Ninth Workshop of the LLP Community (LLP9)

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

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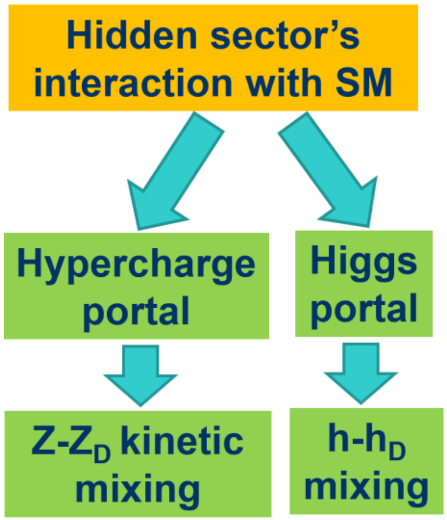
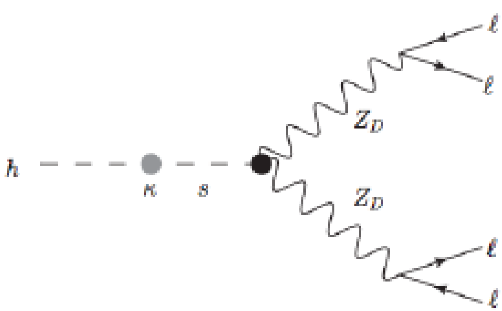
May 27, 2021

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 $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$. We are interested in the final state of two dimuons, displaced by 1–7500 mm. In this context, we inspect the exotic Higgs decay $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ for equal strength of kinetic and Higgs mixings.



Feynman diagram for Higgs boson decay via Higgs mixing mechanism [Ref. 2]

The two exotic decays, $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ (shown) and $h \rightarrow h_D h_D \rightarrow 4Z_D \rightarrow 4\mu^+ 4\mu^-$ (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

Kinetic mixing parameter

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

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

Higgs mixing parameter

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

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

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

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

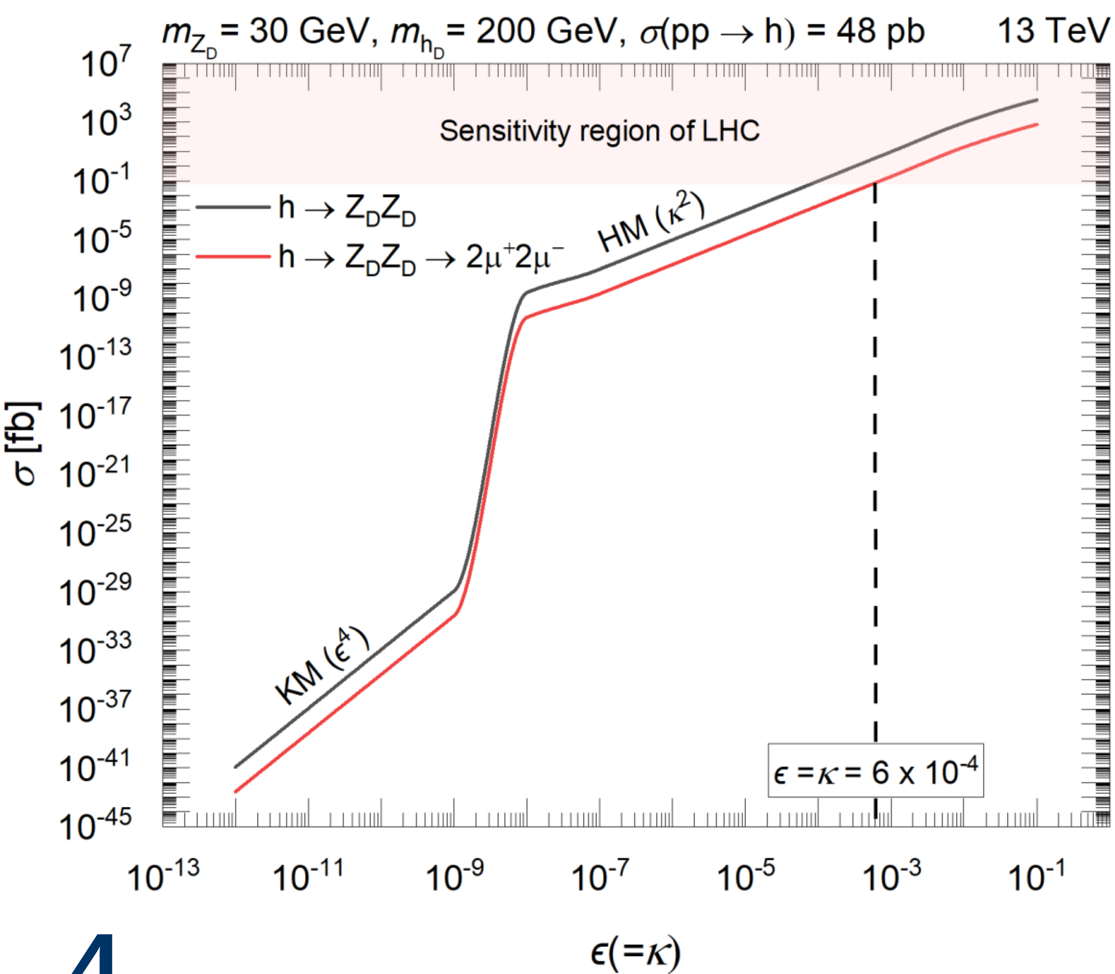
Keys of acronyms used in this presentation:

