APS April Meeting 2021

Study of Higgs and Vector Portals to Dark Matter

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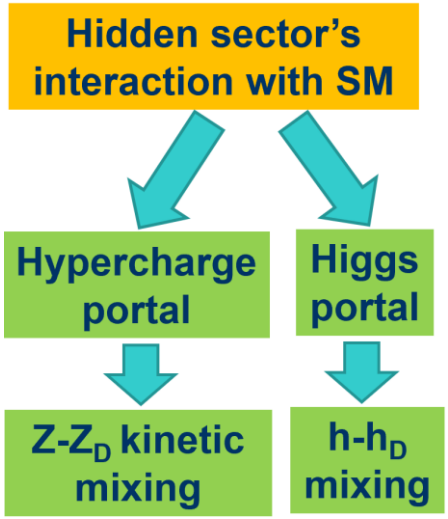
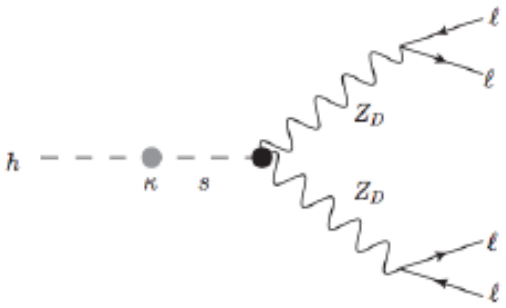
Exotic Higgs Decays with Z-Z_D + h-h_D Mixing



Objective:
The goal of this work is to search for a long-lived dark vector boson (on-shell) 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.



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

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
Long-Lived Particle = LLP

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Scan over Higgs mixing parameter *k*

Scan over Higgs mixing parameter *k*

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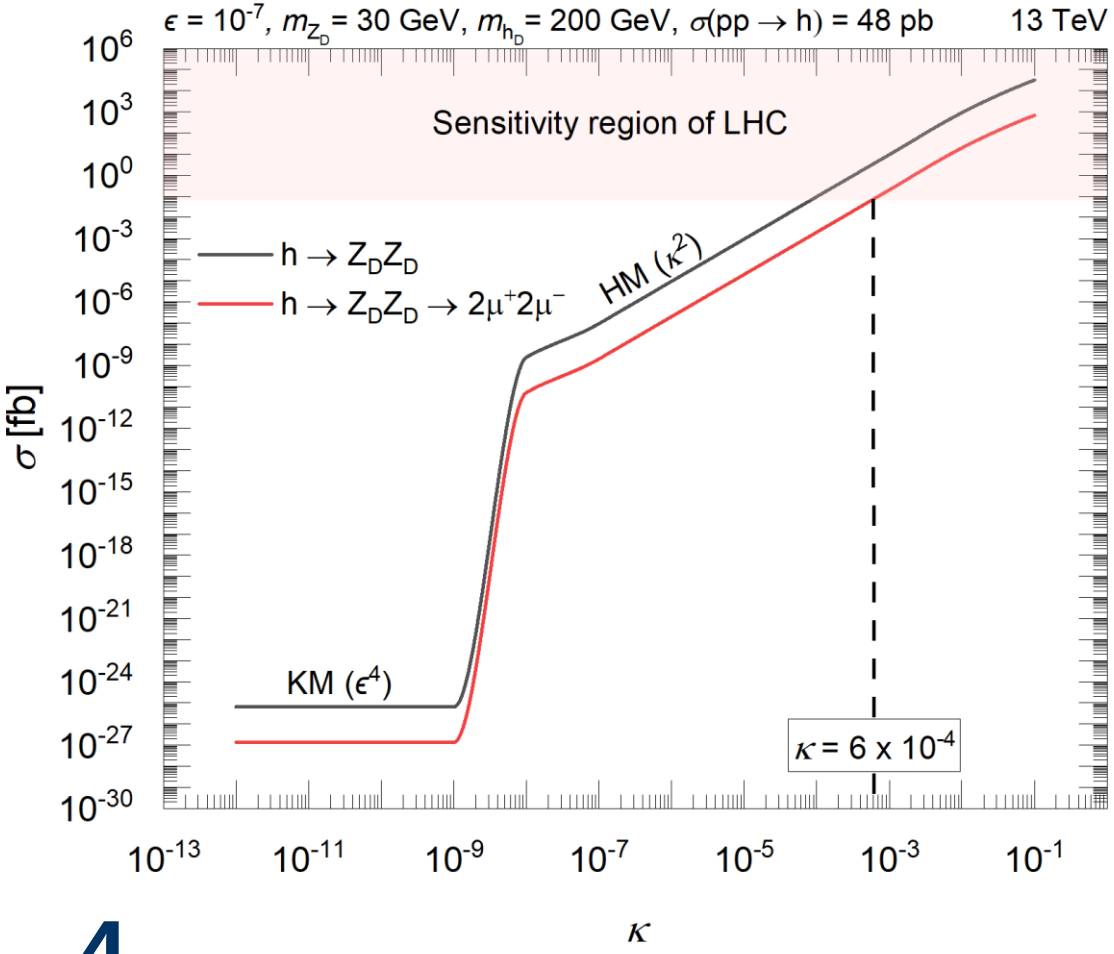
Is the LHC sensitive to measure Z_D for any expected strength of HM?



Z_D could have been produced via h➔Z_DZ_D (black curve) and measured indirectly via h➔Z_DZ_D➔$2\mu^+2\mu^-$ (red curve) at the LHC in Run 2 only if HM is dominant ($k \geq 6\times10^{-4}$) where an acceptance of 100% is assumed.

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO 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}.

