2 Exotic Higgs decays (and long-lived particles) at future colliders

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2.1 Exotic Higgs decays: motivations and signatures

The theoretical motivations and the large breadth of signatures for exotic Higgs decays have been thoroughly reviewed in Ref. [1]. They were first considered as a discovery mode of new physics in the context of a hidden valley scenario [2–4]. In the last few years, exotic Higgs decays have been revisited, as they arise ubiquitously in models of neutral naturalness, such as twin Higgs [5], folded supersymmetry [6], fraternal twin Higgs [7], hyperbolic Higgs [8], and singlet scalar top partners [9].

A simple proxy model for hidden valleys is obtained via a Higgs portal set-up,

$$\mathcal{L} \supset \frac{1}{2}\Big(\partial_\mu \phi\Big)^2 - \frac{1}{2}M^2\phi^2 - A|H|^2\phi - \frac{1}{2}\kappa|H|^2\phi^2 - \frac{1}{6}\mu\phi^3 - \frac{1}{24}\phi^4 - \frac{1}{2}\lambda_{\mathrm{H}}|H|^4 \,. \tag{2.1}$$

The fields H and ϕ mix, depending on κ and A, giving rise to physical states $h(125)$ and $X(m_{\mathrm{X}})$. Note that the phenomenology is fully encapsulated by three free parameters: $m_X, c\tau(X) \equiv c\tau$, and $\mathrm{Br}(\mathrm{h} \to \mathrm{XX})$. We will assume that the $\mathrm{h} \to \mathrm{XX}$ is always kinematically open. Existing constraints on the $h(125)$ properties imply that currently the room for an exotic Higgs branching ratio, $\mathrm{Br}(\mathrm{h} \to \mathrm{XX})$ is below about 10%. Since the mixing controls the X decay widths, a small mixing naturally gives rise to particles that travel a macroscopic distance $c\tau \gtrsim$ mm before decaying. Exotic Higgs decays are then encompassed within the larger class of 'long-lived particles' (LLP) signatures. For concreteness, we review LLPs in the next subsection.

It is worth stressing that the HL-LHC will produce about 10^8 Higgs bosons, while the CEPC and FCC-ee (240) will only give about 10^6. Hence, there is a trade-off between the clean environment provided by the collider and the corresponding production cross-section. This already tells us that future electron–positron colliders might probe exotic Higgs branching fractions down to 10^{-5}, while at the HL-LHC one could, in principle, go down to 10^{-6} or even 10^{-7}, depending on the visibility of the target final state.

2.2 Long-lived particles (LLPs)

Long-lived particles are Beyond Standard Model states with macroscopic lifetimes ($\gtrsim$ nanoseconds). These are theoretically well motivated in extensions of the SM trying to solve fundamental problems of the SM, such as dark matter or neutrino masses. A comprehensive overview of the theoretical motivations for LLPs can be found in Ref. [10], while a signature-driven document was put forward by the LLP@LHC community in Ref [11].

In a nutshell, to obtain a macroscopic lifetime (or a very narrow width), one is led to one of three choices: a large mass hierarchy (e.g., muon decay), a compressed spectrum (e.g., neutron lifetime), and feeble interactions. The latter is the one that concerns exotic Higgs decays.

