section presents the projected sensitivities from LHCb Run 1 limits for supersymmetric neutralinos decaying semileptonically into a high-p_{T} muon and two jets [6].

The results are obtained from a preliminary, unoptimised analysis of a subset of data collected for pp collisions at centre-of-mass energy of 13 TeV. To account for a possible deterioration in the background rejection due to multiple primary interactions at high luminosity, a penalty factor of two has been applied to the background yield. The signal efficiency is obtained from the full simulation of the Higgs boson produced via gluon-gluon fusion at 13 TeV. As mentioned in previous section, no other change in the signal and background efficiencies due to the upgrade of the detector are considered. As part of the selection, a multivariate classifier is trained and optimised using different simulated samples for each signal mass and lifetime hypotheses, as done for the Run 1 analysis [6]. Some examples of the efficiencies and background yields assumed for these calculations can be found in Table 2.

The upper limits on the branching fraction of the Higgs boson decay to a pair of neutralinos are calculated for different assumptions of neutralino masses and lifetimes and for different values of integrated luminosity. The Higgs boson production cross section is assumed to be that of the SM [25]. The actual limit is computed by comparing the 13 TeV efficiencies and background yields to Run 1, and by extrapolating the results published in Ref. [6]. This extrapolation assumes the presence of a significant amount of background in the whole scanned mass range, which is slightly conservative for the highest masses. Differences between 13 and 14 TeV centre-of-mass energies are neglected. Moreover, the systematic uncertainties, which are sub-dominant for this result in the published analysis, are assumed to be the same as those in Run 1.

The results are shown in Fig. 1, while Fig. 2 shows a comparison of the parameter space for where $\mathcal{B}(H^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0) < 2\%$ or 0.5% is excluded at 95% C.L. for different integrated luminosities. The region for which the mass of the neutralino is above 60 GeV/c^2 is not shown in these projections, since no simulation was available. It should be possible to explore this region in the Upgrade I and Upgrade II of the LHCb experiment. In any case, focus is given to the region below 60 GeV/c^2, where the LHCb detector will have the best sensitivity compared to other LHC experiments. Also, it is worth to notice that the

Table 2: Examples of the acceptance and total efficiencies assumed to detect a $\tilde{\chi}_1^0$ decaying semileptonically at a pp collision energy of $\sqrt{s} = 13$ TeV at the LHCb detector. Background yields at an integrated luminosity of 1.7 fb^{-1} are also presented. Differences in these yields are due to the effect of a multivariate classifier which is trained differently for each mass-lifetime case.

$\mathbf{m}_{\tilde{\chi}_1^0}$ **(GeV/c^2)**	$c\tau_{\tilde{\chi}_1^0}$ **(mm)**	Acceptance (%)	Total (%)	Background yield (1.7 fb^{-1})
	3	28.0	0.27	2
20	**15**	28.1	0.30	1
	30	27.8	0.24	3
	3	28.7	0.78	4
30	**15**	28.4	1.21	4
	30	28.7	0.75	2
	3	31.7	1.53	1
50	**15**	31.5	2.33	2
	30	31.7	1.58	1
	10	35.2	1.38	1
60	**50**	35.5	2.84	2
	100	35.2	2.63	3

Table 3: Background yields assumed for the HV pion analysis at an integrated luminosity of 23 fb^{-1}. The yields are divided in bins of $R_{xy} = \sqrt{x^2 + y^2}$, where x, y are the coordinates of the π_v particle decay vertex position. Values are extrapolated from Ref. [5].

$\boldsymbol{R_{xy}}$ **(mm)**	0.4-1	1-1.5	1.5-2	2-3	3-5	5-50
Background yield (23 fb^{-1})	$1.1{\times}10^5$	$5.4{\times}10^5$	$3.3{\times}10^5$	$9.8{\times}10^5$	$2.1{\times}10^6$	$3.3{\times}10^5$

lifetime range covered is constrained by the physical length of the VELO detector, since the LLP is required to decay within the VELO region in order to be able to reconstruct it.

2.2 Projected sensitivities for LLPs decaying hadronically

Projected sensitivities from LHCb Run 1 limits for HV pions decaying hadronically into a pair of jets [5] are presented in this section. These results are obtained by scaling signal and background and taking into account the increase of cross sections (from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 14$ TeV) and of the integrated luminosities. The scaling of the signal includes both the increase in the cross section of the Higgs boson production and that of the amount of signal falling in the acceptance of the LHCb detector. This last factor depends on the mass of the LLP, so an approximate value is taken for the whole scanned parameter space. The background is scaled by a factor obtained using simulated $b\bar{b}$ QCD events, which are expected to be the dominant contribution. As an example, the assumed yields, extrapolated from Ref. [5], can be found in Tab. 3 for an integrated luminosity of 23 fb^{-1}. Following the same reference, the yields are divided in bins of the radial coordinate of the HV pion decay vertex position.