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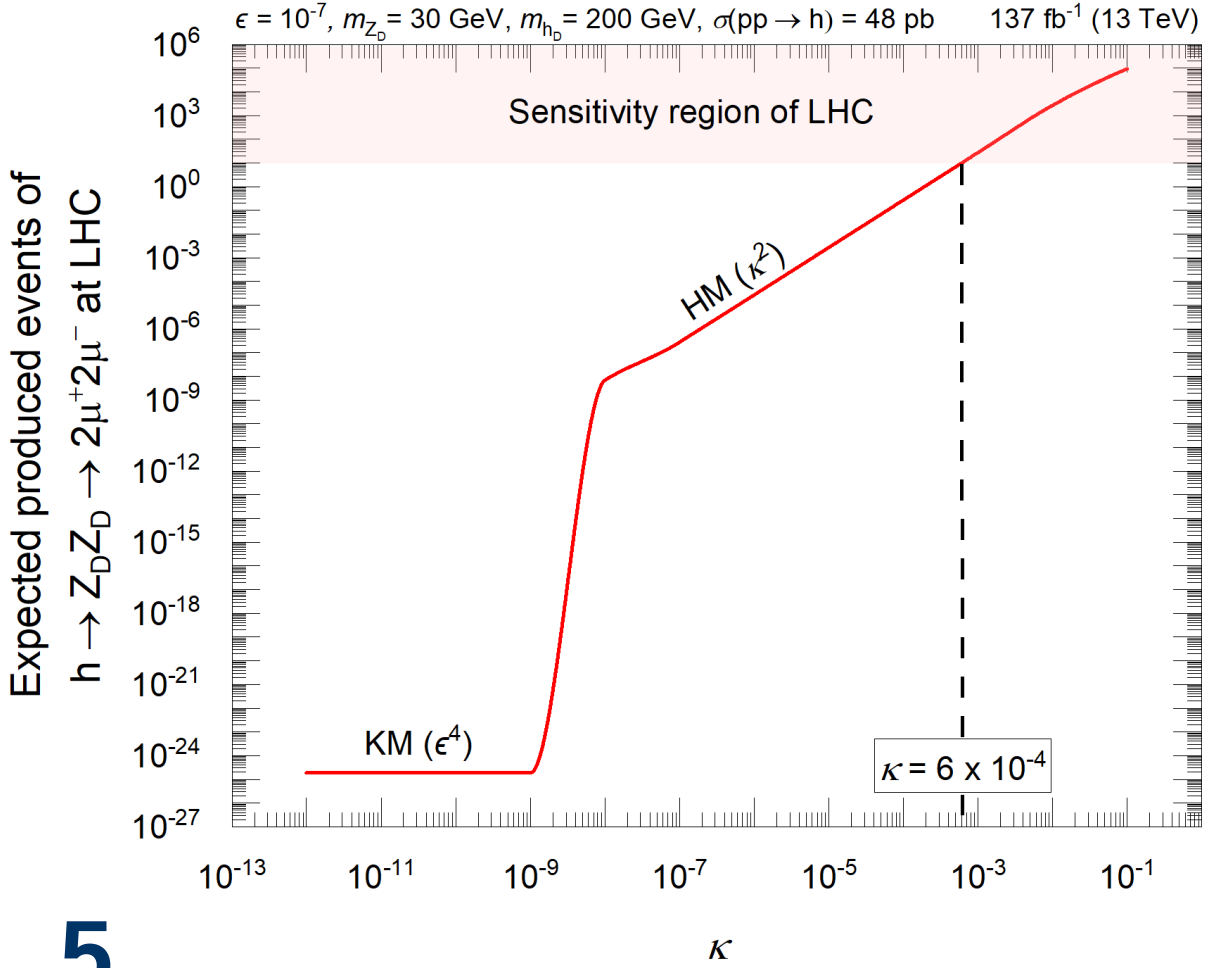
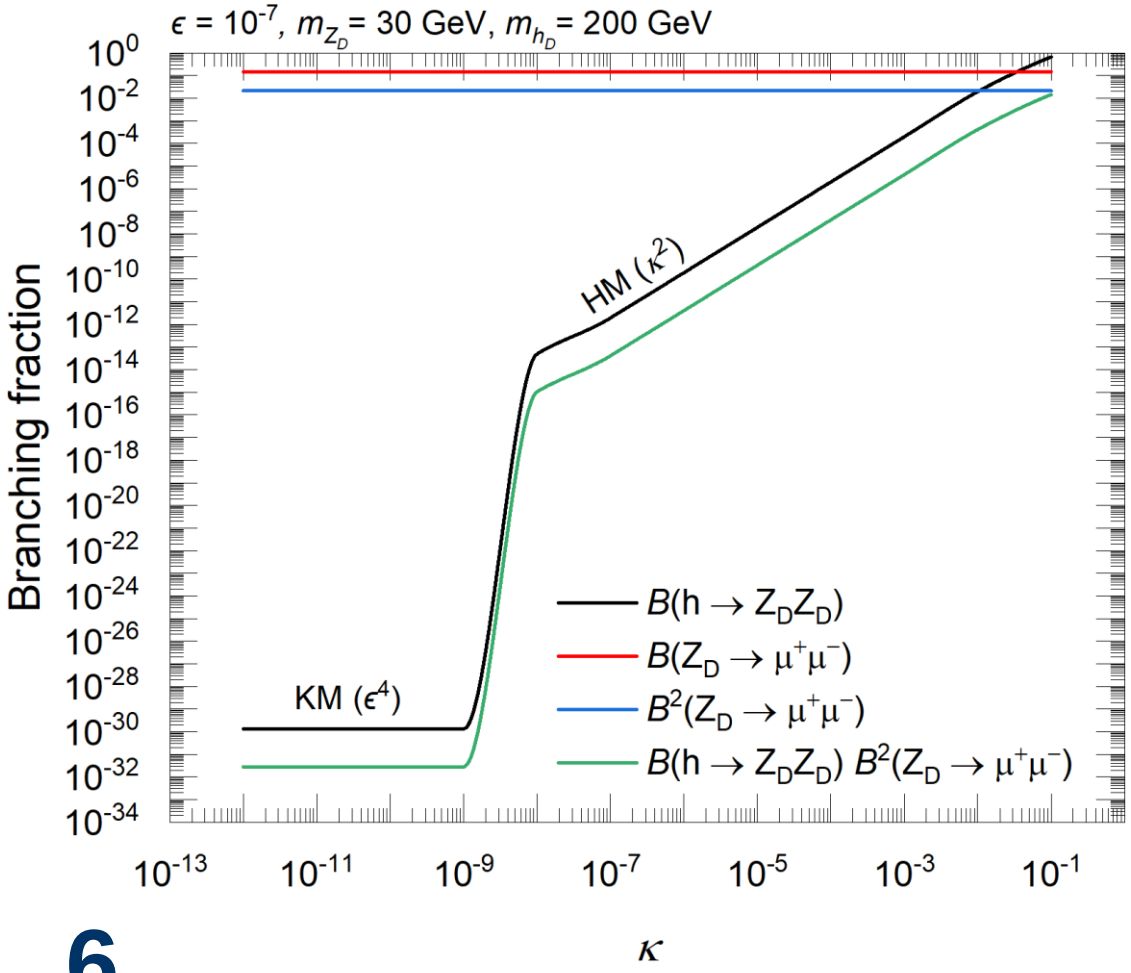
How many produced events are expected at the LHC in Run 2 as impacted by HM strength?



If 0.1 is taken as the highest possible value of *k*, 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, i.e., $k \geq 6 \times 10^{-4}$, where an acceptance of 100% is assumed.

Sensitivity of the LHC is assumed to be down to 10 events.

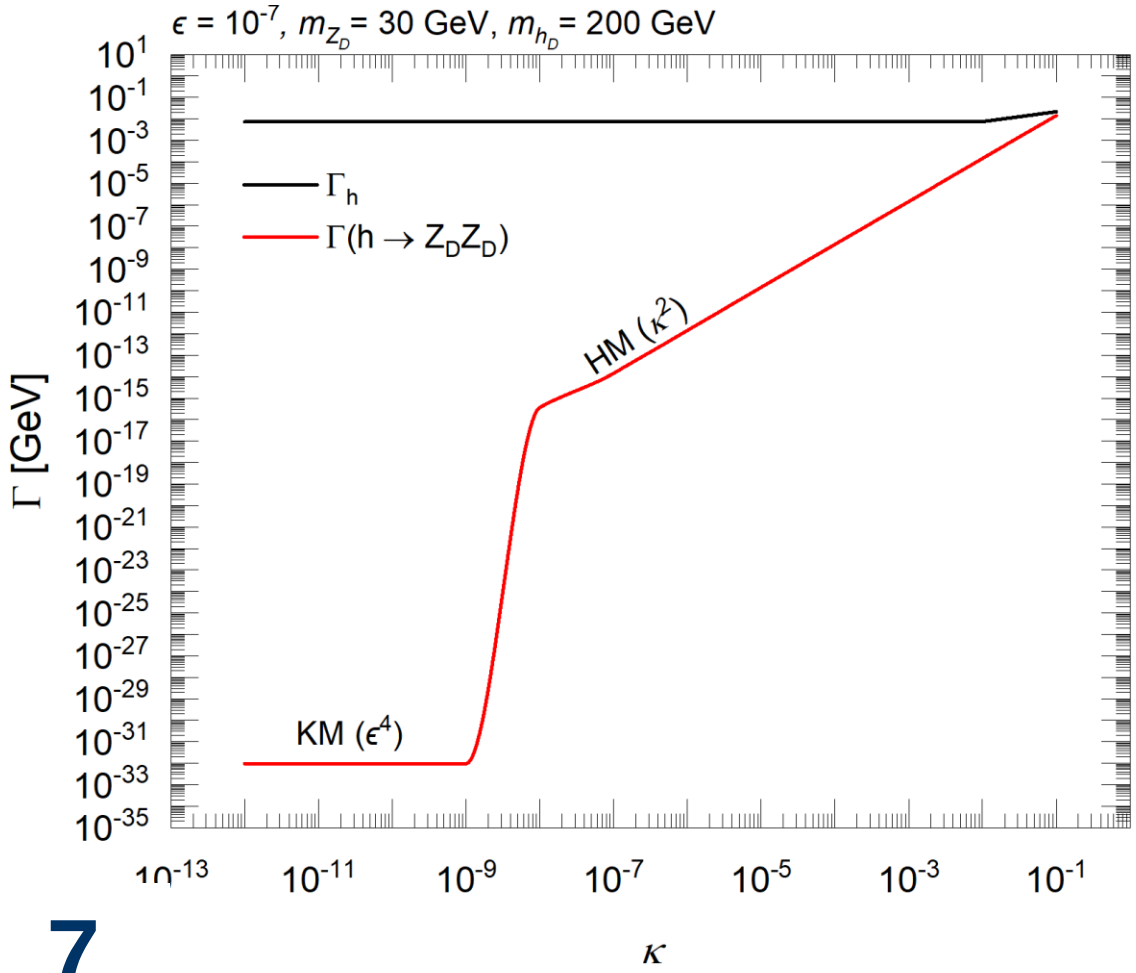
Which branching fraction impacts the cross section the most as HM strength varies?



