

## Illuminating long-lived dark vector bosons via exotic Higgs decays at $\sqrt{s} = 13$ TeV

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The possibility of producing a measurable long-lived dark  $Z$  boson, that is assumed to mix kinetically with the hypercharge gauge boson in Higgs decays and to be produced also in Higgs decays through Higgs-to-dark-Higgs mixing, at the Large Hadron Collider (LHC) is investigated. Displaced dimuons in the final state are considered where each of the  $Z$  and the dark  $Z$  bosons decays directly to a dimuon. The total cross sections for the decay modes of interest as well as the decay widths and decay lengths are calculated to next-to-leading order (NLO) by using Monte Carlo (MC) simulation in the framework of MADGRAPH5\_aMC@NLO and compared to the available analytical calculations to leading order (LO). The sensitivity of the LHC in Runs 2 and 3 to such searches is discussed.

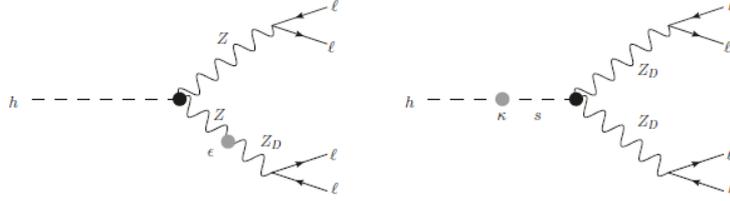
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## 1. Introduction

Exotic Higgs decays involve new light states beyond the Standard Model (BSM) and are best searched at the LHC. In this context, the observed Standard Model (SM) Higgs boson  $h$  is assumed to be responsible for breaking the electroweak symmetry and to decay to new particles such as dark Higgs boson and dark  $Z$  boson, usually referred to as  $h_D$  (or  $s$ ) and  $Z_D$ , respectively. The only possible interaction of  $Z_D$  with the SM sector is through its kinetic mixing (KM) with  $Z$  boson [1–3], while if the Higgs mixing (HM) exists,  $h_D$  will have a renormalizable coupling to  $h$ . The high luminosities achieved by the LHC offer a promising insight into the search for hidden sectors through these two portals. The search for  $Z_D$  has been mostly performed for  $m_{Z_D} < 10 \text{ GeV}$ , while several efforts were recently devoted to higher ranges of  $m_{Z_D}$  [4–8]. Heavier  $Z_D$  could explain the  $\sim 3.6\sigma$  discrepancy between the measured and SM value of the muon anomalous magnetic moment [9–11] as well as various dark matter (DM)-related anomalies via new DM- $Z_D$  interactions [12–15]. In this investigation, decays are assumed to proceed through on-shell  $Z_D$ 's (i.e.,  $m_{Z_D} < m_h/2$  in the case of  $h \rightarrow Z_D Z_D$  and  $m_{Z_D} < m_h - m_Z$  in the case of  $h \rightarrow Z Z_D$ ) for which cross sections are enhanced as compared to the off-shell  $Z_D$ 's for which cross sections are suppressed by the second power of the kinetic mixing parameter  $\epsilon^2$  [16]. Kinematic acceptances and efficiencies of 100% are assumed for all NLO simulated observables, enabling us to come up with constraints on the corresponding free parameters. Samples are generated by using MC simulation in the framework of MADGRAPH5\_aMC@NLO v2.7.0. Feynman diagrams of the two decays are given in Fig. 1.



**Figure 1:** Exotic Higgs decays to a final state of four leptons with an intermediate  $Z_D$  produced through Kinetic mixing via the hypercharge portal (left) or Higgs mixing via the Higgs portal (right) [4]. The dashed line indicates that mixing of the SM bosons with their dark sector counterparts is occurring in the decays.