As explained above, the signal and background detector related efficiencies are assumed to remain unchanged in this analysis with respect to the published Run 1 results. The only exception is the increased acceptance of the detector due to the additional boost of the Higgs boson at $\sqrt{s} = 14$ TeV. As an example, Table 4 shows examples of the

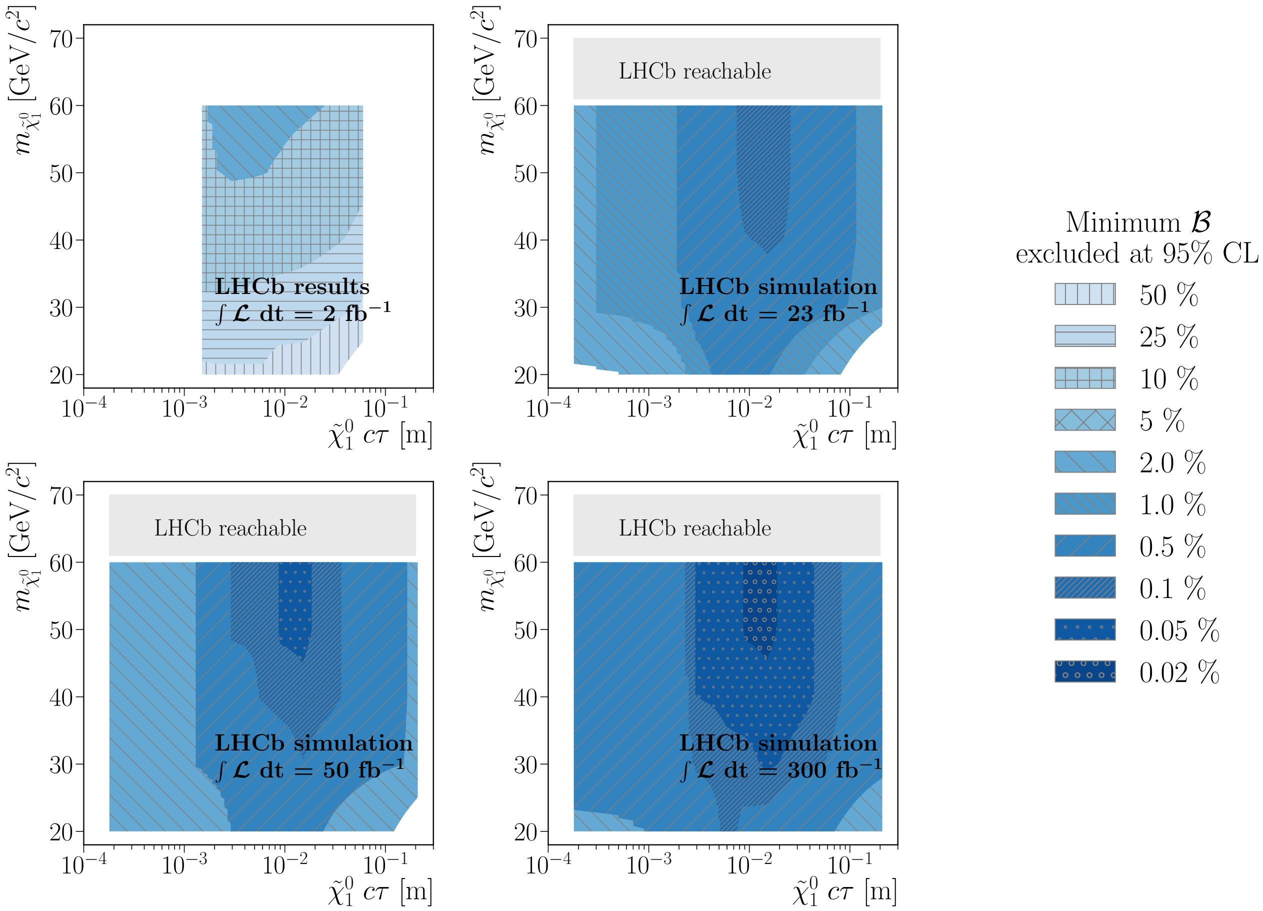

Figure 1: Projected sensitivities of the search for RPV supersymmetric neutralinos decaying semileptonically [6] and produced through a Higgs boson exotic decay. The results are extrapolated from Run 1 results (top left), for luminosities of 23 fb^{-1} (top right), 50 fb^{-1} (bottom left) and 300 fb^{-1} (bottom right). The results are presented in terms of the excluded parameter space of the neutralinos for different upper limits at 95% C.L. on the branching fractions of the Higgs boson decay.