B(h➔$Z_D Z_D$) is found to vary with k^2 until HM strength becomes too small (here, $k = 10^{-9}$) to handle the decay, then KM takes over and *B*(h➔$Z_D Z_D$) starts to vary with ϵ^4.

The branching fraction *B*(Z_D➔$\mu^+\mu^-$) is unchanged for a range of HM parameter of 10^{-12}–10^{-1}.

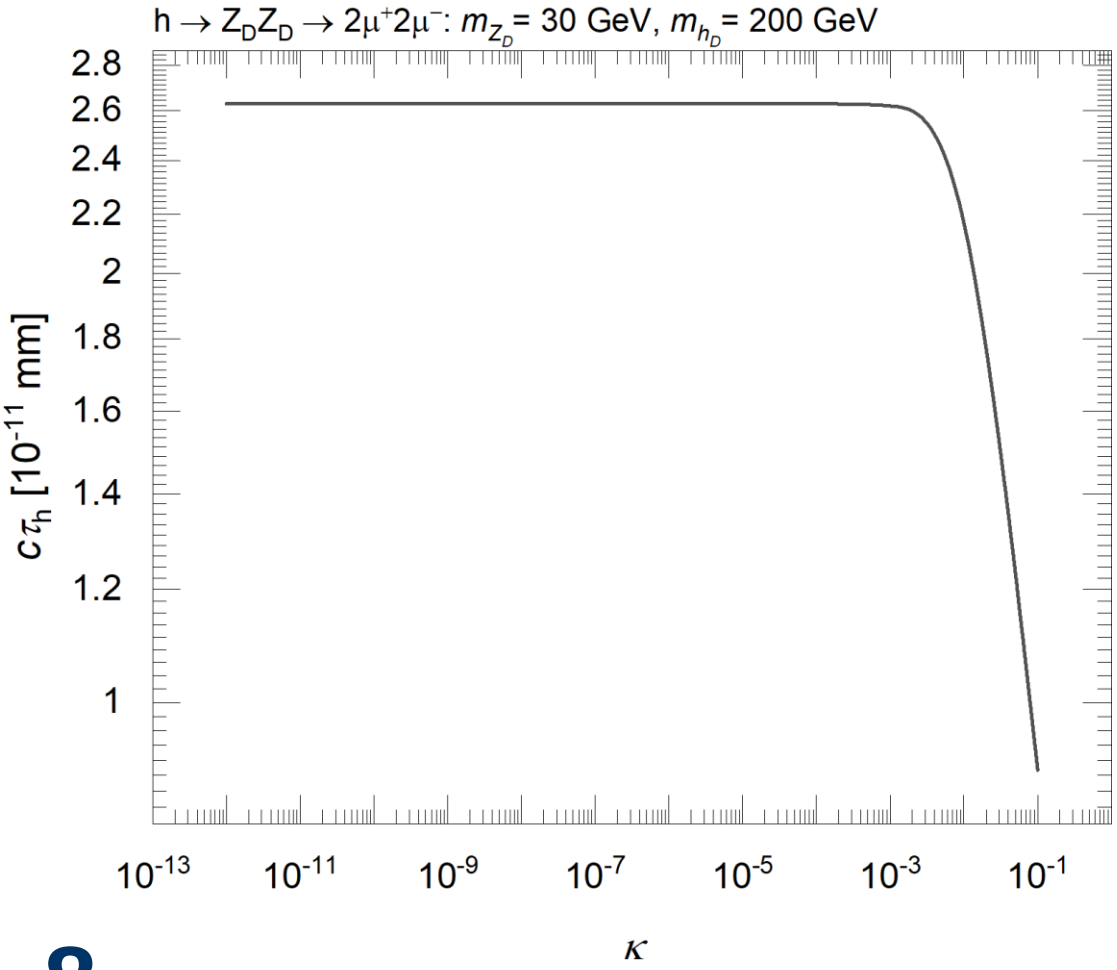
By what factor will the decay width of SM Higgs increase if it decays to $Z_D Z_D$?



The partial decay width of h➔$Z_D Z_D$ varies with k^2 until HM strength becomes too small (here, $k = 10^{-9}$) to handle the decay, then KM takes over, and the partial decay width of h➔$Z_D Z_D$ starts to vary with ϵ^4.

The total decay width of SM Higgs is unchanged for a range of HM parameter of 10^{-12}–10^{-1}.

How can the SM Higgs lifetime change for different strengths of HM?



Expected new lifetime of SM Higgs decreases only over the dominant values of HM ($k \geq 6\times10^{-4}$) and it is unchanged otherwise ($k < 6\times10^{-4}$).

Expected maximal lifetime of SM Higgs is found to be higher than the expected minimal lifetime by a factor of ~3 in the scan over a range of HM parameter of 10^{-12}–10^{-1}.

Scan over Higgs mixing parameter *k*

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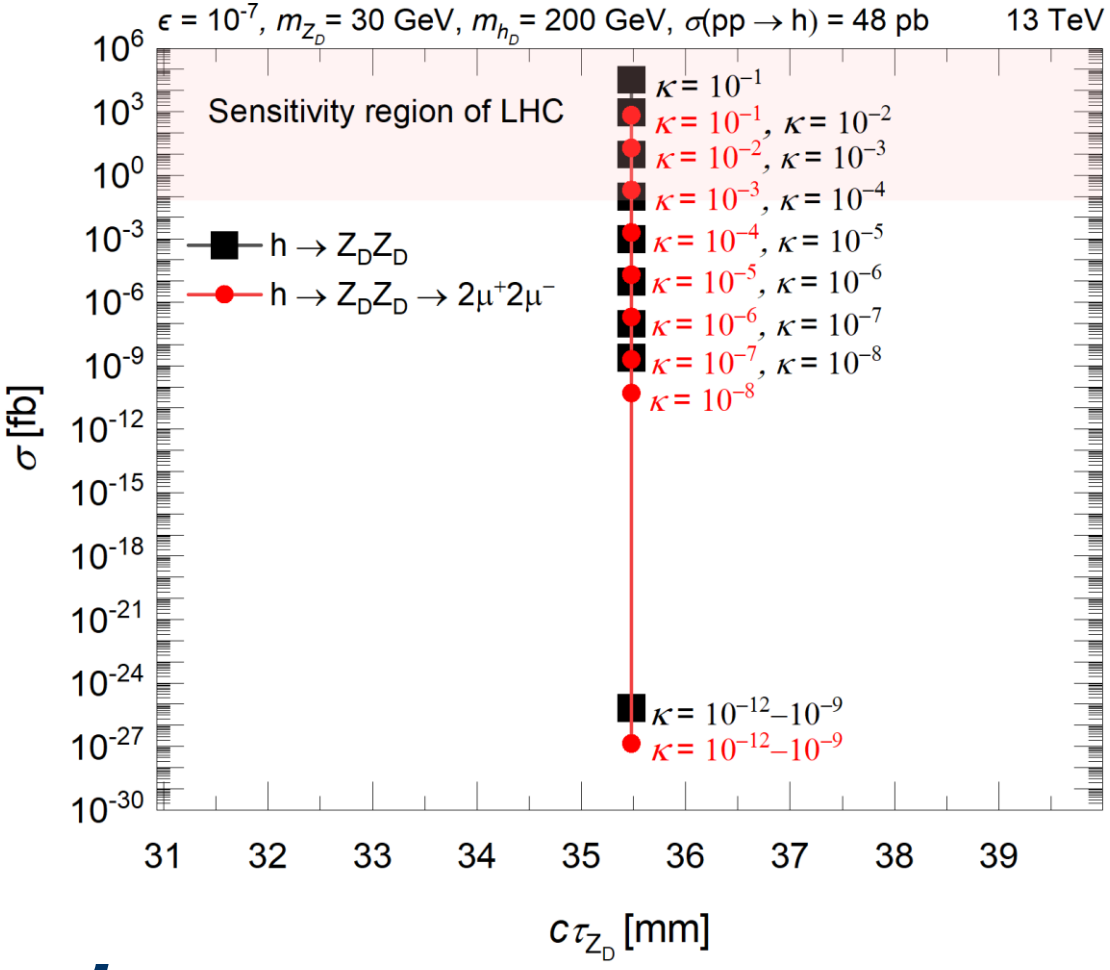
How is the cross section related to the Z_D lifetime in the scan over expected HM strengths?



