SEARCH FOR HIDDEN VALLEY AT FUTURE COLLIDERS*

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Received 20 March 2024, accepted 28 June 2024, published online 5 August 2024

The present document focuses on the sensitivity studies to observe massive long-lived particles predicted by the Hidden Valley models. The study is based on a data sample of e^+e^- collisions at $\sqrt{s} = 350$ GeV and $\sqrt{s} = 3$ TeV, simulated with the CLIC_ILD detector, and corresponding to an integrated luminosity of 1 ab^{-1} and 3 ab^{-1}, respectively. The upper limits on the production cross section for the long-lived particle lifetimes from 1 to 300 ps, masses between 25 and 50 GeV/c^2, and a parent Higgs mass of 126 GeV/c^2 are discussed, together with sensitivities to the production cross section.

DOI:10.5506/APhysPolBSupp.17.5-A24

1. Introduction

Many models of new physics predict the existence of new, long-lived particles (LLP), which would appear with a very distinctive experimental signature. One class of such models, the so-called Hidden Valley [1, 2], is a consequence of the string theory, which predicts the existence of a new non-Abelian gauge group consisting of so-called v-particles, hidden at large energy scales. The hidden region may be accessible through the decay of hidden particles into Standard Model (SM) particles through heavy mediators. In particular, it predicts the SM Higgs boson to decay into the combinations of massive long-lived particles (π_vs) that decay mostly to a $b\bar{b}$ pair, having unobservable partners that could serve as dark matter objects. In the case of the Hidden Valley model, the event topology is a set of displaced vertices (DV), distant from the primary vertex and the beam axis, which can be efficiently reconstructed by the tracking system of the CLIC detector [3]. In the present report, the study of the SM Higgs boson decaying into two Hidden Valley particles, $H \to \pi_v^0\pi_v^0 \to b\bar{b}b\bar{b}$, is described [5, 6] providing four b-jets

* Presented at the 30th Cracow Epiphany Conference on *Precision Physics at High Energy Colliders*, Cracow, Poland, 8–12 January, 2024.

in the final state. At the centre-of-mass energy $\sqrt{s} = 350$ GeV, the Higgs boson is dominantly produced in the Higgsstrahlung process ($e^+e^- \to ZH$), while at $\sqrt{s} = 3$ TeV, the dominant production mechanism is WW fusion. They are simulated employing the CLIC_ILD detector [4], with an integrated luminosity of 1 ab^{-1} at $\sqrt{s} = 350$ GeV and 3 ab^{-1} at $\sqrt{s} = 3$ TeV. The searches for the SM Higgs boson decaying into two LLPs with two $b\bar{b}$ di-jets in the final state have been performed so far by several experiments, such as D0 [7], CDF [8], ATLAS [9], CMS [10], and LHCb [11].

2. Analysis procedure

A search for v-particles is performed using a dataset of Monte Carlo (MC) events generated with Whizard 1.95 [12] as well as PYTHIA 6.4 [13] for fragmentation and hadronization, configured to provide Hidden Valley processes. The Geant4 [14] simulation package and the MOKKA [15] detector description toolkit are used to simulate the response of the CLIC_ILD detector, while the MARLIN software package [16] is used for event reconstruction. The signal samples of e^+e^- collisions at $\sqrt{s} = 350$ GeV and $\sqrt{s} = 3$ TeV, namely $e^+e^- \to ZH(H \to \pi_v^0\pi_v^0)$ and $e^+e^- \to H\nu_e\bar{\nu}_e(H \to \pi_v^0\pi_v^0)$, respectively, with π_v^0 lifetimes from 1 to 300 ps, masses between 25 and 50 GeV$/c^2$, and a parent Higgs mass of 126 GeV$/c^2$ are generated. Background samples of $q\bar{q}$, $q\bar{q}\nu\bar{\nu}$, $q\bar{q}q\bar{q}$, $q\bar{q}q\bar{q}\nu\bar{\nu}$ are generated, with additional samples of $t\bar{t}$ and WWZ for $\sqrt{s} = 350$ GeV. For every signal sample, cross sections of 0.93 pb ($\sqrt{s} = 350$ GeV) and 0.42 pb ($\sqrt{s} = 3$ TeV) with BR($\pi_v^0 \to b\bar{b}$) = 100% are assumed. In the case of the Hidden Valley model, generated π_v^0s are assumed to have a non-zero lifetime, so they are expected to be distant from