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

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

Is the LHC sensitive to measure Z_D for any equal strength of KM and HM?

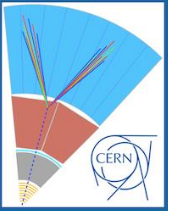


Z_D could have been produced via $h \to Z_D Z_D$ (black curve) and measured indirectly via $h \to Z_D Z_D \to 2\mu^+ 2\mu^-$ (red curve) at the LHC in Run 2 only if HM is dominant ($\epsilon = k \geq 6\text{x}10^{-4}$) where an acceptance of 100% is assumed.

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

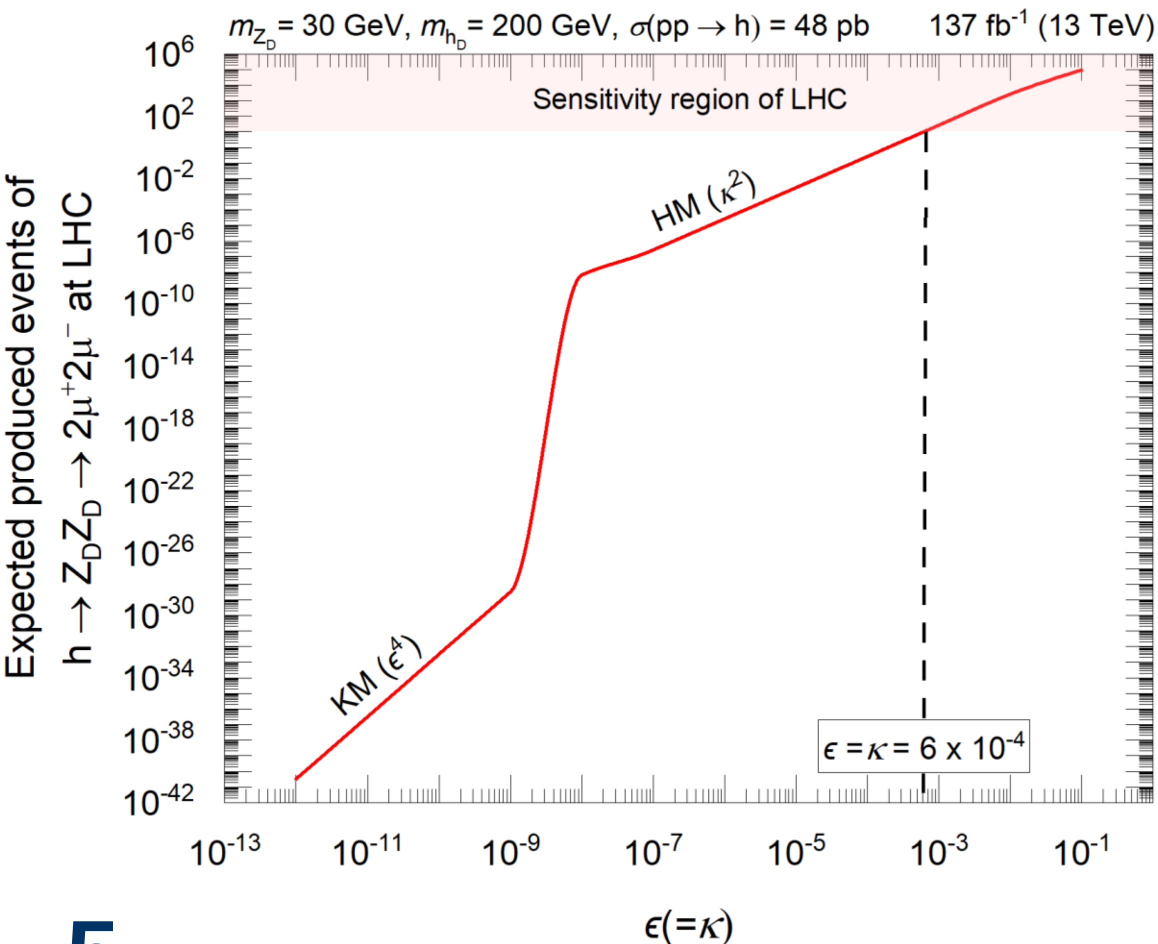
$\sigma(pp \to h)$ = 48 pb for ggF production channel, calculated to N^3LO QCD + NLO EW.