Lifetime of Z_D is unchanged for all expected production/total cross sections in the scan over HM parameter in the range of 10^{-12}–10^{-1}.

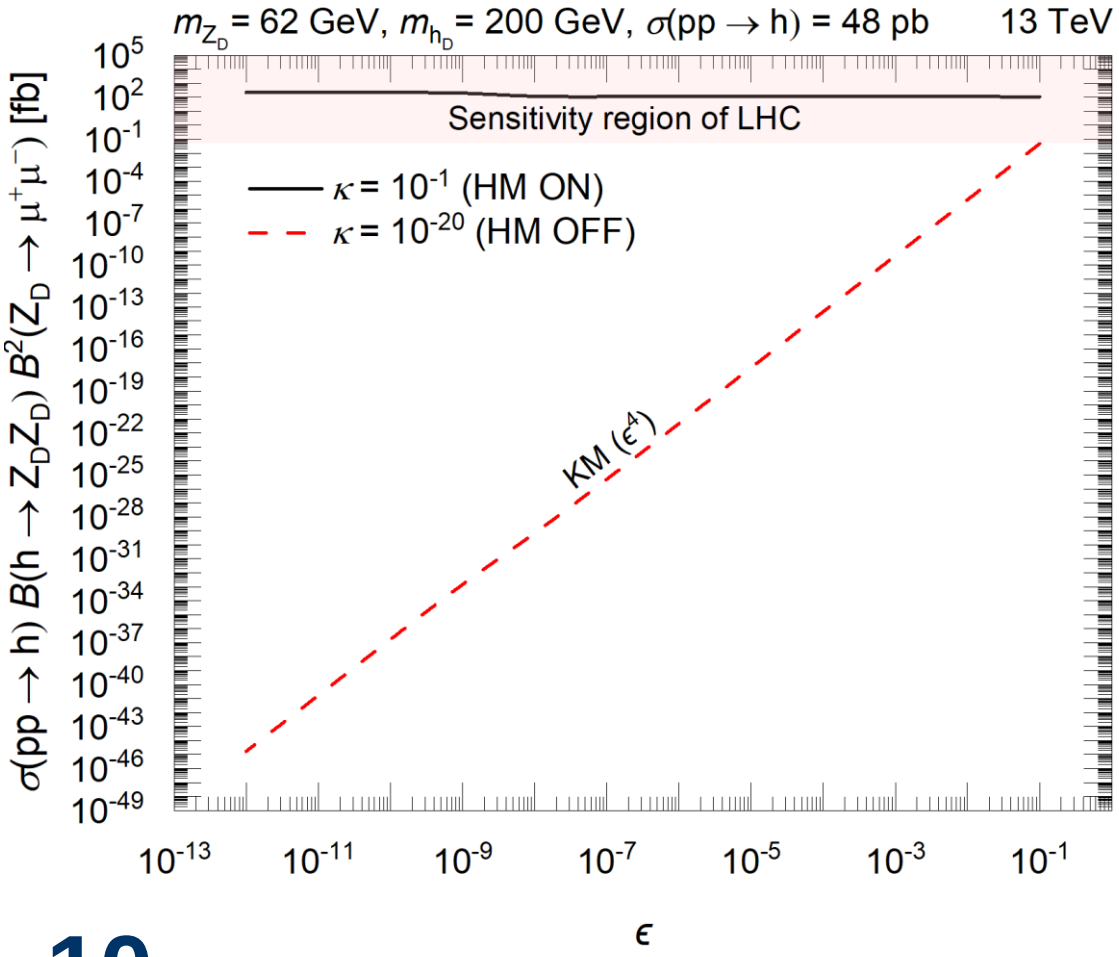
LHC is sensitive to the indirect measurement of Z_D with a decay length controlled by the KM strength and the Z_D mass only if HM is dominant ($k \geq 6\times10^{-4}$).

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO 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 mixing parameter ϵ

How sensitive is the LHC to measure $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ if the KM is OFF? In other words, can KM handle the decay if HM is OFF?



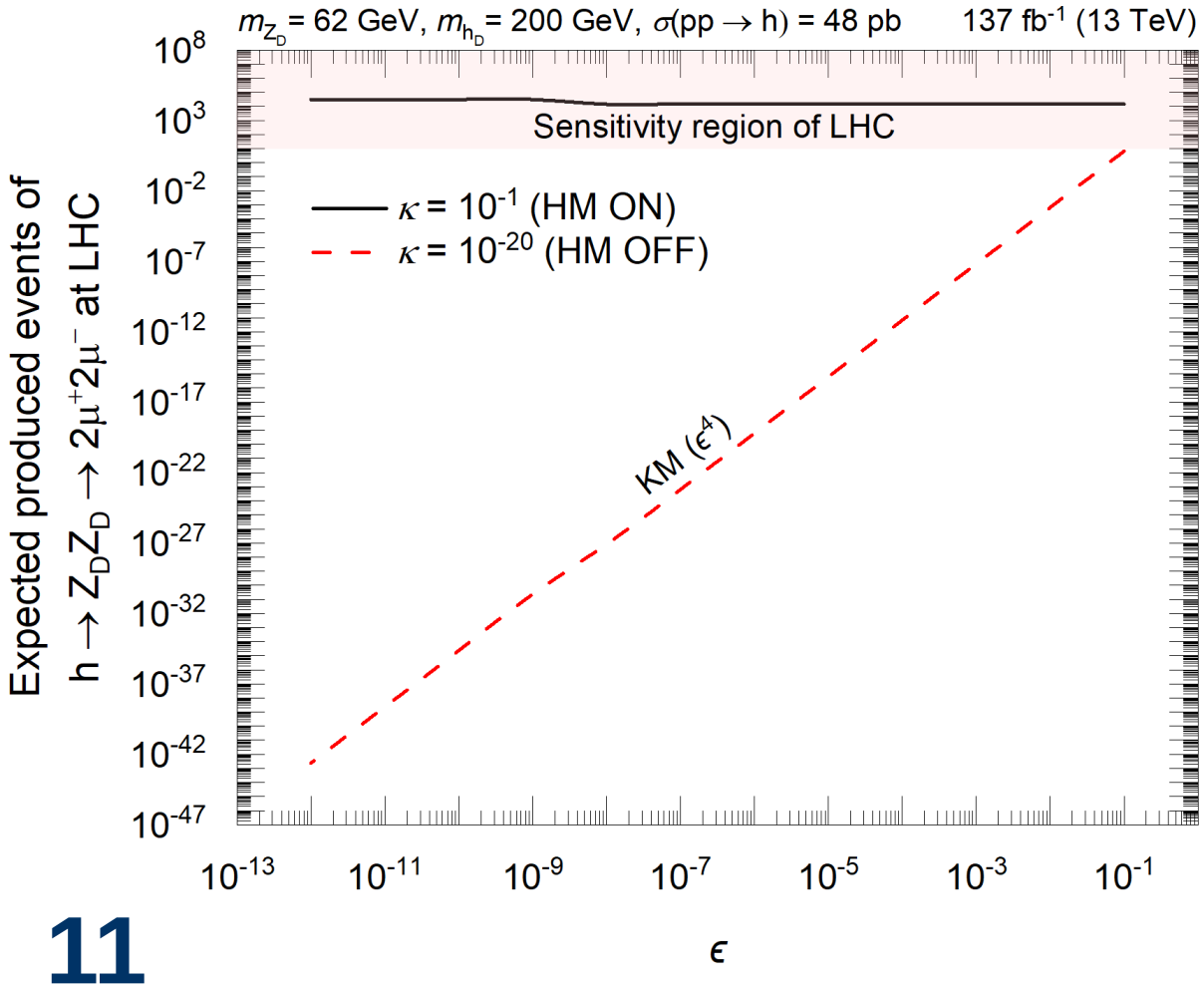
Indirect measurement of Z_D via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ requires HM to be ON where an acceptance of 100% is assumed.

