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Event characterization of dark bosons via exotic Higgs decays with final states of displaced dimuons in high luminosity era of the LHC

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We investigate the potential reach of a search for a long-lived/prompt dark vector boson Z_D, also called dark Z, and a prompt dark Higgs boson h_D through exotic decays of the observed Higgs boson h into either $Z_D Z_D$, $h_D h_D$, or $Z Z_D$ with Z being the hypercharge gauge boson. The Z_D production through the Higgs portal is completed via one of two mechanisms, kinetic mixing of Z_D with Z and the mixing of h_D with h. All production modes of h are considered, while the branching fractions are calculated in Monte Carlo simulation using the MadGraph5_aMC@NLO v2.7.2 framework. We focus on a final state of multiple dimuons, displaced up to 7500 mm, where the muons can be reconstructed without vertex constraint using data from ATLAS and CMS detectors to be collected in Run 3. Integrated luminosities of 137, 300, and 3000 fb^{-1} for Run 2, Run 3, and high luminosity run (HL-LHC), respectively, are used for estimating the expected search sensitivity of the Large Hadron Collider to each of the decay modes.

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1. Introduction

The observed Higgs boson h plays a significant role in the Standard Model (SM) and is believed to impact a wide range of new physics beyond the SM (BSM). It is assumed that h is responsible for breaking the electroweak symmetry and that there is an additional $U(1)_D$ dark gauge symmetry allowing h to decay to new particles such as dark Higgs and dark vector bosons, usually referred to as h_D and Z_D, respectively. The only possible interaction of Z_D with the SM sector is through its kinetic mixing (KM) with Z boson, while if the Higgs mixing (HM) exists, h_D will have a renormalizable coupling to h. The high integrated luminosities $\mathcal{L}$'s achieved by the Large Hadron Collider (LHC) offer a promising opportunity into the search for hidden sectors through these two portals.

Muons are efficiently identified in ATLAS and CMS detectors, and hence we assume the muons can be reconstructed without vertex constraint with kinematic acceptances and efficiencies of 100%. This simplifies our two-dimensional scans over the relevant free parameters of the dark sector using all the current NLO simulated observables and enables us to characterize exotic decays of h by coming up with the most stringent constraints on such free parameters, which are the KM parameter ϵ, HM parameter κ, and the acquired masses by Z_D and h_D, denoted by m_{Z_D} and m_{h_D}, respectively. Feynman diagrams of the three exotic decay modes are given in Fig. 1. In this context, a mass of m_h = 125.09 GeV is considered [1], which is assumed to be produced at the LHC through the production modes of gluon-gluon fusion (ggF), vector-boson fusion (VBF), VH (i.e., W^+h, W^-h, $\ell^+\nu h$, $\ell^-\overline{\nu}h$, Zh, $\ell\bar{\ell}h$, $\nu\overline{\nu}h$), $t\bar{t}h$, th, and $\bar{t}h$ with a production cross section of 55.88 and 63.06 pb for 13 and 14 TeV, respectively, which are calculated to either next-to-leading order with QCD corrections included (NLO QCD), next-to-next-to-leading order with QCD corrections included (N^{2}LO QCD), or next-to-next-to-next-to-leading order with QCD corrections included (N^{3}LO QCD), combined or not combined with next-to-leading order with electroweak corrections included (NLO EW), depending on the production mode [1]. The simulated samples for this work are generated by applying Monte Carlo (MC) simulation using the framework of MadGraph5_aMC@NLO v2.7.2 with Hidden Abelian Higgs Model (HAHM) [2].

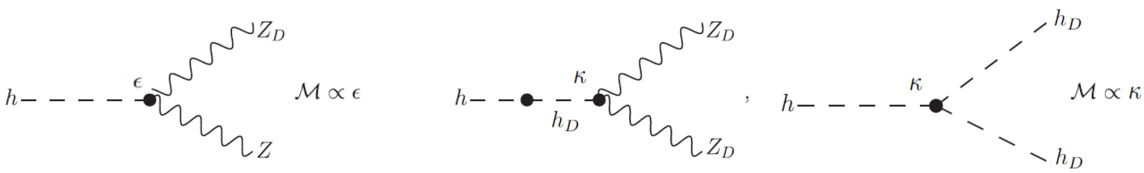

Figure 1: Feynman diagrams for the dominant exotic Higgs decays via KM (left) and HM (middle and right) with $\mathcal{M}$ being the Higgs decay matrix element and ϵ and κ being the kinetic and Higgs mixing parameters, respectively [2]. The vertex hh_DZ_D exists but is highly suppressed by each of the two types of mixing.