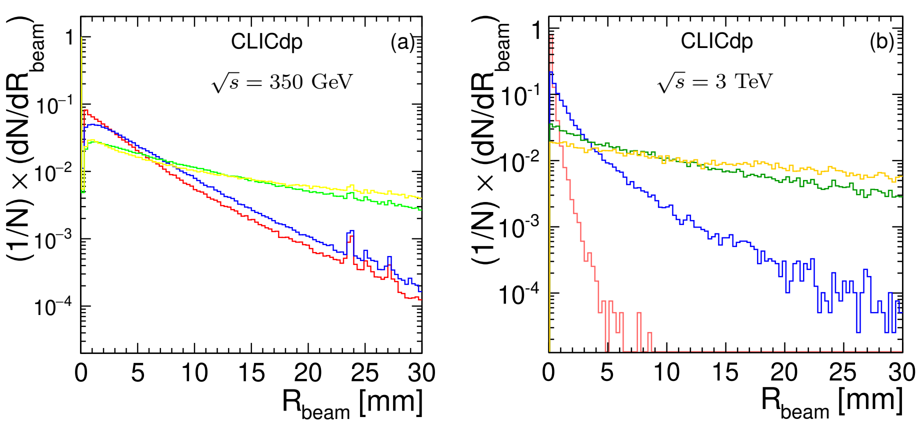

Fig. 1. (Colour on-line) Radial distance of π_v^0 to the beam axis for π_v^0s generated with a mass hypothesis of 50 GeV$/c^2$ and with four different lifetimes (from bottom to top): 1 ps (red), 10 ps (blue), 100 ps (green), and 300 ps (yellow) for (a) $\sqrt{s} =$ 350 GeV and (b) $\sqrt{s} = 3$ TeV.

the primary vertex and the beam axis. Distributions of the radial distance of the generated π_v^0 to the beam axis are shown in Fig. 1. It may be seen that slopes on both distributions depend on the π_v^0 lifetime.

Since the event topology is a set of displaced vertices out of the primary vertex and the beam axis, a dedicated procedure to reconstruct displaced vertices is developed and optimised for the Hidden Valley analysis [5], as the default CLICdp package dedicated to reconstruct secondary vertices [17] was found to be inefficient in the reconstruction of displaced vertices from π_v^0 decays. In order to reconstruct the parent Higgs boson, two b-tagged jets are assigned to each displaced vertex. As the jet reconstruction algorithm does not provide the vertex position, a di-jet is assigned to the reconstructed displaced vertex with the largest number of common charged tracks. The jets are reconstructed using k_{T} algorithm [18] implemented in the FastJet package [19]. The jets are b- and c-tagged employing a set of parameters, such as impact parameters that are determined by the vertexing, through a Boosted Decision Tree (BDT) [20]. All the jets are required to have a b-tag probability of more than 0.95. The R parameter is optimised to minimize the normalized root mean square (RMS/mean) of the di- and four-jet mass, and it is set to 1.0. A multivariate analysis based on the Boosted Decision Tree Gradient (BDTG) [21] is used for the signal-to-background separation. It uses seven variables with significant separation, *i.e.* *(i)* number of tracks assigned to the reconstructed DV, *(ii)* number of reconstructed DVs in the event, *(iii)* invariant mass of the DV, *(iv)* di-jet invariant mass of the two jets assigned to the DV, *(v)* four-jet invariant mass of two di-jets assigned to two DVs, *(vi)* distance $y_{n+1,n}$ at which the transition from a three-jet event to a two-jet event occurs, *(vii)* distance $\mathrm{y}_{n-1,n}$ at which the transition from