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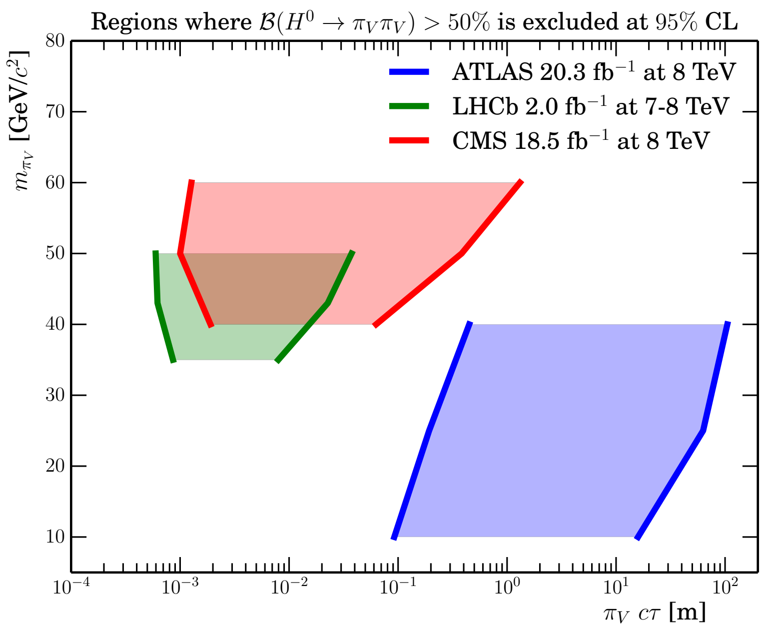

Fig. E.2.1: Reach of the ATLAS [16], CMS [17], and LHCb [18] studies for $\mathrm{X} \to \mathrm{jj}$, where X is taken to be a dark pion π_V of the hidden valley scenario. This model is in one-to-one correspondence with that described in Section 2.1. The shaded regions show where $\mathrm{Br}(\mathrm{H} \to \mathrm{XX}) > 50\%$ is excluded. Note that the area to the lower left cannot be probed by current searches. Plot taken from the supplementary material of Ref. [18].

In the last few years, there several proposed detectors have been targeting neutral LLPs, such as MATHUSLA [12], FASER [13], CODEX-b [14], and AL3X [15]. Exotic Higgs decays constitute a major theoretical motivation in the design of such experiments, which can probe the difficult phase space regions where the standard triggers and object reconstruction became inefficient. These shortcomings will be detailed in the next subsection.

2.3 Exotic Higgs decays vis-à-vis current LHC data

Since, in the simplest scenarios, the X particle decays like a SM Higgs boson of m_X, what occurs is that the predominant decays are into $\mathrm{b\bar{b}}$ pairs, if the channel is open. In that case, the existing programme of LHC searches for displaced hadronic vertexes (see, e.g., Refs. [16–18]) can cover part of the parameter space. We display the current coverage in the $c\tau$–m_X plane in Fig. E.2.1. We immediately see that the current LHC data are not able to cover the region of short lifetimes ($c\tau \lesssim 10$ cm) and low masses ($m_\mathrm{X} < 35\,\mathrm{GeV}$). Low masses for X imply lower boosts, so the soft jets of the event will not pass the typical H_T or $p_\mathrm{T}(j)$ trigger thresholds used by ATLAS and CMS.[†] As a sample, the reported trigger efficiency of CMS for $m_\mathrm{X} = 50\,\mathrm{GeV}$ and $c\tau = 30$ mm is about 2%. The other limitation corresponds to short lifetimes, which is limited by the vertex resolution. Hence, the shortcomings of pp machines can be targeted, instead, with a collider providing better angular resolution, lower p_T thresholds, and more accurate vertexing, which happens at both $\mathrm{e^-p}$ and $\mathrm{e^+e^-}$ machines. We stress that additional data will not alter this picture, and the low $c\tau$ and low m_X region would continue to be extremely hard to probe.

[†] It is worth noting that LHCb has the capability to trigger directly on displaced vertexes.