The total cross section is highly impacted by the KM (it varies as ϵ^4) only if HM is OFF. However, KM is incapable, even with its maximal strength, to induce this decay mode at the LHC in Run 2.

$\sigma(pp \rightarrow h)$ = 48 pb for ggF production channel, calculated to N^{3}LO 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}.

How many produced events are expected at the LHC in Run 2 for $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ if HM is OFF?

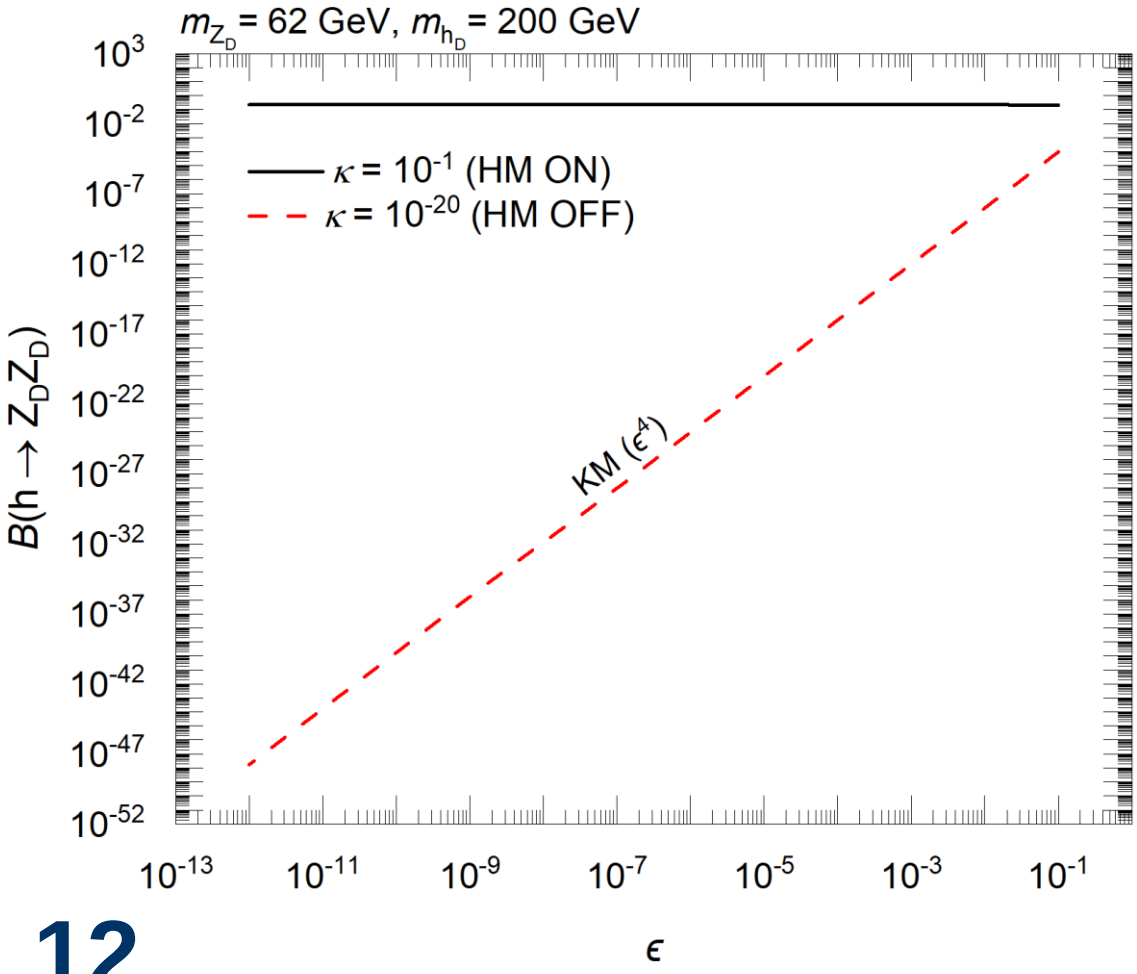


A large number of produced events via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ is expected in Run 2 data of the LHC only if HM is ON where an acceptance of 100% is assumed.

If HM is OFF, the number of expected produced events at LHC in Run 2 varies as ϵ^4 .

10 events are assumed to be the least number for a resonance to be measured at the LHC.

What causes the total cross section to be highly impacted by KM if HM is OFF?

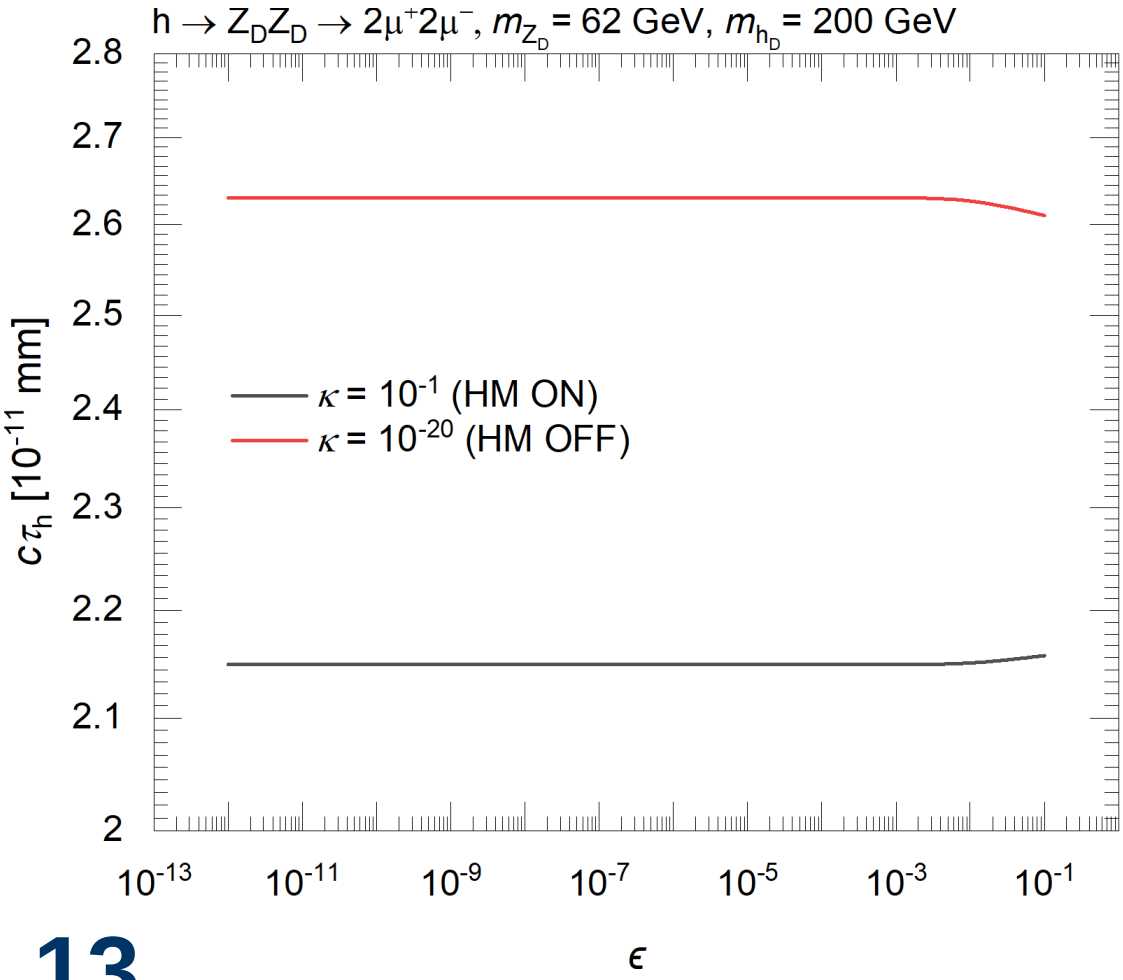


The branching fraction $B(h \rightarrow Z_D Z_D)$ is maximized and unchanged in the scan over KM parameter in the range of 10^{-12}–10^{-1} if HM is ON.