## 2. Exotic Higgs decay widths

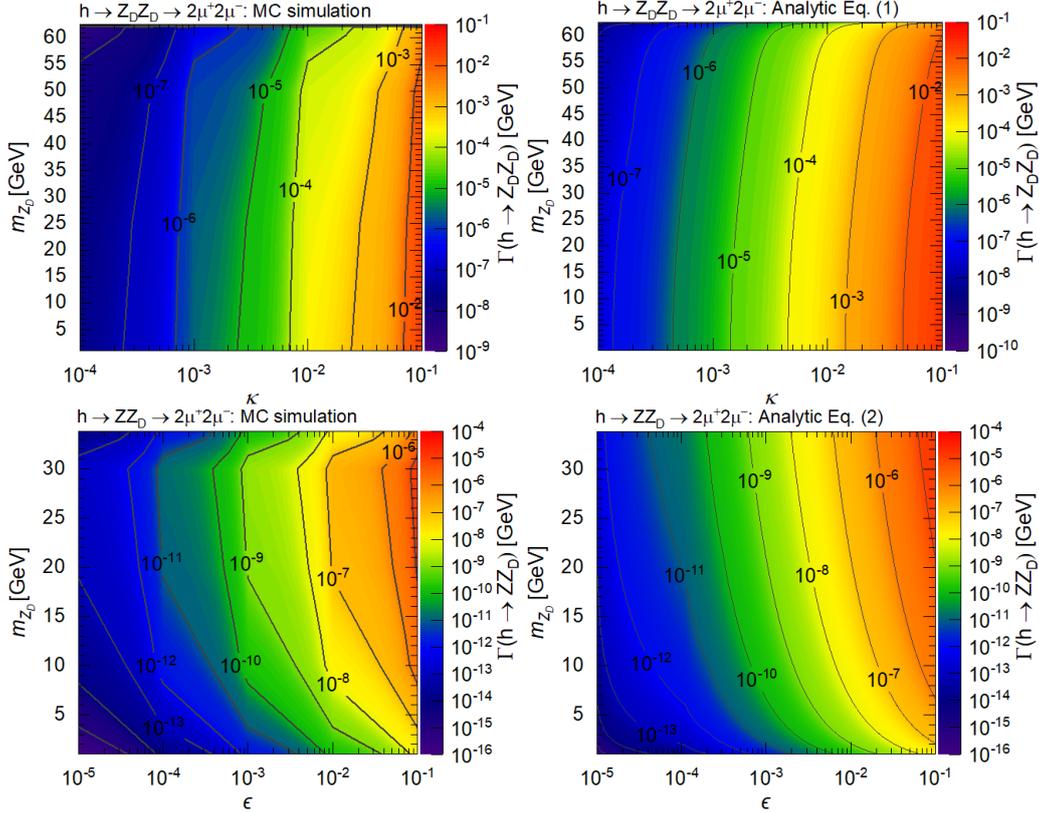
The exotic Higgs decay  $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$  is induced if the HM dominates irrespective of the KM size, while the exotic Higgs decay  $h \rightarrow Z Z_D \rightarrow 2\mu^+ 2\mu^-$  is induced if the KM dominates irrespective of the HM size. The exotic decay width  $\Gamma(h \rightarrow Z_D Z_D)$  to LO in the HM parameter  $\kappa$ , and in turn the corresponding branching fraction and total cross section  $\sigma_{total}$ , is tremendously impacted by  $\kappa$ , less impacted by  $m_{Z_D}$ , and much less impacted by  $m_{h_D}$  as given in Ref. [4] by

$$\Gamma(h \rightarrow Z_D Z_D) = \frac{\kappa^2 v^2}{32\pi m_h} \sqrt{1 - \frac{4m_{Z_D}^2 (m_h^2 + 2m_{Z_D}^2)^2 - 8(m_h^2 - m_{Z_D}^2)m_{Z_D}^2}{m_h^2 (m_h^2 - m_{h_D}^2)^2}}, \quad (1)$$

where  $v = 246 \text{ GeV}$  is the SM Higgs vacuum expectation value (vev). The decay width  $\Gamma(h \rightarrow Z Z_D)$  to LO in  $m_{Z_D}^2/m_Z^2$  is highly impacted by  $\epsilon$  and less impacted by  $m_{Z_D}$  as given in Ref. [4] by

$$\Gamma(h \rightarrow ZZ_D) = \frac{\epsilon^2 \tan^2 \theta_w}{16\pi} \frac{m_{Z_D}^2 (m_h^2 - m_Z^2)^3}{m_h^3 m_Z^2 v^2}, \quad (2)$$