2. Sensitivity of the LHC to the searches for long-lived dark vector bosons

The observed Higgs boson h is considered to be produced through all possible production modes with production cross sections of 55.88 and 63.06 pb for 13 and 14 TeV, respectively. The values of 0.073, $0.0\overline{3}$, and $0.00\overline{3}$ fb are taken as the smallest σ_{total} to which the LHC is sensitive based on 10 events at least to be measured in Run 2, Run 3, and HL-LHC with a full $\mathcal{L}$'s of 137, 300, and 3000 fb^{-1}, respectively, and accordingly the contour lines of σ_{total} are shown in all panels of Fig. 2 where σ_{total} equals to $\sigma(pp \to h)\ \mathcal{B}(h \to ZZ_D)\ \mathcal{B}(Z \to \mu^+\mu^-)\ \mathcal{B}(Z_D \to \mu^+\mu^-)$, $\sigma(pp \to h)\ \mathcal{B}(h \to Z_D Z_D)\ \mathcal{B}^2(Z_D \to \mu^+\mu^-)$, and $\sigma(pp \to h)\ \mathcal{B}(h \to h_D h_D)\ \mathcal{B}^2(h_D \to Z_D Z_D)\ \mathcal{B}^4(Z_D \to \mu^+\mu^-)$ in the case of $h \to ZZ_D \to 2\mu^+2\mu^-$, $h \to Z_D Z_D \to 2\mu^+2\mu^-$, and $h \to h_D h_D \to 4Z_D \to 4\mu^+4\mu^-$, respectively. The contour lines of $c\tau_{Z_D}$ and $c\tau_{h_D}$ are superimposed on those of σ_{total} with any consecutive lines separated by one order of magnitude. The chosen value of $\epsilon = 10^{-7}$ and the m_{Z_D} region of $1 - m_h/2 \approx 62.5$ GeV correspond to $c\tau_{Z_D}$ in the range of $10 - 2000$ mm for $h \to Z_D Z_D \to 2\mu^+2\mu^-$ as seen in the middle column of Fig. 2.

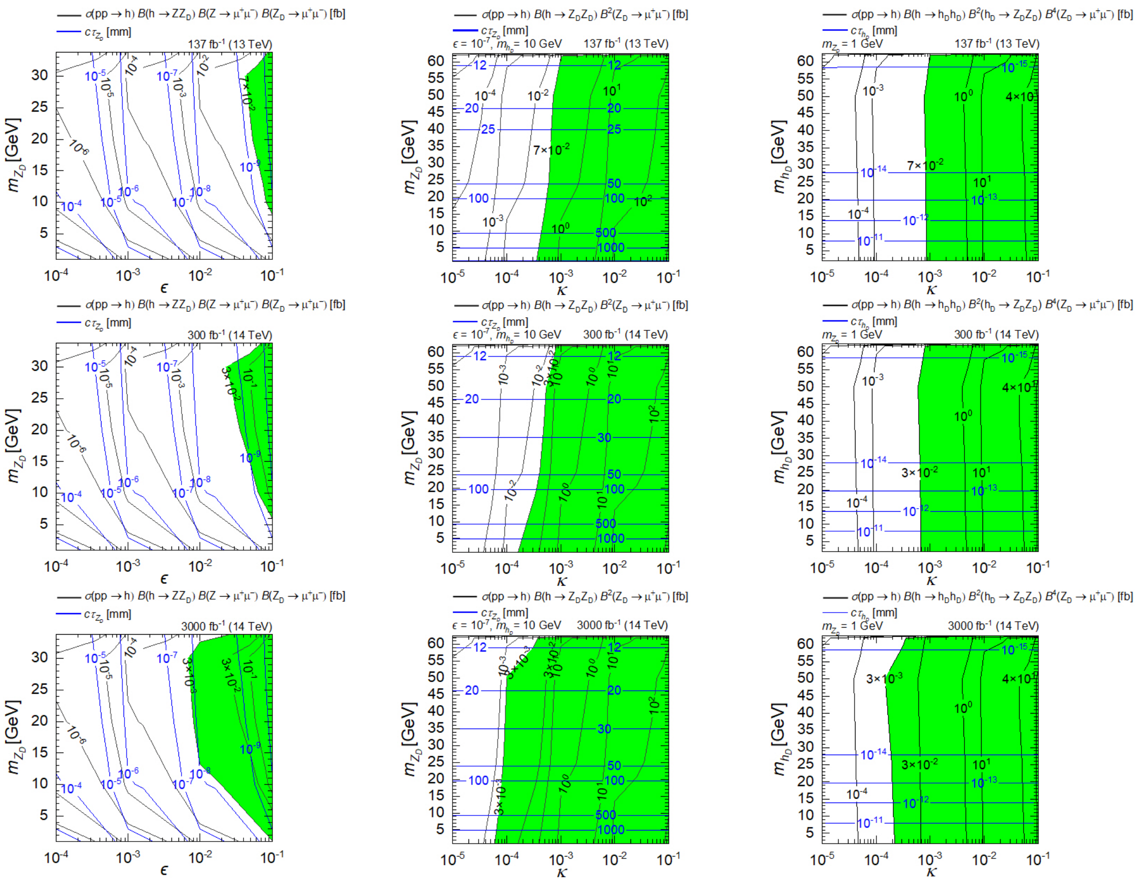

Figure 2: MC simulations showing the contour lines of σ_{total} (black) and $c\tau_{Z_D}$ (or $c\tau_{h_D}$) (blue) for $h \to ZZ_D \to 2\mu^+2\mu^-$ (left column), $h \to Z_D Z_D \to 2\mu^+2\mu^-$ (middle column), and $h \to h_D h_D \to 4Z_D \to 4\mu^+4\mu^-$ (right column) in a scan over the ϵ-m_{Z_D}, the κ-m_{Z_D}, and the κ-m_{h_D} planes, respectively, for Run 2 (top row), Run 3 (middle row), and HL-LHC (bottom row) with sensitivity regions shaded in green.