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 ϵ 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

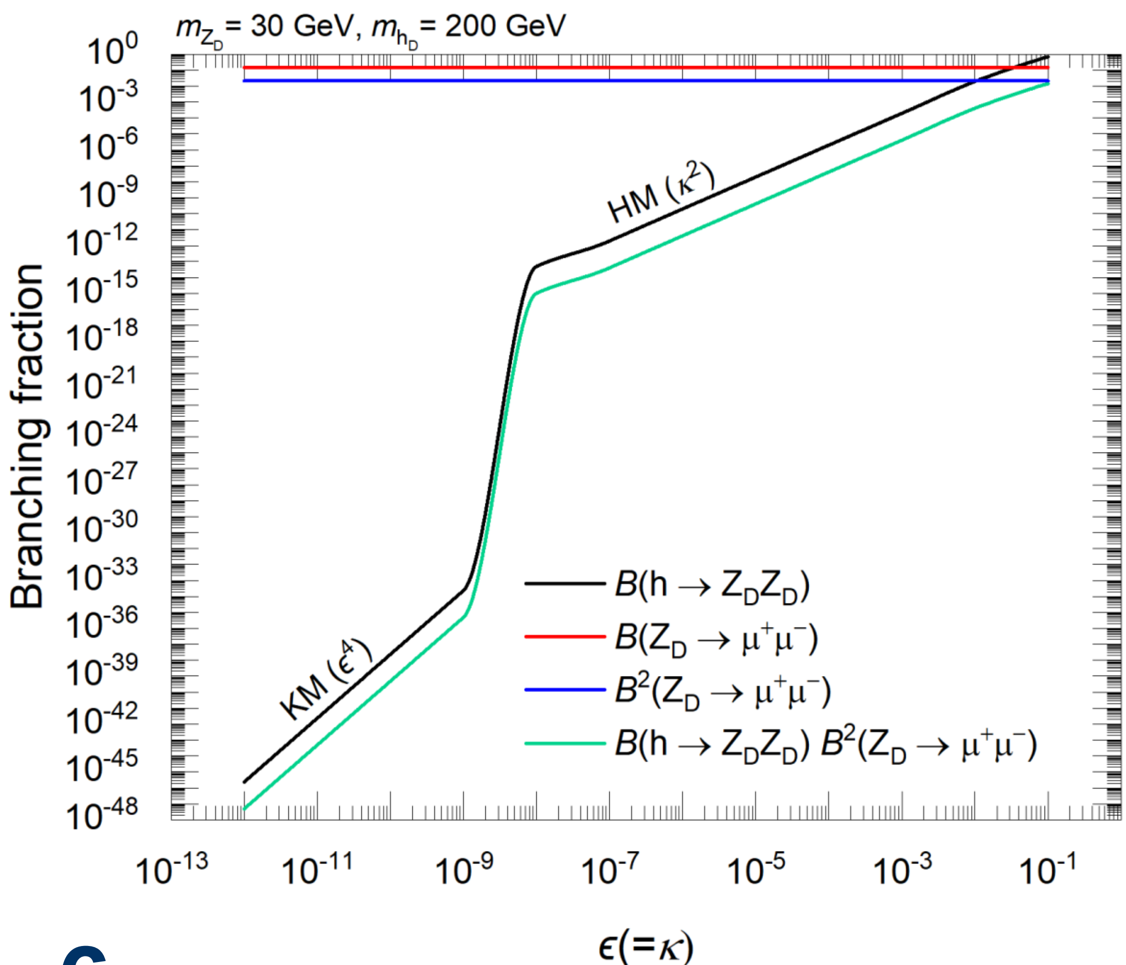


If 0.1 is taken as the highest possible value of k *and* ϵ, a large number (up to 10^5 events) could have been produced via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ at the LHC in Run 2 only if HM is dominant ($\epsilon = k \geq 6 \times 10^{-4}$) where an acceptance of 100% is assumed.

However, changing ϵ 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?