If HM is OFF, $B(h \rightarrow Z_D Z_D)$ is "drastically" impacted ny KM (it varies as ϵ^4), while $B(Z_D \rightarrow \mu^+\mu^-)$ is not impacted (not shown).

$B(h \rightarrow Z_D Z_D)$ is responsible for the large change of the production and total cross section of Z_D if HM is OFF.

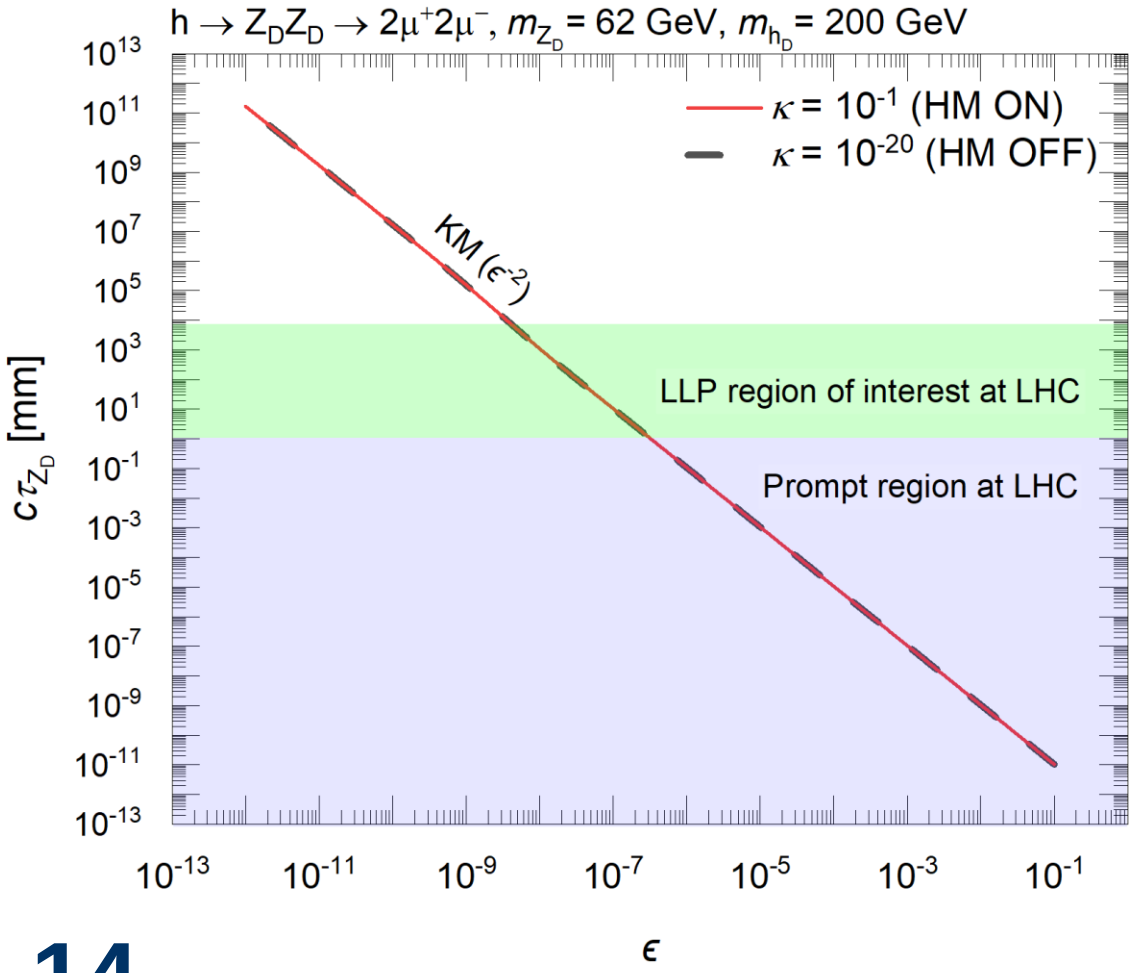
How long can SM Higgs live if it is found to decay to $Z_D Z_D$?



The HM mixing has a negligible impact, while the KM has no impact, on the lifetime of SM Higgs.

Literature predicts the known decay length $c\tau$ of SM Higgs of ~4.68×10^{-11} mm versus less than half of this value from the current simulation (black curve) if SM Higgs is found to decay to two Z_D's.

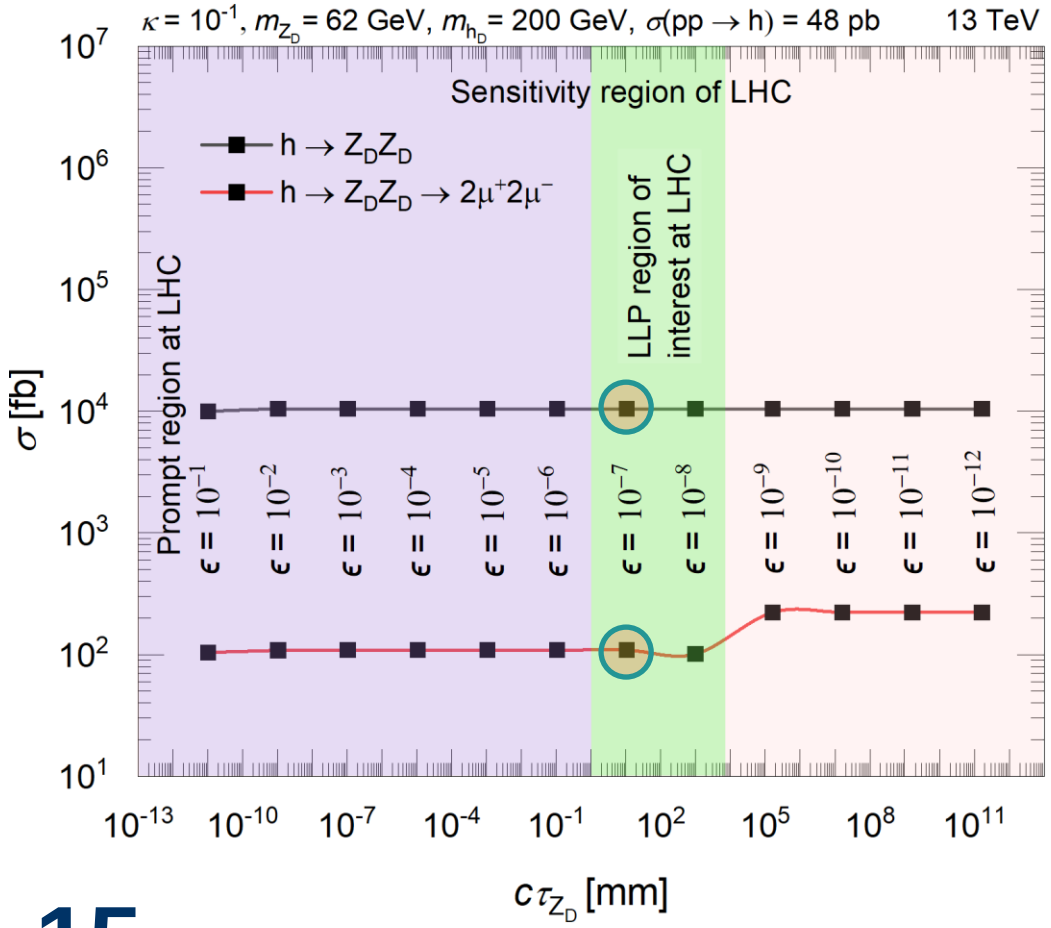
How long can Z_D live if produced at the LHC?