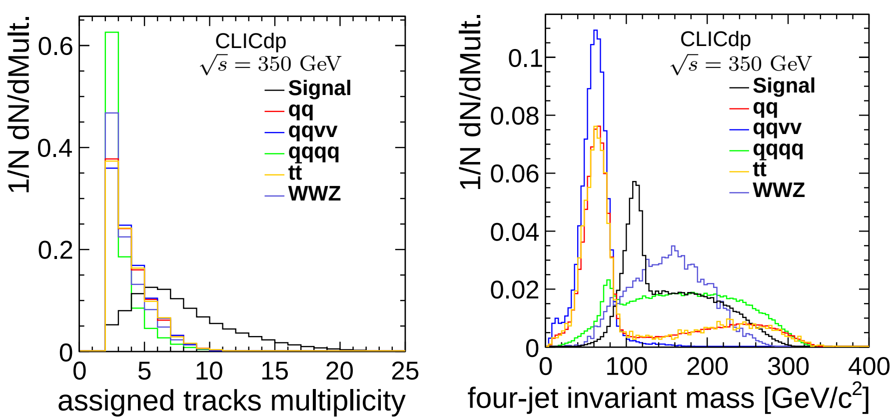

Fig. 2. Number of tracks assigned to the reconstructed DV (left) and four-jet invariant mass (right) for signal samples at $\sqrt{s} = 350$ GeV with π_v^0 mass of 35 GeV/c^2 and the lifetime of 10 ps, compared to $q\bar{q}$, $q\bar{q}\nu\bar{\nu}$, $q\bar{q}q\bar{q}$, $t\bar{t}$, and WWZ background events.

a four-jet event to a three-jet event occurs. In addition, the procedure for $\sqrt{s} = 350$ GeV includes as well the invariant mass of a Z-boson candidate, reconstructed from b-jets not assigned to any displaced vertex. As an example, in Fig. 2, there are distributions of a number of tracks assigned to the reconstructed DV and four-jet invariant mass for the signal and background samples. The requirement on BDTG response to be greater than 0.95 for all the π_v^0 masses and lifetimes is imposed in order to maximize the significance.

3. Sensitivity

The sensitivity of the CLIC_ILD detector for the Hidden Valley particles observed through the SM Higgs-boson decay $H \to \pi_v^0 \pi_v^0$ is determined, where the Higgsstrahlung is chosen for $\sqrt{s} = 350$ GeV, while for $\sqrt{s} = 3$ TeV, the