$B(h \to Z_D Z_D)$ varies with k^2 regardless of ϵ'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 $B(h \to Z_D Z_D)$ starts to vary with ϵ^4.

The branching fraction $B(Z_D \to \mu^+\mu^-)$ is unchanged for an equal strength of KM and HM over the range of 10^{-12}–10^{-1}.

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

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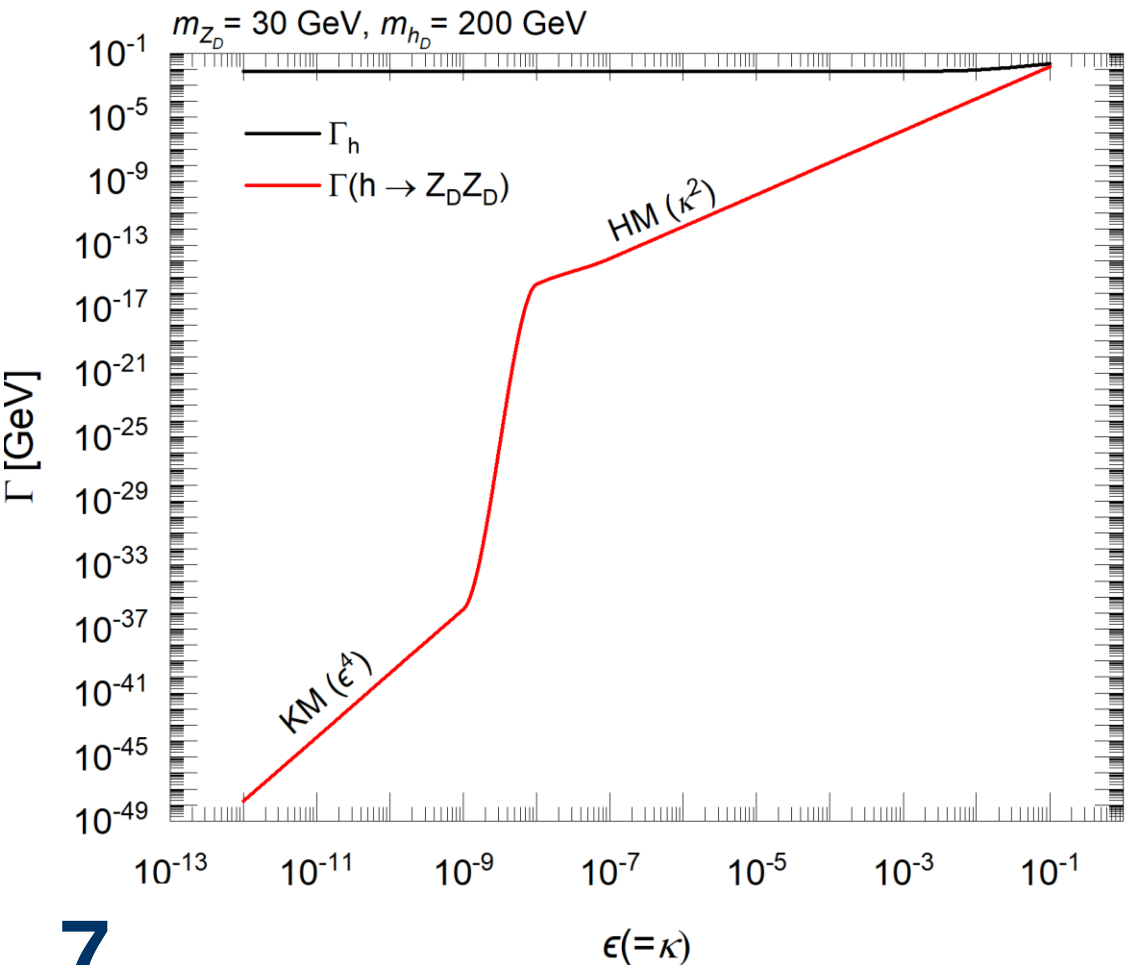
How will the decay width of SM Higgs be impacted if it decays to $Z_D Z_D$?