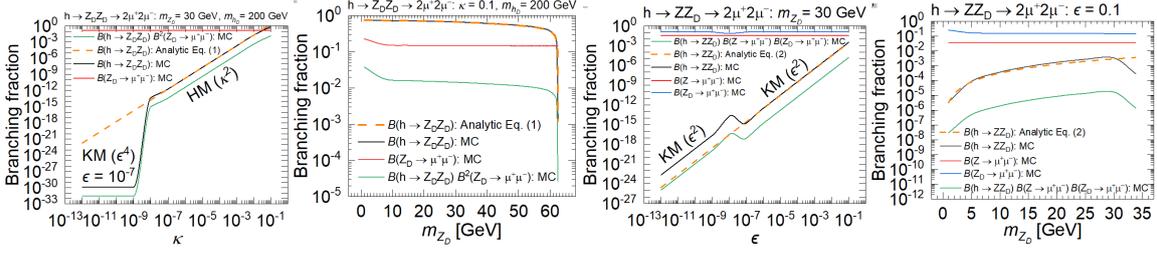
where  $\theta_w$  is the Weinberg mixing angle that is measured as  $\sim 28.75^\circ$  by LHCb [17]. The upper two panels of Fig. 2 are generated to compare the analytical calculation (upper right) as given by Eq. (1) to the simulation (upper left) of  $\Gamma(h \rightarrow Z_D Z_D)$  in a scan over the  $\kappa$ - $m_{Z_D}$  plane, while the lower two panels of this figure are generated for the same sake of comparison for  $\Gamma(h \rightarrow ZZ_D)$ .



**Figure 2:** MC simulation (upper left) against an analytical calculation (upper right) from Eq. (1) of  $\Gamma(h \rightarrow Z_D Z_D)$  in a scan over the  $\kappa$ - $m_{Z_D}$  plane for  $m_{h_D} = 10 \text{ GeV}$  as well as MC simulation (lower left) against an analytical calculation (lower right) from Eq. (2) of  $\Gamma(h \rightarrow ZZ_D)$  in a scan over the  $\epsilon$ - $m_{Z_D}$  plane.

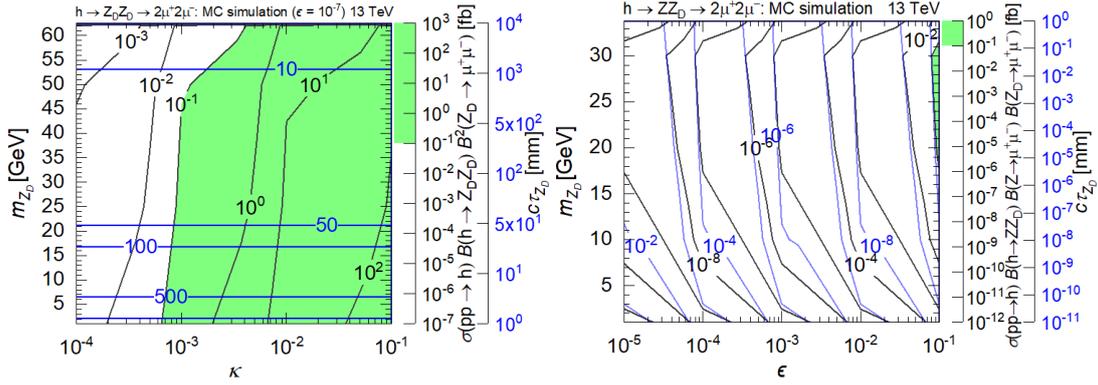
### 3. Branching fractions of exotic Higgs decays to long-lived dark $Z$ boson at the LHC