Table 4: Examples of the acceptance and total efficiencies assumed to detect a π_v particle decaying to a pair of jets at a pp collision energy $\sqrt{s} = 14$ TeV at the LHCb detector. The main inefficiencies arise from the requirements to have π_v particle in the VELO and to have the decay products in the LHCb acceptance and from the reconstruction of the secondary vertex. More details can be found in Ref. [5].

$c\tau_{\pi_v}$ (mm)	Efficiency (%)	m_{π_v} (GeV/c^2)			
		25	**35**	**43**	**50**
3	Acceptance	26.8	21.2	17.4	14.6
	Total	0.9	1.7	1.5	1.1
30	Acceptance	16.1	15.1	13.7	12.3
	Total	0.2	0.4	0.4	0.3

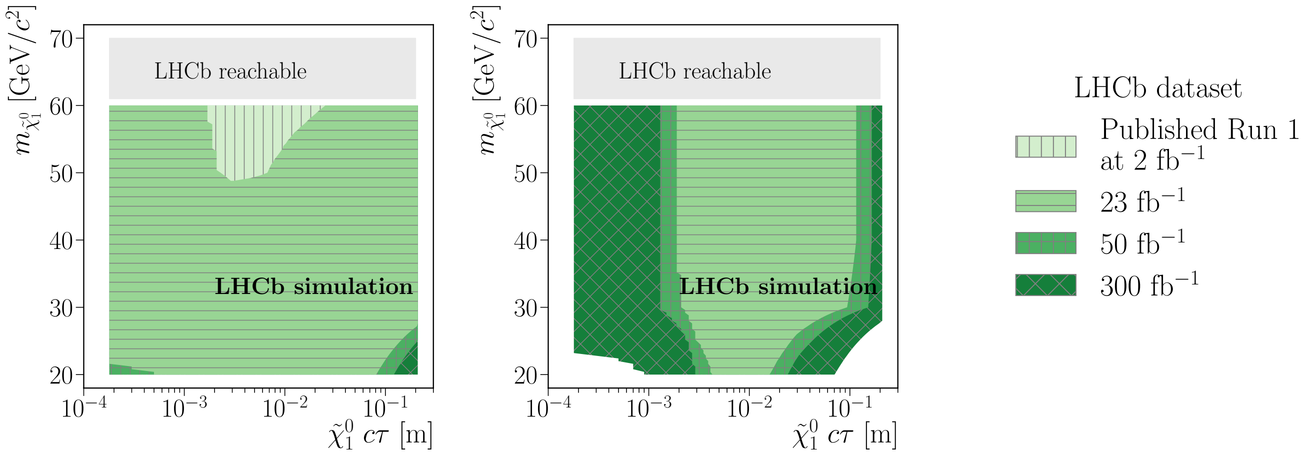

Figure 2: Comparison of projected sensitivities in the search for RPV supersymmetric neutralinos decaying semileptonically [6] and produced through a Higgs boson exotic decay. The sensitivities are extrapolated from Run 1 results, and the figure compares parameter regions where the branching fraction of the Higgs boson decay to a $\tilde{\chi}_1^0\tilde{\chi}_1^0$ pair is constrained to be smaller than 2% (left) and 0.5% (right) at 95% CL.

acceptance and total efficiencies assumed for this extrapolation for different masses and lifetimes of the HV pion. With the updated backgrounds and expected signal yields, the $\mathrm{CL_S}$ method [26] is used to compute the expected upper limits for different assumptions in the integrated luminosity and of the Higgs decay branching fraction. As above, the Higgs boson production cross section is assumed to be the SM one. The systematic uncertainties, which are not dominant in the computation of these limits in the published analysis, are considered to be the same as in Run 1, and added as a correction factor to the limits obtained using just statistical uncertainties. With all these assumptions, the HV pion masses and lifetimes excluded at 95% CL are obtained. The results are shown in Fig. 3. Finally Fig. 4 shows a comparison of the excluded parameter space for where the upper limit on $\mathcal{B}(H^0 \to \pi_v\pi_v)$ at 95% C.L. results to be smaller than 20% or 2%.

The regions for higher lifetimes and masses of the HV pion could be also explored by the LHCb experiment. However, a naive extrapolation of the current results from ATLAS [27] and CMS [28] (recasted in Ref. [29]) collaborations to higher luminosities shows that these regions are likely to be dominated by these experiments. Thus, it is chosen here to focus on the region where the LHCb experiment has the best sensitivity. Again, the covered lifetime range is constrained by the physical length of the VELO detector.