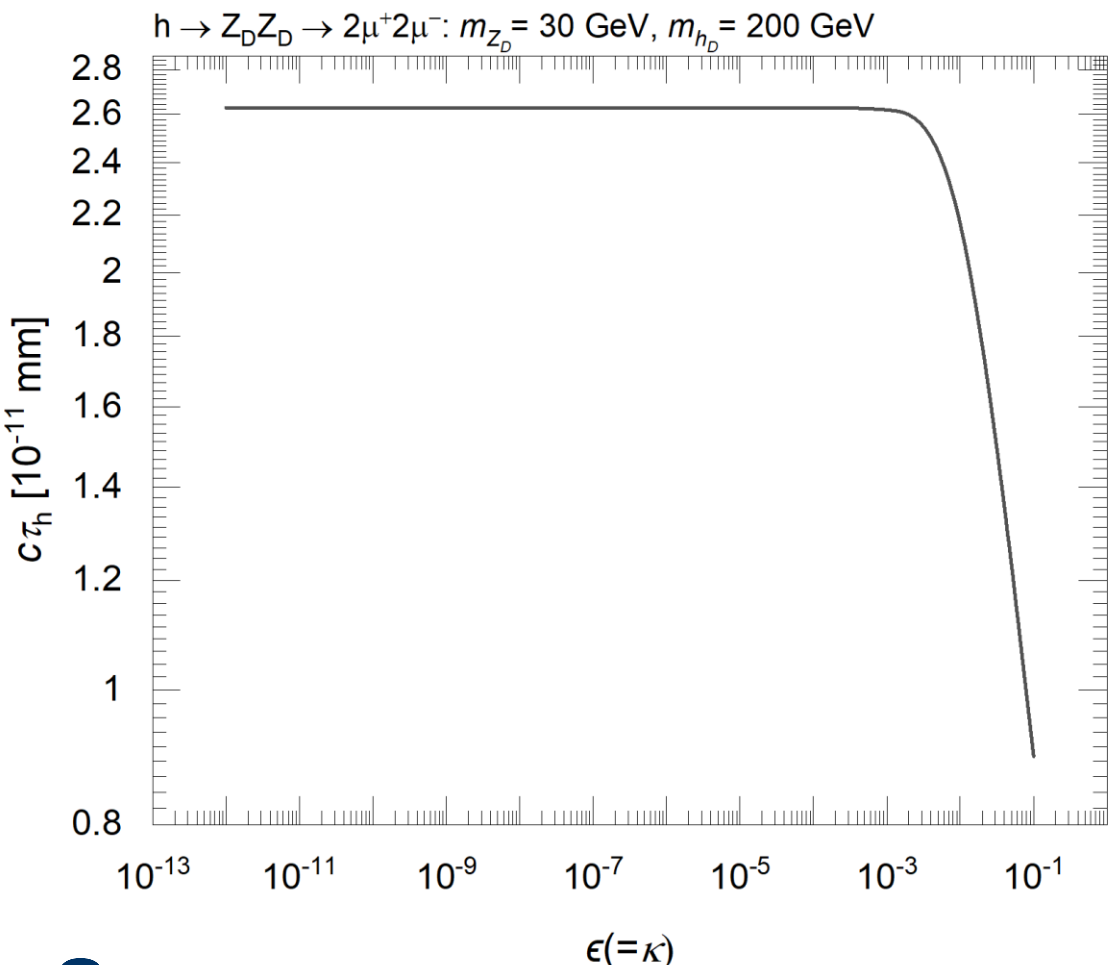


The total decay width of SM Higgs is unchanged for an equal strength of KM and HM in the range of 10^{-12}–10^{-1}.