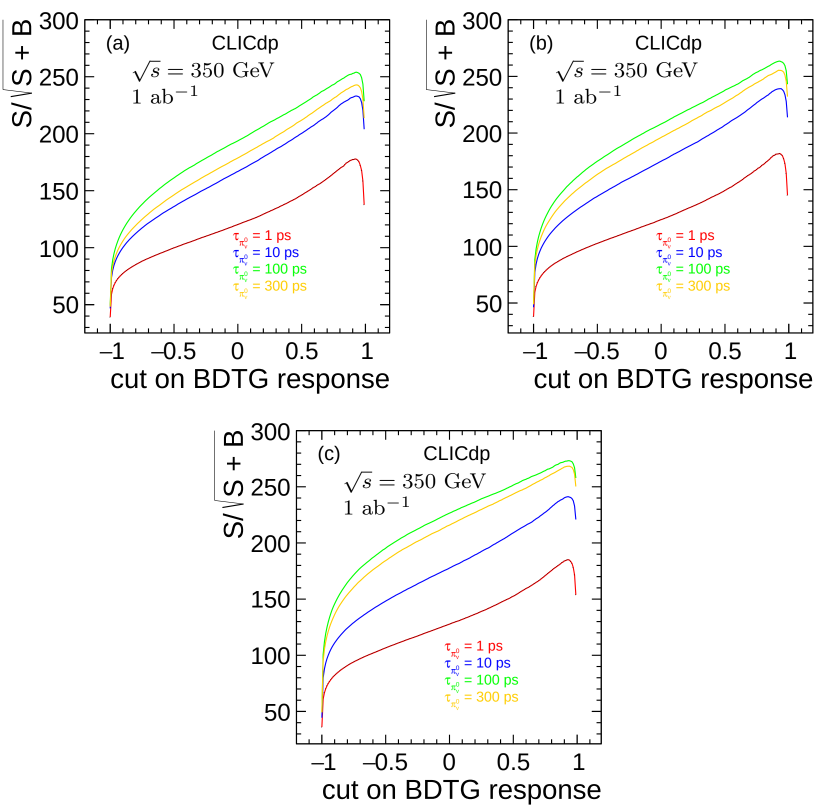

Fig. 3. (Colour on-line) Sensitivity for the expected number of events as a function of the requirement on the BDTG response at $\sqrt{s} = 350$ GeV, for signal samples of π_v^0 with a mass of (a) 25 GeV$/c^2$, (b) 35 GeV$/c^2$, and (c) 50 GeV$/c^2$, and for four different lifetimes (from bottom to top): 1 ps (red line), 10 ps (blue line), 300 ps (yellow line), and 100 ps (green line). An integrated luminosity of 1 ab^{-1} at $\sqrt{s} = 350$ GeV and 3 ab^{-1} at $\sqrt{s} = 3$ TeV is assumed.

Higgs-boson production via WW fusion is used. It is estimated for $\sqrt{s} =$ 350 GeV and $\sqrt{s} = 3$ TeV collision energy, with an integrated luminosity of 1 ab^{-1} and 3 ab^{-1}, respectively. Figure 3 shows the sensitivity at $\sqrt{s} =$ 350 GeV as a function of the requirement on the BDTG response for signal samples with different masses and lifetimes, where the combined background is used. Figure 4 shows the same for $\sqrt{s} = 3$ TeV.