3 Possible improvements

Most of the searches presented here use tracks traversing the full LHCb spectrometer. These tracks have an excellent spatial and momentum resolution, and in general correspond to LLPs decaying within the VELO region. However, for long-lived candidates decaying outside or close to the boundaries of the VELO region, the tracks do not have hits in the VELO. Unfortunately, these “downstream” tracks, referring to tracks with hits only in the pre- and post-magnet tracking stations, not including the VELO, have worse vertex and

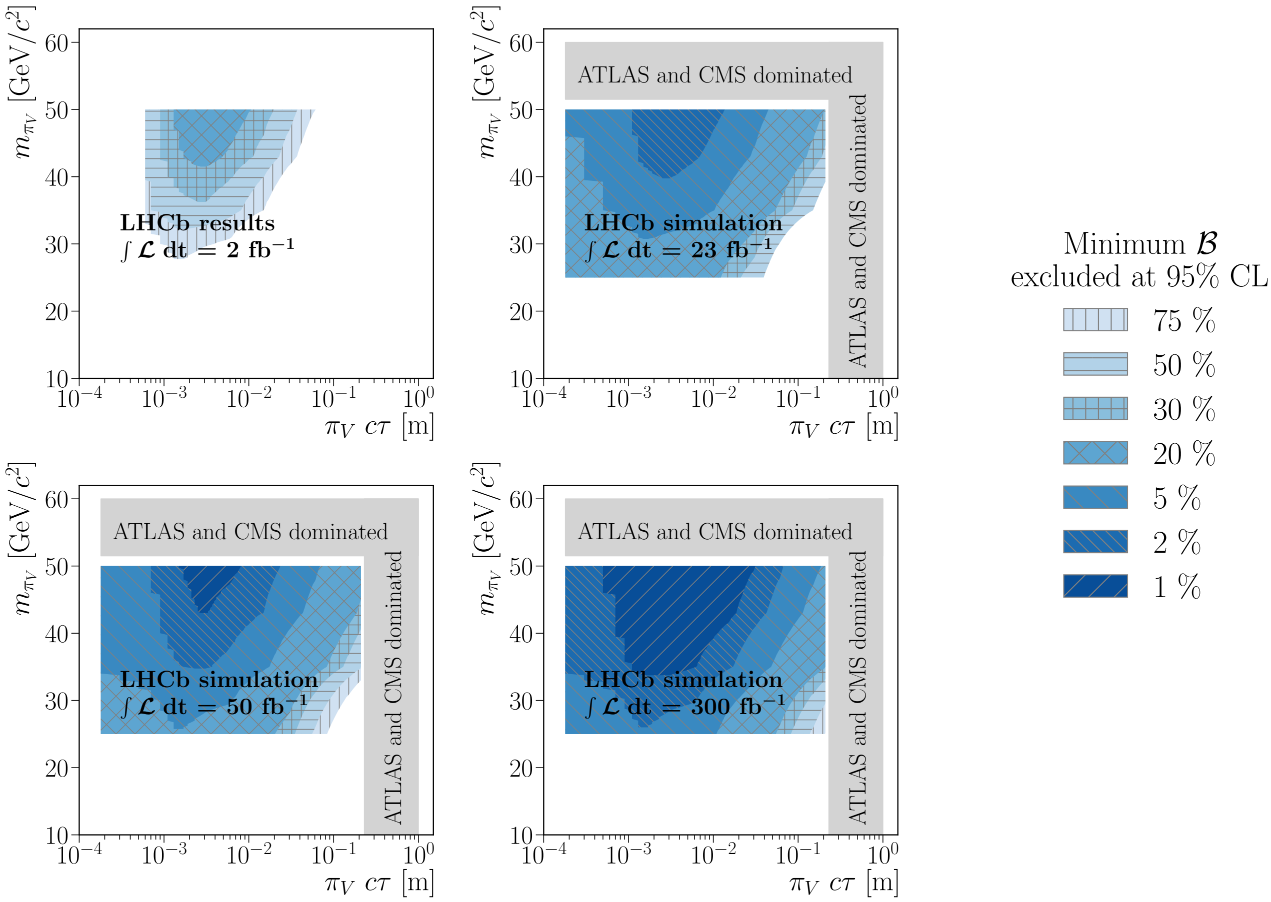

Figure 3: Projected sensitivities of the search for HV pions decaying hadronically [5] and produced through a Higgs boson exotic decay. The results are extrapolated from Run 1 results (top left), for luminosities of 23 fb^{-1} (top right), 50 fb^{-1} (bottom left) and 300 fb^{-1} (bottom right). The results are presented in terms of the excluded parameter space of the HV pions for different upper limits at 95% C.L. on the branching fractions of the Higgs boson decay.

momentum resolution, limiting the capabilities of the LHCb detector for this displacement range. Efforts to develop new trigger lines to select downstream tracks are summarised in Ref. [21]. Apart from these, upstream tracks are also considered useful for LLP searches: a proposal to add Magnet Stations inside the LHCb magnet to improve low momentum resolution can be found in Ref. [12].