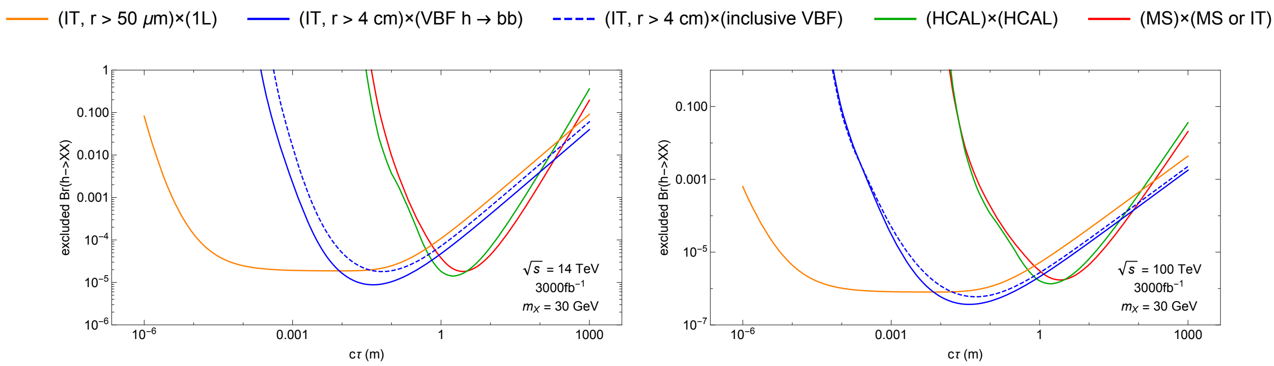

Fig. E.2.2: Sensitivities of the displaced searches for exotic Higgs decays at the HL-LHC (left) and FCC-hh (right), in the $c\tau$–Br(h $\to$ XX) plane, for $m_{\mathrm{X}} = 30\,\mathrm{GeV}$. The curves correspond to the use of different triggers and different assumptions about the reconstruction of the displaced vertexes. Plot taken from Ref [19].

2.4 Future experiments: HL-LHC, FCC, CEPC, LHeC

2.4.1 Proton–proton colliders

We show in Fig. E.2.2 (taken from Ref. [19]) the expected reach at the HL-LHC ($\sqrt{s} = 14\,\mathrm{TeV}$ and total integrated luminosity of $3\,\mathrm{ab}^{-1}$) and at the FCC-hh ($\sqrt{s} = 100\,\mathrm{TeV}$ and total integrated luminosity of $3\,\mathrm{ab}^{-1}$) for a scalar mass of $m_{\mathrm{X}} = 30\,\mathrm{GeV}$. The curves indicate different choices of trigger and of reconstruction capabilities of the displaced vertex. In particular, the orange curve corresponds to one displaced vertex in the inner tracker with an impact parameter of 50 µm, which poses an interesting experimental challenge and thus should be regarded as an optimistic case. The blue curve corresponds to the realistic case of using VBF, h $\to$ b$\bar{\mathrm{b}}$ triggers down to an impact parameter of 4 cm.

We see that one can cover lifetimes as short as a millimetre (or even one micrometre for the optimistic scenario), while the probed exotic branching ratios can reach down to 10^{-5} (10^{-6}) for the HL-LHC (FCC-hh), for the benchmark case of $m_{\mathrm{X}} = 30\,\mathrm{GeV}$. As discussed before, lower masses would suffer from a poor trigger efficiency, which opens a window of opportunity for both electron–proton and electron–positron colliders.

2.4.2 Electron–proton colliders

The reach on exotic Higgs decays for future electron–proton colliders is displayed in Fig. E.2.3. We see that the electron–proton colliders, owing to their better resolution, can test masses down to 5 GeV for exotic branching fractions of about 10^{-4}. This mass range is almost impossible to probe at the LHC, because of the overwhelming multijet background. We also note that electron–proton colliders provide a smaller luminosity.[‡] Hence, electron–proton colliders provide a window of opportunity to overcome the gaps in coverage discussed for proton–proton colliders.

[‡]During a 25 year run period of the Future Circular Collider (FCC), the proton–proton incarnation (FCC-hh) is expected to collect 15–30 ab^{-1} while the electron–proton version will collect only 1 ab^{-1} [20].