Lifetime of Z_D is varies inversely as ϵ^2, while it is not impacted by HM at all (curves of having HM ON and OFF are identical).

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

How do the expected lifetime and cross section change with each other if HM is ON?



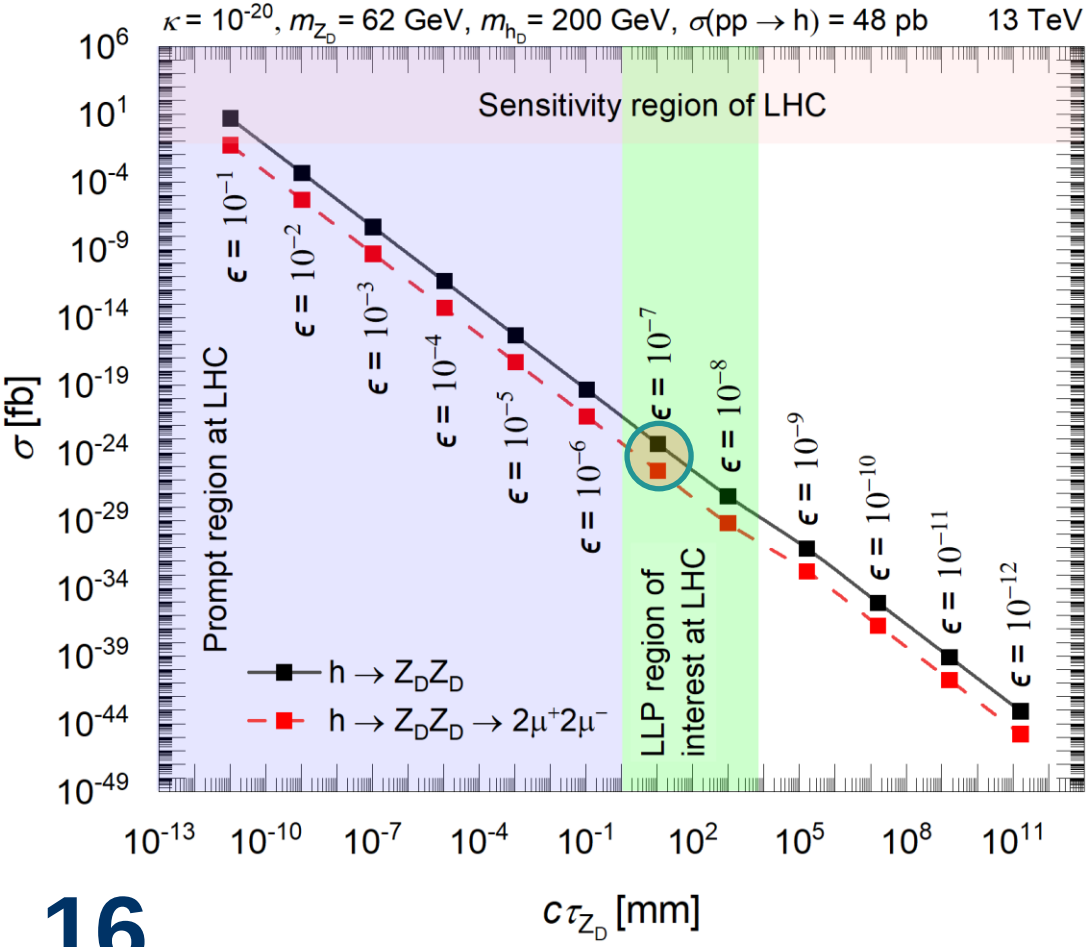
Prompt/long-lived Z_D could have been produced via h➔Z_DZ_D and measured indirectly via h➔Z_DZ_D➔$2\mu^+2\mu^-$ at the LHC in Run 2 if HM is ON.

$c\tau_{ZD}$ is inversely proportional to ϵ^2, while production cross section of Z_D is unchanged with the variation of ϵ if HM is ON.

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO 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}.

How do the expected lifetime and cross section change with each other if HM is OFF?



For HM being OFF, although prompt Z_D could have been produced via $h \to Z_D Z_D$ for $\epsilon \geq 0.06$, the LHC in Run 2 is insensitive to the indirect measurement of Z_D via $h \to Z_D Z_D \to 2\mu^+2\mu^-$ for $\epsilon \leq 0.1$.

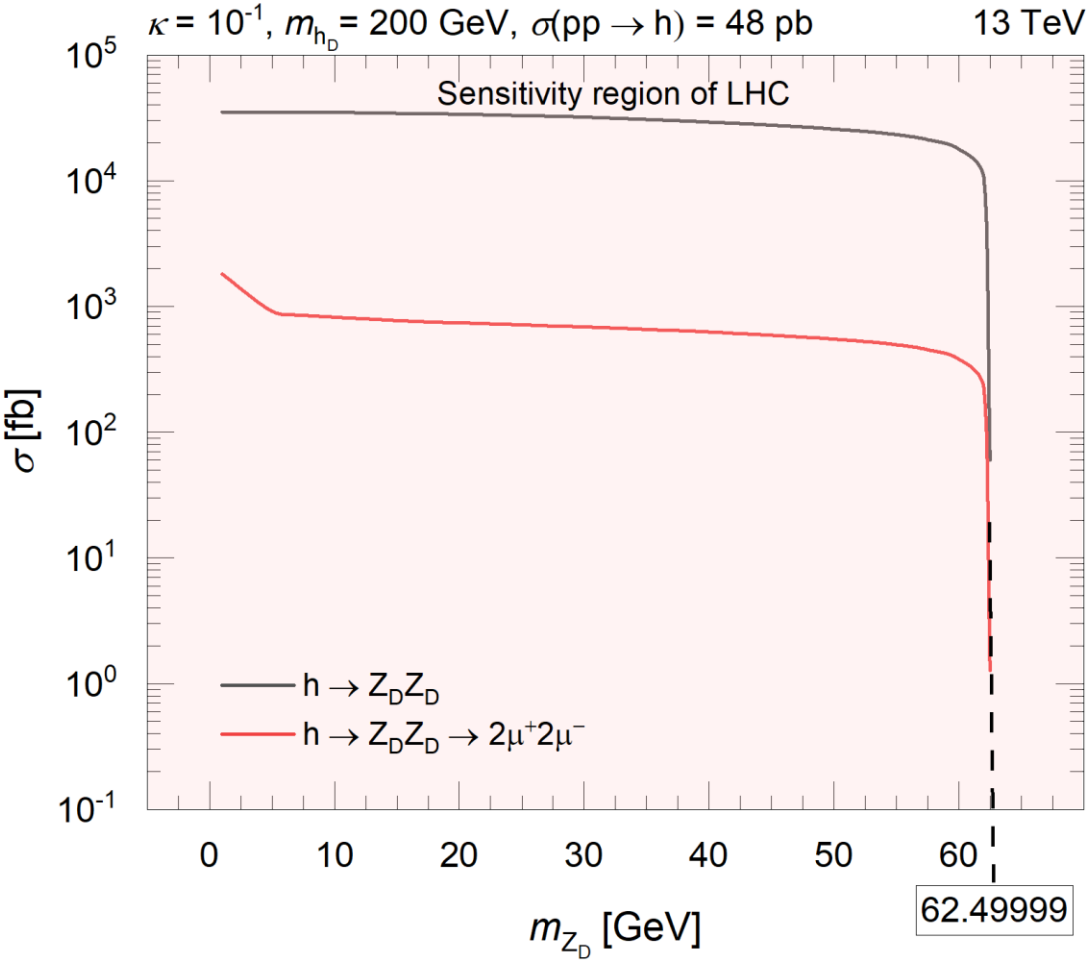
$c\tau_{Z_D}$ is inversely proportional to ϵ^2, while production/total cross section of Z_D is directly proportional to ϵ^4 if HM is OFF, which causes that production/total cross section of Z_D is inversely proportional to $c\tau^2_{Z_D}$ if HM is OFF.