The RF foil [11] strongly affects the background composition of LLP searches in the LHCb experiment. Namely, for LLP candidates decaying within 5 mm from the beam line, the main source of background is due to heavy-flavour decays, while material interactions with the RF foil compose the main background contribution for those LLP decaying beyond 5 mm from the beam line. While the former is purely due to QCD processes and hence not reducible, the latter is kept under control by the use of a very detailed veto map [4]. However, the removal of the RF foil would further enhance the sensitivity to this kind of analyses, since it would both significantly increase the IP resolution and reduce the background due to material interactions.

Furthermore, the search for exotic massive LLPs decaying into a pair of jets suffers

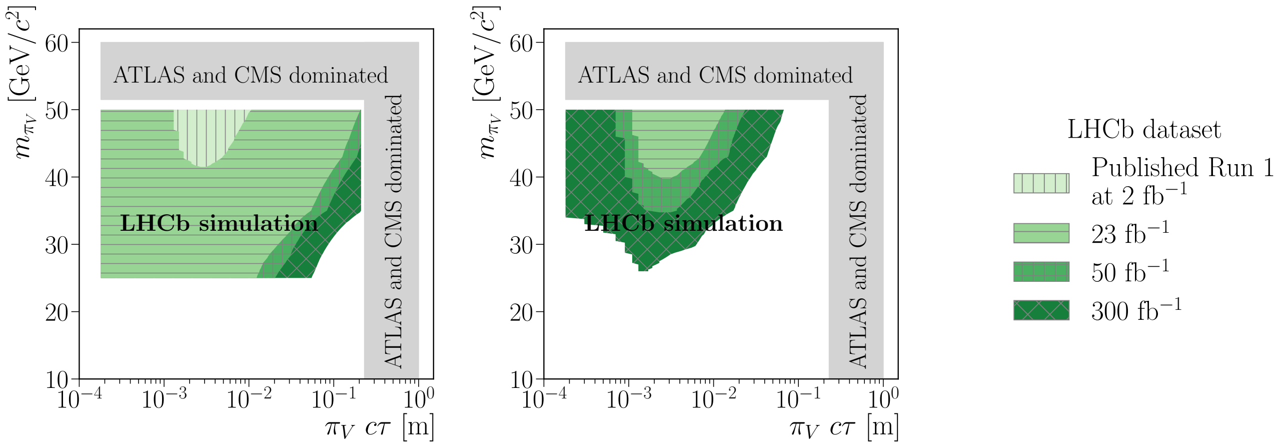

Figure 4: Comparison of projected sensitivities in the search for HV pions decaying hadronically [5] and produced through a Higgs boson exotic decay. The sensitivities are extrapolated from Run 1 results, and the figure compares parameter regions where the branching fraction of the Higgs boson decay to a $\pi_v\pi_v$ pair is constrained to be smaller than 20% (left) and 2% (right) at 95% CL.

from low efficiency in low-mass region, *i.e.* below 20 GeV/c^2. At low masses the final state cannot always be reconstructed as two resolved jets but as a single jet (merged jet). It has been shown [30] that the substructure of such merged jets can be exploited to improve the selection efficiency. More studies are needed, in particular for the development of new tagging algorithms for the identification of merged jets over the multi-jet background. The CMS collaboration already showed promising results in this field [31] by employing machine learning techniques, in particular Boosted Decision Trees and Deep Neural Networks. For the Upgrade II similar techniques are expected to be used by the LHCb collaboration.

4 Conclusions

In this document, projections for searches of long-lived particles decaying either hadronically or semileptonically, and using proton-proton data at $\sqrt{s} = 14$ TeV to be collected by the LHCb detector during Run 3 and beyond; are presented. The upgraded LHCb detector can exploit its excellent triggering, tracking and vertexing capabilities to produce the most competitive upper limits for long-lived particles with low masses and low lifetimes. The removal of the first hardware level trigger, a better impact parameter resolution due to the upgraded vertex locator, a better knowledge of material interactions, and improved jet reconstruction algorithms, will play a crucial role in order to achieve unprecedent sensitivites for these searches.

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