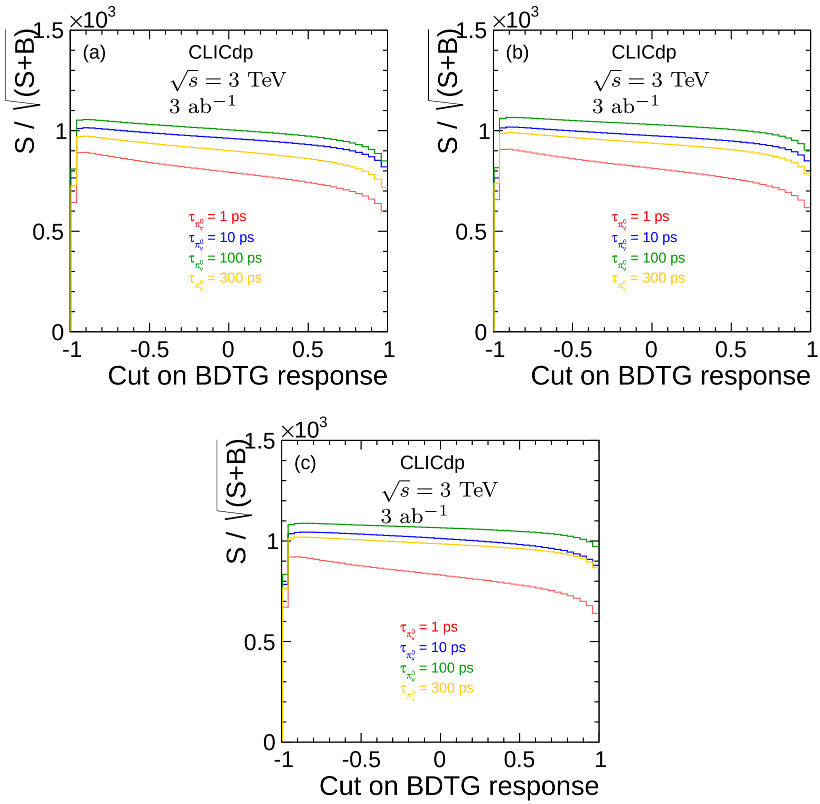

Fig. 4. (Colour on-line) Sensitivity for the expected number of events as a function of the requirement on the BDTG response at $\sqrt{s} = 3$ TeV, for signal samples of π_v^0 with a mass of (a) 25 GeV/c^2, (b) 35 GeV/c^2 and (c) 50 GeV/c^2, and for four different lifetimes (from bottom to top): 1 ps (red line), 300 ps (yellow line), 10 ps (blue line), and 100 ps (green line). An integrated luminosity of 1 ab^{-1} at $\sqrt{s} = 350$ GeV and 3 ab^{-1} at $\sqrt{s} = 3$ TeV is assumed.

4. Upper limits

Expected upper limits on the product of the Higgs production cross section and the branching fraction of the Higgs-boson decay into long-lived particles, $\sigma(H) \times \mathrm{BR}(H \to \pi_v^0 \pi_v^0)$, are set using the C.L.(s) method [22]. In the absence of signal observation, the 95% C.L. upper limits on $\sigma(H) \times \mathrm{BR}(H \to \pi_v^0 \pi_v^0)$ are determined, with the assumption of a 100% branching fraction for $\pi_v^0 \to b\bar{b}$ and the cut on the BDTG response > 0. The results are shown in Fig. 5, including the upper limits normalized to the Standard