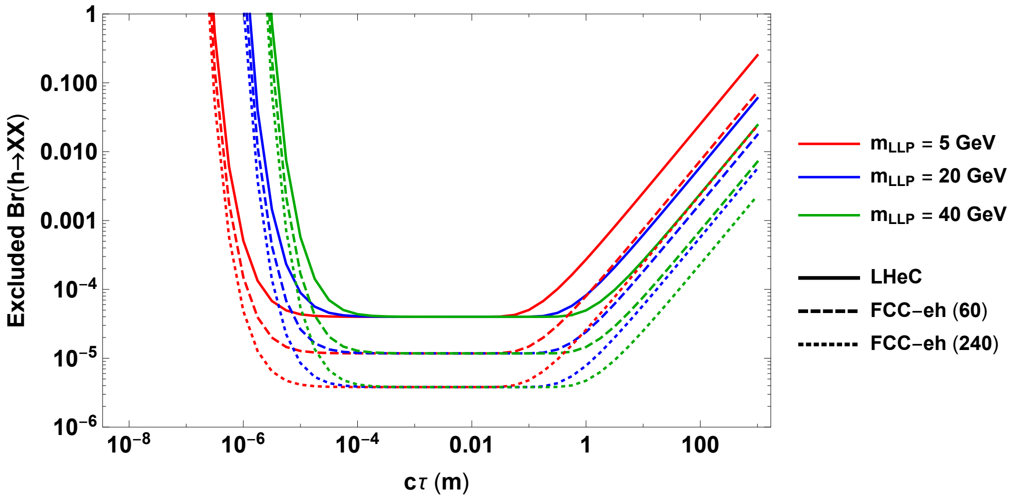

Fig. E.2.3: Reach of the future electron–proton colliders: LHeC (solid), FCC-eh (60), and FCC-eh (240). The LHeC would collide a 7 TeV proton from the LHC against a 50 GeV electron beam, while for the FCC-eh a 50 TeV proton beam will collide against a 60 GeV (design case) or 240 GeV beam (optimistic scenario). Taken from Refs. [21, 22].

2.4.3 Electron–positron colliders

Finally, we take a look at the e^+–e^- case. A detailed analysis is reported in Ref [23]; here, we briefly summarise the most salient points. This study considers the Higgs-strahlung process $e^+e^- \to hZ$ with leptonic decays of the Z boson for both the FCC-ee [24] and the CEPC [25, 26]. A set of basic selection cuts allows us to achieve a zero-background regime for the irreducible SM processes.[§] Two different strategies are pursued: the large mass and the long-lifetime regime. The main difference between the two is in the requirements on the minimal distance between the displaced vertexes. The results are shown in Fig. E.2.4.

One immediately sees that the e^+e^- colliders can test exotic branching fractions down to 5×10^{-5}. Moreover, they can go low in mass, down to a few gigaelectronvolts, and they can also probe decay lengths down to micrometres, where the proton–proton colliders would be ineffective.

2.5 Conclusions

In this contribution, I have summarised the existing studies on exotic Higgs decays at current and future colliders. While the proton–proton machines would, in principle, be the best option, owing to their larger energies and luminosities, we have also seen that the phase space regions where the LHC and FCC-hh lose steam, namely, low X masses and short lifetimes provide a unique window of opportunity for both e^-p and e^+e^- colliders. The latter two types of machine have only recently been studied, and thus there is naturally much room for improvement. It should also be stressed that these kinds of study can help to optimise the detector design of future colliders.

[§]Backgrounds from particles originating away from the interaction point (e.g., beam halo, cosmic muons, cavern radiation) are not considered.