3. Lifetime of dark bosons and impact on Γ_W by the hidden sector via $h \to Z_D Z_D$

The decay length $c\tau_{Z_D}$ via $h \to ZZ_D$ and $h \to Z_D Z_D$ is fully described by the scan over the ϵ-m_{Z_D} plane, which is given by the left column of Fig. 2 and the left panel of Fig. 3, respectively, where $c\tau_{Z_D}$ is seen to be inversely proportional to ϵ^2 and m_{Z_D}. The inverse proportionality between $c\tau_{Z_D}$ and m_{Z_D} is noticed by the middle column of Fig. 2 where a smaller m_{Z_D} decays to as few as eight particles, d, u, s quarks, e^-, μ^-, ν_e, ν_μ, and ν_τ and in turn has a narrower decay width and longer $c\tau_{Z_D}$, while a heavier Z_D can produce up to three more particles, c, b, and τ, leading to a wider decay width and shorter $c\tau_{Z_D}$. On the other hand, the decay length $c\tau_{h_D}$ via $h \rightarrow h_D h_D$ is fully described by the scan over the κ-m_{h_D} plane, which is given by the right column of Fig. 2. The decay width of W boson Γ_W is found to change by $\sim 2\%$ in the scan over the ϵ-m_{Z_D} plane where it is maximal for the highest values of m_{Z_D} and ϵ, and vice versa as seen in the right panel of Fig. 3.

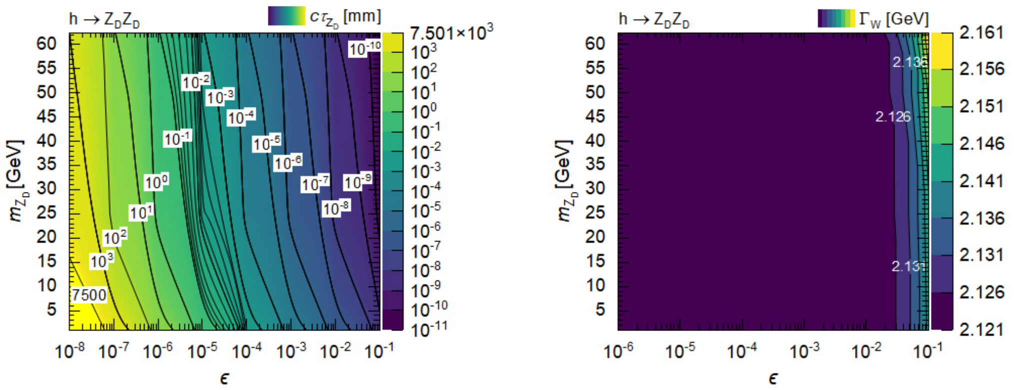

Figure 3: MC simulation of $c\tau_{Z_D}$ (left) and Γ_W (right) as scanned over the ϵ-m_{Z_D} plane for $h \rightarrow Z_D Z_D$.

4. Conclusion

The LHC is found to be more sensitive to $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ and $h \rightarrow h_D h_D \rightarrow 4Z_D \rightarrow 4\mu^+ 4\mu^-$, irrespective of the mass acquired by Z_D and h_D, than $h \rightarrow ZZ_D \rightarrow 2\mu^+ 2\mu^-$. New constraints on KM and HM parameters are obtained for the first two decay modes in Run 2, Run 3, and HL-LHC as down to ($\kappa = 3.5 \times 10^{-4}$, 1.5×10^{-4}, and 6.0×10^{-5}) and ($\kappa = 8.5 \times 10^{-4}$, 6.5×10^{-4}, and 2.0×10^{-4}), respectively. For $h \rightarrow ZZ_D \rightarrow 2\mu^+ 2\mu^-$, the constraints are down to $\epsilon = 4.0 \times 10^{-2}$ for the m_{Z_D} range of $8.5 - 33.8$ GeV in Run 2, $\epsilon = 2.0 \times 10^{-2}$ for the m_{Z_D} range of $6.0 - 33.8$ GeV in Run 3, and $\epsilon = 7.0 \times 10^{-3}$ for the m_{Z_D} range of $1.0 - 33.8$ GeV in HL-LHC. The LHC is found to be sensitive to the production of prompt or long-lived Z_D's ($10^{-10} - 7500$ mm depending on ϵ and m_{Z_D}) via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$, while it is sensitive only to the production of prompt Z_D's ($10^{-10} - 10^{-8}$ mm) and prompt h_D's ($10^{-15} - 10^{-10}$ mm) via $h \rightarrow ZZ_D \rightarrow 2\mu^+ 2\mu^-$ and $h \rightarrow h_D h_D \rightarrow 4Z_D \rightarrow 4\mu^+ 4\mu^-$, respectively.

Acknowledgments

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