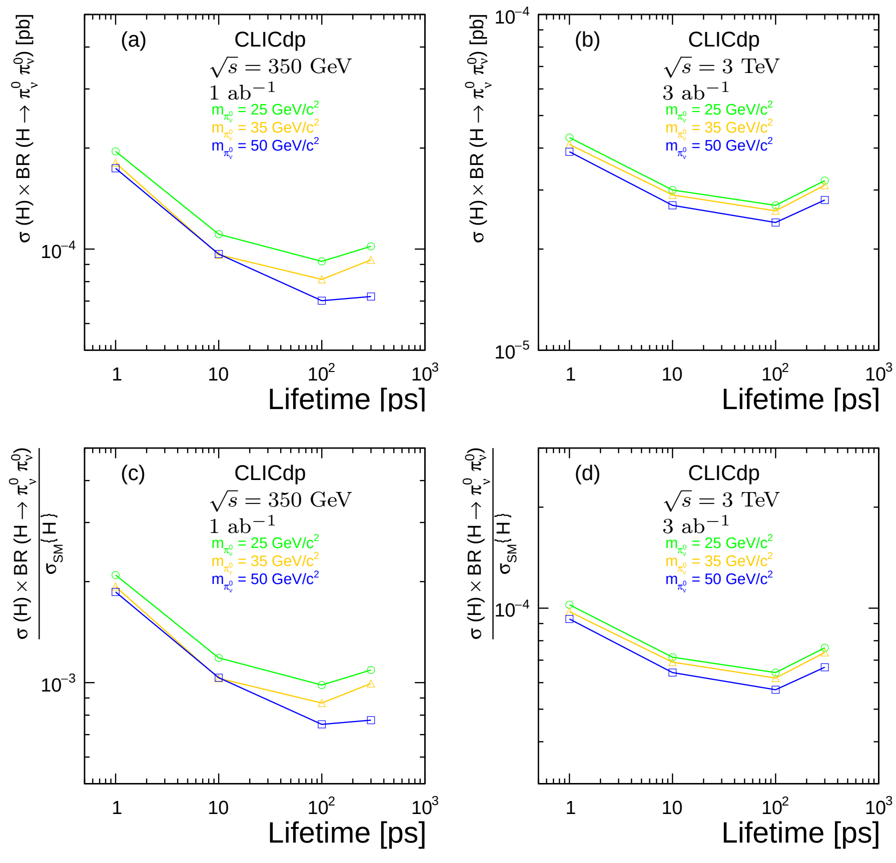

Fig. 5. Expected 95% C.L. cross-section upper limits on the $\sigma(H) \times \mathrm{BR}(H \to \pi_v^0 \pi_v^0)$, within the Hidden Valley model [2], for three different π_v^0 masses (from top to bottom): 25 GeV$/c^2$ (green), 35 GeV$/c^2$ (yellow), 50 GeV$/c^2$ (blue), as a function of π_v^0 lifetime for $\sqrt{s} = 350$ GeV (a) and $\sqrt{s} = 3$ TeV (b). The bottom row shows the upper limits normalized to the SM production cross section of the Higgs boson at $\sqrt{s} = 350$ GeV (c) and $\sqrt{s} = 3$ TeV (d). An integrated luminosity of 1 ab^{-1} at $\sqrt{s} = 350$ GeV and 3 ab^{-1} at $\sqrt{s} = 3$ TeV is assumed.

Model production cross section of the Higgs boson. The limits tend to be stronger with increasing π_v^0 mass, as the background decreases with the observed di-jet invariant mass.

5. Summary

In the present document, the sensitivities and upper limits on the SM Higgs-boson production cross section times branching fraction of its decay into exotic long-lived particles are reported. This is determined for the CLIC_ILD detector for the first ($\sqrt{s} = 350$ GeV) and the last ($\sqrt{s} = 3$ TeV) stage of its planned operation, where assumed integrated luminosities are 1 ab^{-1} and 3 ab^{-1}, respectively. The analysis is based on reconstructed displaced vertices, providing a significant reduction of the background using multivariate analysis. The expected upper limits, determined in the absence of signal observation, are calculated using the C.L.(s) method, largely exceeding those of the currently operating detectors [9–11].

REFERENCES

[1] M.J. Strassler, K.M. Zurek, *Phys. Lett. B* **651**, 374 (2007).

[2] M.J. Strassler, K.M. Zurek, *Phys. Lett. B* **661**, 263 (2008).

[3] CLICdp Collaboration, CLICdp-Note-2018-005, 2018.

[4] A. Munnich, A. Sailer, LCD-Note-2011-002, 2011.

[5] M. Kucharczyk, T. Wojton, CLICdp-Note-2018-001, 2018.

[6] M. Kucharczyk, M. Goncerz, *J. High Energy Phys.* **2023**, 131 (2023).

[7] D0 Collaboration (V.M. Abazov *et al.*), *Phys. Rev. Lett.* **103**, 071801 (2009).

[8] CDF Collaboration (T. Aaltonen *et al.*), *Phys. Rev. D* **85**, 012007 (2012).

[9] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. D* **102**, 112006 (2020).

[10] CMS Collaboration (A.M. Sirunyan *et al.*), *Phys. Rev. D* **104**, 052011 (2021).

[11] LHCb Collaboration (R. Aaij *et al.*), *Eur. Phys. J. C* **77**, 812 (2017).

[12] W. Kilian, T. Ohl, J. Reuter, *Eur. Phys. J. C* **71**, 1742 (2011).

[13] T. Sjöstrand, S. Mrenna, P. Skands, *J. High Energy Phys.* **2006**, 026 (2006).

[14] Geant4 Collaboration, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).

[15] P. Mora de Freitas, H. Videau, LC-TOOL-2003-010, 2002.

[16] F. Gaede, *Nucl. Instrum. Methods Phys. Res. A* **559**, 177 (2006).

[17] T. Suehara, T. Tanabe, *Nucl. Instrum. Methods Phys. Res. A* **808**, 109 (2016).

[18] S. Catani *et al.*, *Nucl. Phys. B* **406**, 187 (1993).

[19] C. Cacciari, G.P. Salam, G. Soyez, *Eur. Phys. J. C* **72**, 1896 (2012).

[20] J. Zhu *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **543**, 577 (2005).

[21] H. Voss, A. Höcker, J. Stelzer, F. Tegenfeldt, *PoS* **(ACAT)**, 040 (2007).

[22] A.L. Read, *J. Phys. G: Nucl. Part. Phys.* **28**, 2693 (2002).