The branching fraction of  $Z_D$  to light leptons is appreciable for any  $m_{Z_D} < m_h/2$  [4]. Owing to the caption of Fig. 3, the far left panel shows an excellent agreement between the analytical calculation (dashed orange), derived from Eq. (1), and the MC simulation (solid black) of  $B(h \rightarrow Z_D Z_D)$ , which varies directly with  $\kappa^2$  [4, 16] until the HM becomes too small to handle the decay, which then proceeds through KM and varies directly with  $\epsilon^4$  [16]. The later behavior disappears from the LO-based analytic curve (dashed orange) but still exists in the NLO-based simulated curve (solid black). In the middle left panel of this figure,  $B(h \rightarrow ZZ_D)$  is shown to vary directly with  $\epsilon^2$  [4, 16], while the scans over  $m_{Z_D}$  go as low as 1 GeV. The four panels of this figure show that  $B(Z \rightarrow \mu^+ \mu^-)$  and  $B(Z_D \rightarrow \mu^+ \mu^-)$  are unchanged regardless of the scan.



**Figure 3:** MC simulation of  $B(h \rightarrow Z_D Z_D)$ ,  $B(Z_D \rightarrow \mu^+ \mu^-)$ , and the product of  $B(h \rightarrow Z_D Z_D)$  and  $B^2(Z_D \rightarrow \mu^+ \mu^-)$  as well as an analytical calculation of  $B(h \rightarrow Z_D Z_D)$  from Eq. (1) in a scan over  $\kappa$  (far left) and  $m_{Z_D}$  (middle left), and also MC simulation of  $B(h \rightarrow Z Z_D)$ ,  $B(Z \rightarrow \mu^+ \mu^-)$ ,  $B(Z_D \rightarrow \mu^+ \mu^-)$ , and their product as well as an analytical calculation of  $B(h \rightarrow Z Z_D)$  from Eq. (2) in a scan over  $\epsilon$  (middle right) and  $m_{Z_D}$  (far right).

The decay length of  $Z_D$ , denoted by  $c\tau_{Z_D}$ , is impacted by  $\epsilon$  and  $m_{Z_D}$  only and inversely proportional to  $\epsilon^2$  regardless of the exotic decay mode. The value of  $\epsilon = 10^{-7}$  is selected to give a  $c\tau_{Z_D}$  that is measurable within the geometrical size of the Compact Muon Solenoid (CMS) detector and used for generating the left panel of Fig. 4 where  $c\tau_{Z_D}$  is seen to be controlled by  $m_{Z_D}$  only. The value of 0.1 fb is taken as an estimate of the smallest  $\sigma_{total}$  to which the LHC is sensitive.



**Figure 4:** MC simulation showing the contour lines of  $c\tau_{Z_D}$  and  $\sigma_{total}$  for the exotic Higgs decay mode  $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$  for  $m_{h_D} = 10 \text{ GeV}$  (left) and the exotic Higgs decay mode  $h \rightarrow Z Z_D \rightarrow 2\mu^+ 2\mu^-$  (right) in a scan over in a scan over the  $\kappa$ - $m_{Z_D}$  plane and the  $\epsilon$ - $m_{Z_D}$  plane, respectively, for Run 2 of the LHC for which its sensitivity regions are shaded in green.

#### 4. Conclusion

Searches for the dark  $Z$  boson via  $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$  at the LHC in Run 2 are sensitive down to  $\kappa = 7 \times 10^{-4}$  irrespective of the mass acquired by the dark  $Z$  boson. A measurable long-lived dark  $Z$  boson at the LHC has to have a corresponding kinetic mixing parameter of  $\epsilon \sim 10^{-7}$ , while larger kinetic mixing leads to the production of a prompt dark  $Z$  boson. The dark  $Z$  boson is much less likely to be measured in Runs 2 and 3 of the LHC via  $h \rightarrow Z Z_D \rightarrow 2\mu^+ 2\mu^-$  and the chances for the LHC in Run 2 of being sensitive to this decay are limited to the range of  $\epsilon \geq 10^{-1}$ , which restricts the dark  $Z$  boson to being prompt, while the acquired mass by the dark  $Z$  boson has to fall in the range of 18 – 31 GeV if  $\epsilon = 10^{-1}$  and in a wider range if  $\epsilon > 10^{-1}$ .

