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Modeling exotic Higgs decays to vector bosons with displaced dimuons in the final states

Tamer Elkafrawy* and Marcus Hohlmann

Florida Institute of Technology

‘Email:
telkafrawy@fit.edu
tamer.elkafrawy@cern.ch

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Exotic Higgs Decays with Z-Z_D + h-h_D Mixing

Objective:
The goal of this work is to search for a long-lived on-shell dark boson Z_D via the exotic Higgs decay h→Z_DZ_D→2μ^+2μ^- . We are interested in the final state of two dimuons, displaced by 1–7500 mm. In this context, we inspect the exotic Higgs decay h→Z_DZ_D→2μ^+2μ^- for equal strength of kinetic and Higgs mixings.

The two exotic decays, h→Z_DZ_D→2μ^+2μ^- (shown) and h→h_Dh_D→4Z_D→4μ^+4μ^- (not shown), are induced and about equally possible if Higgs mixing (HM) dominates.
Exotic Higgs Decays with Z-Z_D + h-h_D Mixing

**Vector Portal:** Dark boson with broken U(1)’ group mixes through hypercharge portal with photon and Z boson.

Lagrangian with relevant gauge terms indicated

\[
\mathcal{L} \supset -\frac{1}{4} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} - \frac{1}{4} \hat{Z}_{D\mu\nu} \hat{Z}^{\mu\nu}_D + \frac{1}{2} \frac{\epsilon}{\cos\theta} \hat{Z}_{D\mu\nu} \hat{B}^{\mu\nu} + \frac{1}{2} m_{D,0}^2 \hat{Z}^\mu_D \hat{Z}_{D\mu}
\]

**Higgs Portal:** U(1)’ is broken by Higgs mechanism where the dark Higgs mixes with the SM Higgs.

Renormalizable potential for SM and dark Higgs fields

\[
V_0(H, S) = -\mu^2 |H|^2 + \lambda |H|^4 - \mu^2_S |S|^2 + \lambda_S |S|^4 + \kappa |S|^2 |H|^2
\]

H = SM Higgs real scalar doublet
S = dark Higgs real scalar singlet

Higgs mixing parameter

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The current samples are generated by applying Monte Carlo (MC) simulation using the framework of MadGraph5_aMC@NLO v2.7.0.

Keys of acronyms used in this presentation:
Standard-Model (SM) Higgs boson = $h$
Dark Higgs boson = $h_D$
Dark boson = $Z_D$
Kinetic mixing = KM
Higgs mixing = HM
Dominant = ON
Negligible = OFF
Scan over equal strength of kinetic and Higgs mixings
Is the LHC sensitive to measure $Z_D$ for any equal strength of $KM$ and $HM$?

$Z_D$ could have been produced via $h \rightarrow Z_D Z_D$ (black curve) and measured indirectly via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ (red curve) at the LHC in Run 2 only if $HM$ is dominant ($\epsilon = k \geq 6 \times 10^{-4}$) where an acceptance of 100% is assumed.

However, changing $\epsilon$ from being equal to $k$ will not change the constraint of $k \geq 6 \times 10^{-4}$.

$\sigma(pp \rightarrow h) = 48$ pb for ggF production channel, calculated to $N^3LO$ QCD + NLO EW.

The LHC is assumed to be sensitive down to 0.073 fb based on 10 events to be measured for $L_{int} = 137$ fb$^{-1}$. 

Scan over kinetic $\epsilon$ and Higgs $k$ mixing parameters, $\epsilon = k$
Scan over kinetic $\epsilon$ and Higgs $k$ mixing parameters, $\epsilon = k$

Expected produced events at the LHC in Run 2 as impacted by equal strength of KM and HM

If 0.1 is taken as the highest possible value of $k$ and $\epsilon$, a large number (up to $10^5$ events) could have been produced via $h \rightarrow Z_DZ_D \rightarrow 2\mu^+2\mu^-$ at the LHC in Run 2 only if HM is dominant ($\epsilon = k \geq 6 \times 10^{-4}$) where an acceptance of 100% is assumed.

However, changing $\epsilon$ from being equal to $k$ will not change the constraint of $k \geq 6 \times 10^{-4}$.

Sensitivity of the LHC is assumed to be down to 10 events.
Which branching fraction impacts the cross section the most in the scan over equal strength of KM and HM?

\[ B(h \rightarrow Z_D Z_D) \] varies with \( k^2 \) regardless of \( \epsilon \)'s value (however, here \( \epsilon = k \)) until HM strength becomes too small to handle the decay (here, \( k = 10^{-9} \)), then KM takes over and \( B(h \rightarrow Z_D Z_D) \) starts to vary with \( \epsilon^4 \).