The partial decay width of $h \rightarrow Z_D Z_D$ varies as k^2 regardless of ϵ'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 $h \rightarrow Z_D Z_D$ starts to vary as ϵ^4 over the range of 10^{-12}–10^{-9}.

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

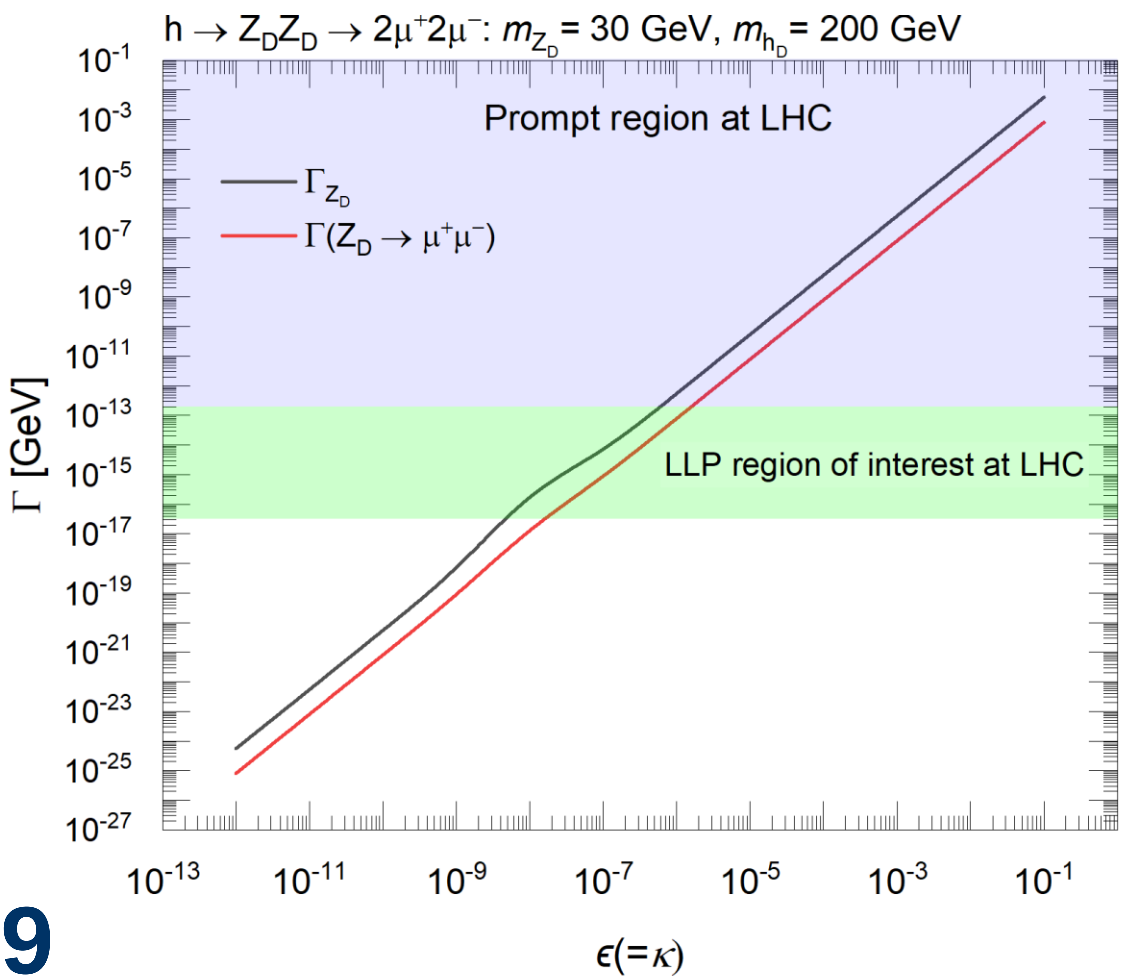
How does the SM Higgs lifetime change for different equal strengths of KM and HM?



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

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_D's, which implies a larger decay width, and in turn a shorter lifetime, of the SM Higgs.