## References

- [1] P. Galison and A. Manohar, *Two  $Z$ 's or not two  $Z$ 's?*, *Phys. Lett. B* **136** (1984) 279.
- [2] B. Holdom, *Two  $U(1)$ 's and  $\epsilon$  charge shifts*, *Phys. Lett. B* **166** (1986) 196.
- [3] K.R. Dienes, C.F. Kolda, and J. March-Russell, *Kinetic mixing and the supersymmetric gauge hierarchy*, *Nucl. Phys. B* **492** (1997) 104 [arXiv:hep-ph/9610479].
- [4] D. Curtin *et al.*, *Exotic decays of the 125 GeV Higgs boson*, *Phys. Rev. D* **90** (2014) 075004 [arXiv:1312.4992].
- [5] H. Davoudiasl, H.-S. Lee, I. Lewis, and W.J. Marciano, *Higgs decays as a window into the dark sector*, *Phys. Rev. D* **88** (2013) 015022 [arXiv:1304.4935].
- [6] S. Gopalakrishna, S.Jung, and J.D. Wells, *Higgs boson decays to four fermions through an abelian hidden sector*, *Phys. Rev. D* **78** (2008) 055002 [arXiv:0801.3456].
- [7] C.-F. Chang, E. Ma, and T.-C. Yuan, *Multi lepton Higgs Decays through the Dark Portal*, *JHEP* **03** (2014) 054 [arXiv:1308.6071].
- [8] A. Falkowski and R. Vega-Morales, *Exotic Higgs decays in the golden channel*, *JHEP* **12** (2014) 037 [arXiv:1405.1095].
- [9] M. Pospelov, *Secluded  $U(1)$  below the weak scale*, *Phys. Rev. D* **80** (2009) 095002 [arXiv:0811.1030].
- [10] G. Bennett *et al.* (Muon  $g-2$  Collaboration), *Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL*, *Phys. Rev. D* **73** (2006) 072003 [arXiv:hep-ex/0602035].
- [11] B. Abi *et al.* (Muon  $g-2$  Collaboration), *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, *Phys. Rev. Lett.* **126** (2021) 141801 [arXiv:2104.03281].
- [12] N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, and N. Weiner, *A Theory of Dark Matter*, *Phys. Rev. D* **79** (2009) 015014 [arXiv:0810.0713].
- [13] M. Pospelov and A. Ritz, *Astrophysical Signatures of Secluded Dark Matter*, *Phys. Lett. B* **671** (2009) 391 [arXiv:0810.1502].
- [14] D.P. Finkbeiner and N. Weiner, *Exciting Dark Matter and the INTEGRAL/SPI 511 keV signal*, *Phys. Rev. D* **76** (2007) 083519 [arXiv:astro-ph/0702587].
- [15] P. Fayet, *Light spin 1/2 or spin 0 dark matter particles*, *Phys. Rev. D* **70** (2004) 023514 [arXiv:hep-ph/0403226].
- [16] D. Curtin, R. Essig, S. Gori, and J. Shelton, *Illuminating dark photons with high-energy colliders*, *JHEP* **02** (2015) 157 [arXiv:1412.0018].
- [17] R. Aaij *et al.* (The LHCb Collaboration), *Measurement of the forward-backward asymmetry in  $Z/Y^* \rightarrow \mu^+ \mu^-$  decays and determination of the effective weak mixing angle*, *JHEP* **11** (2015) 190 [arXiv:1509.07645].