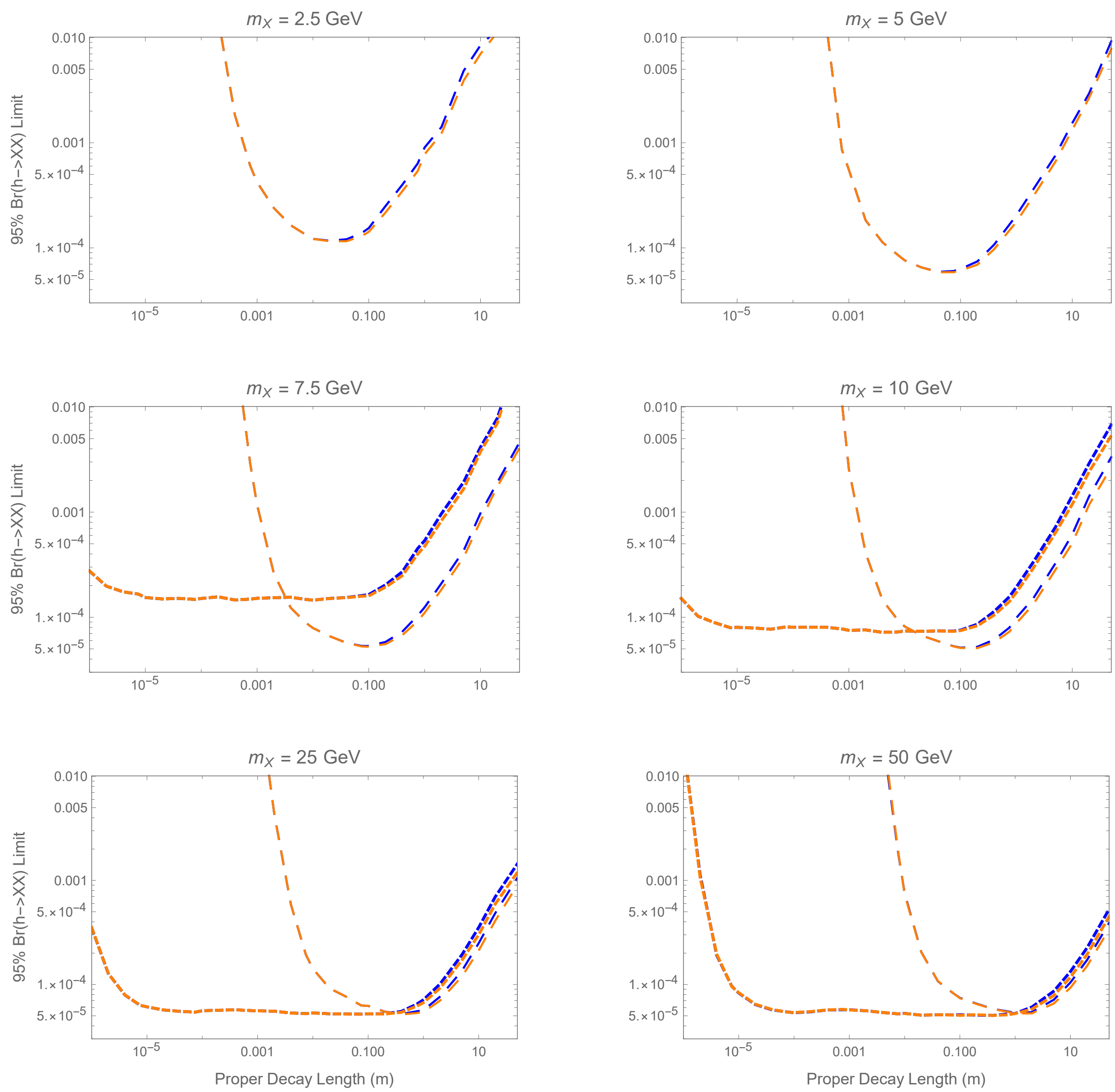

Fig. E.2.4: FCC-ee (blue) and CEPC (orange) limits on the exotic branching ratio h $\rightarrow$ XX at the 95% CL. The 'long-lifetime' analysis is shown with larger dashes, while smaller dashes correspond to the 'large-mass' study. Taken from Ref. [23].

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