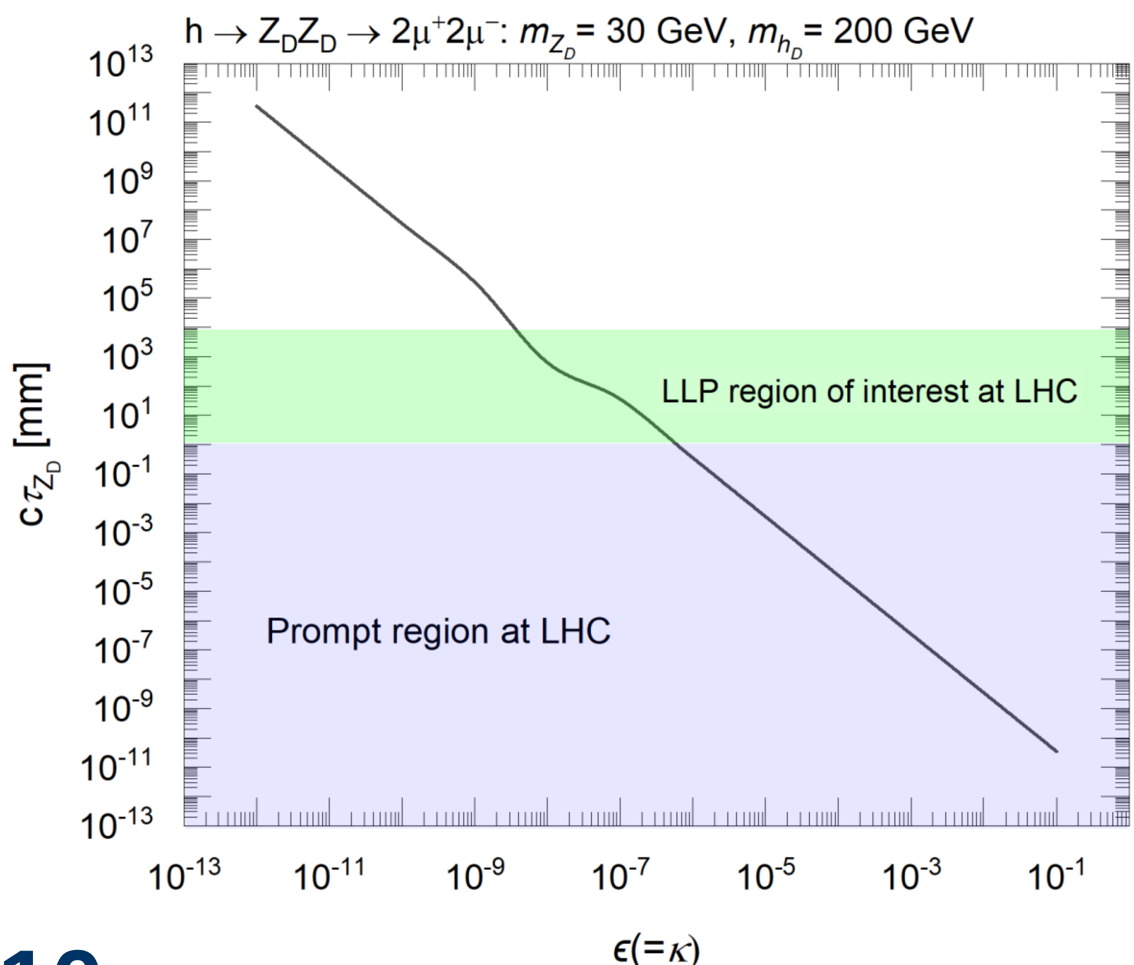
What is the contribution of the partial decay width of $Z_D \rightarrow \mu^+\mu^-$ to the total decay width of Z_D?



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 ϵ^2 regardless of k's value.

Is Z_D lifetime impacted by HM Strength?