The branching fraction \( B(Z_D \rightarrow \mu^+ \mu^-) \) is unchanged for an equal strength of KM and HM over the range of \( 10^{-12} – 10^{-1} \).
How will the decay width of SM Higgs be impacted if it decays to $Z_DZ_D$?

The total decay width of SM Higgs is unchanged for an equal strength of KM and HM in the range of $10^{-12}$–$10^{-1}$.

The partial decay width of $h \to Z_DZ_D$ varies as $k^2$ regardless of $\epsilon$’s value (however, here $\epsilon = k$) in the range of $10^{-8}$–$10^{-1}$ until HM strength becomes too small to handle the decay (here, $k = 10^{-9}$), then KM takes over, and partial decay width of $h \to Z_DZ_D$ starts to vary as $\epsilon^4$ over the range of $10^{-12}$–$10^{-9}$.
How does the SM Higgs lifetime change for different equal strengths of KM and HM?

Expected new lifetime of SM Higgs decreases by the increase of an equal strength of KM and HM over the range of $\epsilon = k \geq 6 \times 10^{-4}$ and is unchanged otherwise (i.e., $\epsilon = k < 6 \times 10^{-4}$).

The minor impact of HM on lifetime of the SM Higgs makes sense since greater HM means it is more likely for SM Higgs to decay to two $Z_\Delta$'s, which implies a larger decay width, and in turn a shorter lifetime, of the SM Higgs.
What is the contribution of the partial decay width of $Z_D \rightarrow \mu^+\mu^-$ to the total decay width of $Z_D$?

The partial decay width of $Z_D \rightarrow \mu^+\mu^-$ is lower by one order of magnitude than the total decay width of $Z_D$ for an equal strength of $KM$ and $HM$ in the range of $10^{-12}$–$10^{-1}$.

Although $\epsilon = k$ in this study, the total decay width of $Z_D$ and the partial decay width of $Z_D \rightarrow \mu^+\mu^-$ vary with $\epsilon^2$ regardless of $k$'s value.
Is $Z_D$ lifetime impacted by HM Strength?

Although $\epsilon = k$ in this study, the lifetime of $Z_D$ varies inversely with $\epsilon^2$ regardless of $k$'s value over the range of $10^{-12} - 10^{-1}$.

Prompt (defined here as <1 mm) and LLP (1–7500 mm) regions of interest at the LHC are shown on the plot.
How is the cross section related to the $Z_D$ lifetime in the scan over equal strength of KM and HM?

If kinetic and Higgs mixings are equal by nature, the constraint of $\epsilon = k \geq 6 \times 10^{-4}$ must be verified so that the LHC in Run 2 can be sensitive to the indirect measurement of $Z_D$ via $h \rightarrow Z_DZ_D \rightarrow 2\mu^+2\mu^-$. If nature imposes an equal strength of kinetic and Higgs mixings, only a prompt (and not long-lived) $Z_D$ can be measured at the LHC in Run 2.
Summary

If kinetic and Higgs mixings are equal by nature, the constraint of $\epsilon = k \geq 6 \times 10^{-4}$ must be verified so that the LHC in Run 2 can be sensitive to the indirect measurement of $Z_D$ via $h\rightarrow Z'_D Z'_D \rightarrow 2\mu^+ 2\mu^-$. 

If nature imposes an equal strength of kinetic and Higgs mixings, only a prompt ($< 10^{-6}$ mm) (and not long-lived) $Z_D$ can be measured at the LHC in Run 2.
Future Perspectives

Perform an inspection of cross section and lifetime of $Z_D$ for the exotic Higgs decay modes:

- $h \rightarrow h_D h_D \rightarrow 4Z_D \rightarrow 4\mu^+4\mu^-$ for dominant HM
- $h \rightarrow ZZ_D \rightarrow 2\mu^+2\mu^-$ for dominant KM

Investigate kinematics of the final states of displaced dimuons for fully reconstructed samples for the three exotic Higgs decay modes:

- $h \rightarrow Z_D Z_D \rightarrow 2\mu^+2\mu^-$ for dominant HM
- $h \rightarrow h_D h_D \rightarrow 4Z_D \rightarrow 4\mu^+4\mu^-$ for dominant HM
- $h \rightarrow ZZ_D \rightarrow 2\mu^+2\mu^-$ for dominant KM
References

For the UFO model used to produce the current samples:

For the current project:
4) The current presentation of LLP9 can be downloaded from ([https://indico.cern.ch/event/980853/timetable/](https://indico.cern.ch/event/980853/timetable/))
5) “Search for the dark boson through exotic Higgs decays,” Tamer Elkafrawy and Marcus Hohlmann, LHCP2021 Conference, June 7–12, 2021, ([upcoming](https://indico.cern.ch/event/905399/contributions/4335593/)).