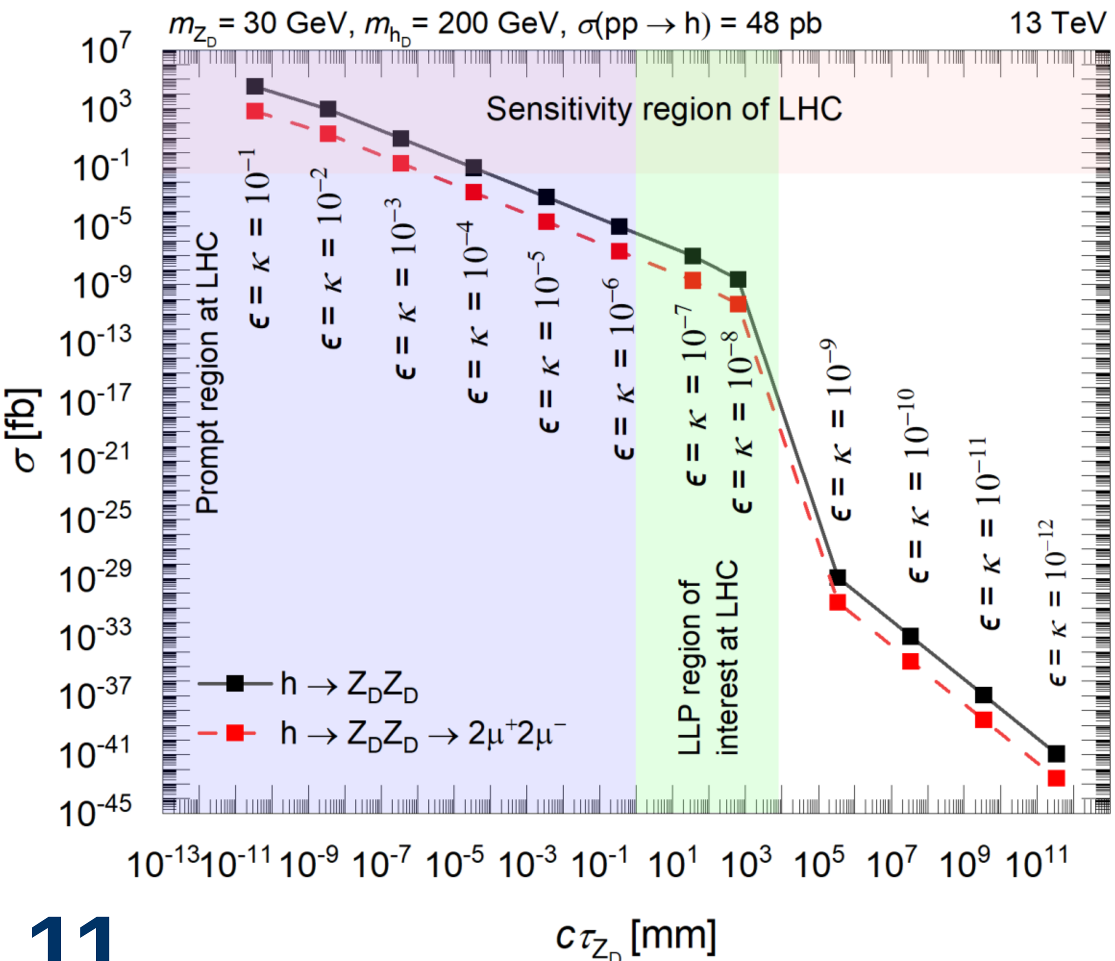


Although $\epsilon = k$ in this study, the lifetime of Z_D varies inversely with ϵ^2 regardless of k's value over the range of 10^{-12}–10^{-1}.

Prompt (defined here as <1 mm) and LLP (1–7500 mm) regions of interest at the LHC are shown on the plot.

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

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 $\epsilon = k \geq 6\times10^{-4}$ 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 (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 $\epsilon = k \geq 6\text{x}10^{-4}$ 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:

1) "Exotic decays of the 125 GeV Higgs boson," David Curtin *et al.*, *Phys. Rev. D* **90**, 075004 (2014) (10.1103/PhysRevD.90.075004).
2) "Illuminating dark photons with high-energy colliders," David Curtin *et al.*, *Journal of High Energy Physics* **2015**, 157 (2015) (10.1007/JHEP02(2015)157).

For the current project:

3) “Study of Higgs and Vector Portals to Dark Matter," Tamer Elkafrawy *et al.,* APS April Meeting, April 17–20, 2021, (https://absuploads.aps.org/presentation.cfm?pid=19067).
4) The current presentation of LLP9 can be downloaded from (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/).