$\sigma(pp \to h) = 48$ pb for ggF production channel, calculated to N^{3}LO 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 Z_D mass

Is the LHC sensitive to measure Z_D with any expected mass?



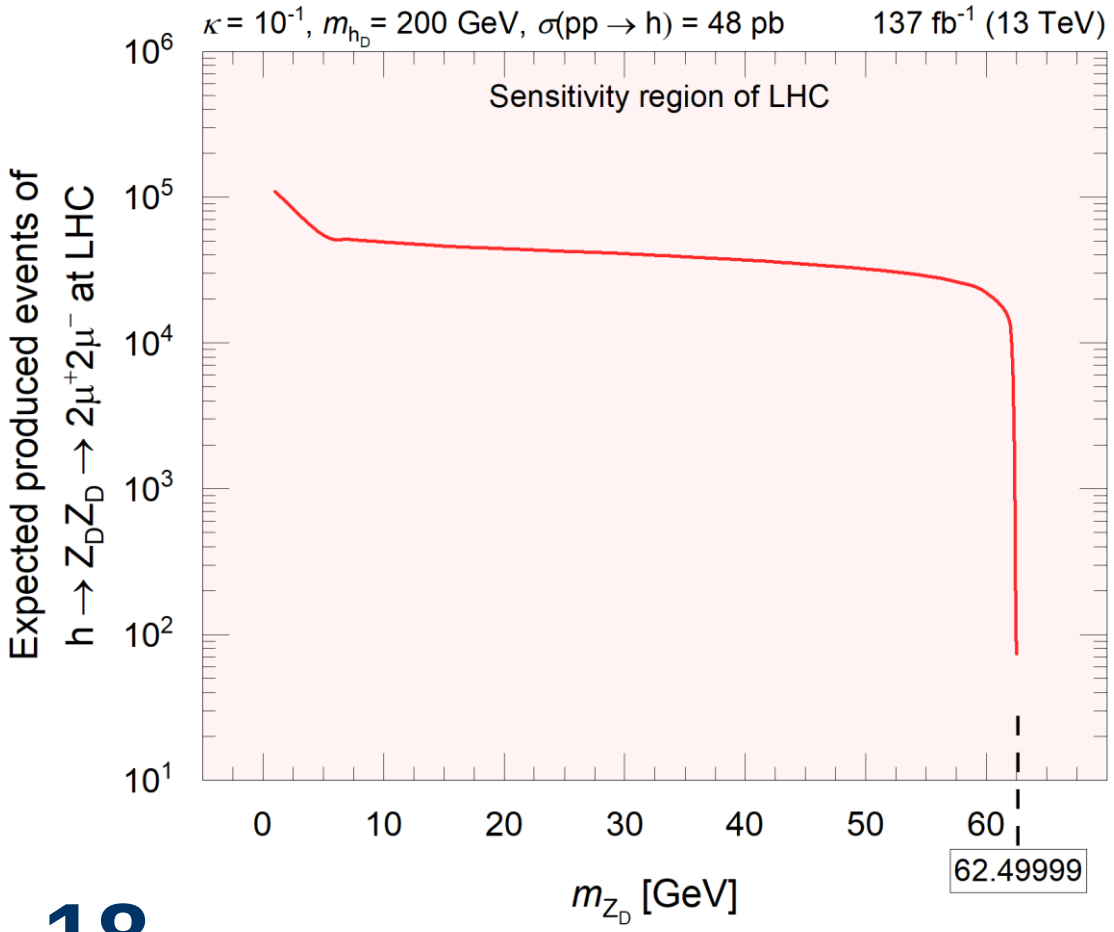
Z_D could have been produced via h➔Z_DZ_D and measured indirectly via h➔Z_DZ_D➔$2\mu^+2\mu^-$ during Run 2 of the LHC with any expected mass in the range of 1 – <62.5 GeV where an acceptance of 100% is assumed.

Away from the threshold of 62.5 GeV, production and total cross sections of Z_D are not impacted by its mass except for a little impact on the total cross section over the range of $m_{ZD} < 4$ GeV.

Abrupt decrease of production and total cross sections of Z_D by about two orders of magnitude is seen in the vicinity of the threshold of 62.5 GeV.

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO QCD + NLO EW.

How many produced events are expected in Run 2 of the LHC in a scan over Z_D mass?



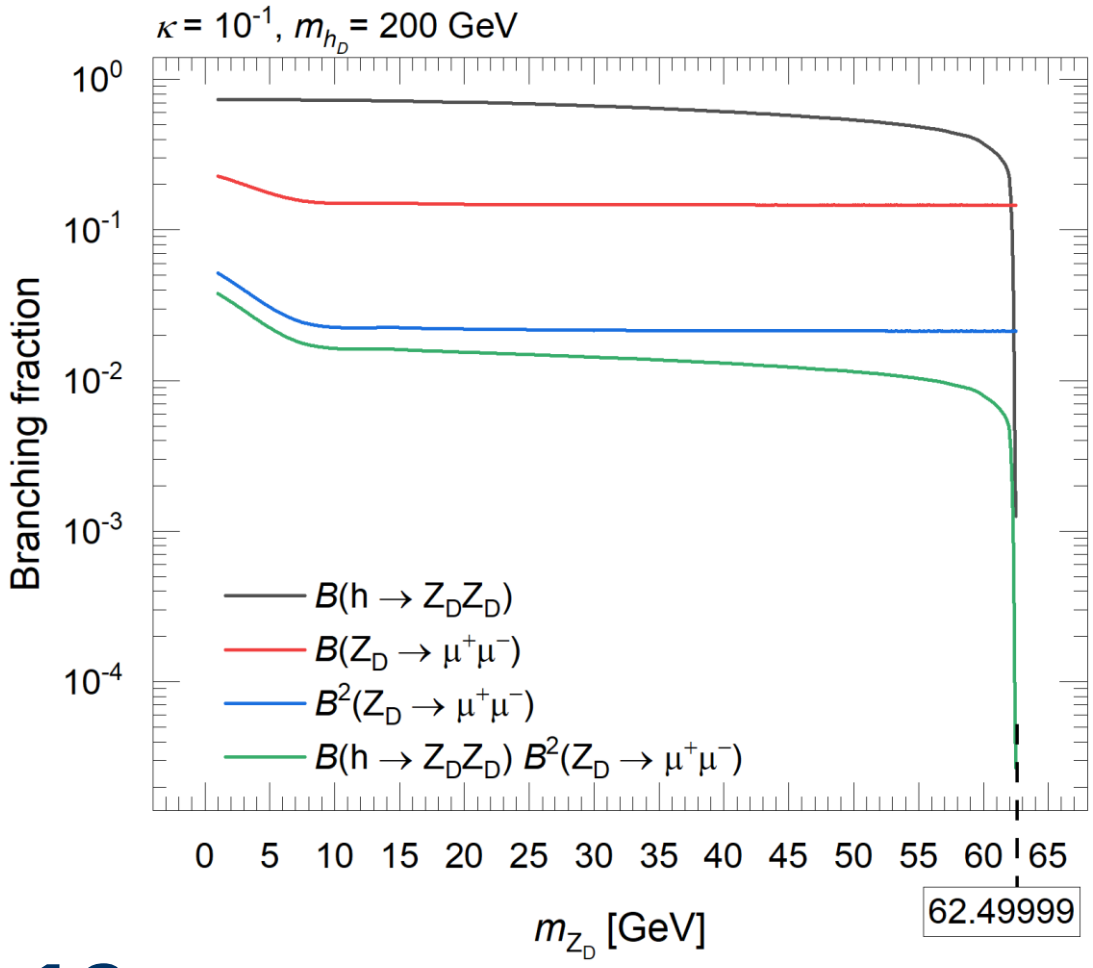
A large number (up to 10^5 events) could have been produced and measured indirectly in Run 2 of the LHC for any expected mass of Z_D in the range of 1 – <62.5 GeV where an acceptance of 100% is assumed.

The expected number of events is shown to decrease abruptly near the threshold of 62.5 GeV.

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO QCD + NLO EW.

10 events are assumed to be the least number for a resonance to be measured at the LHC.

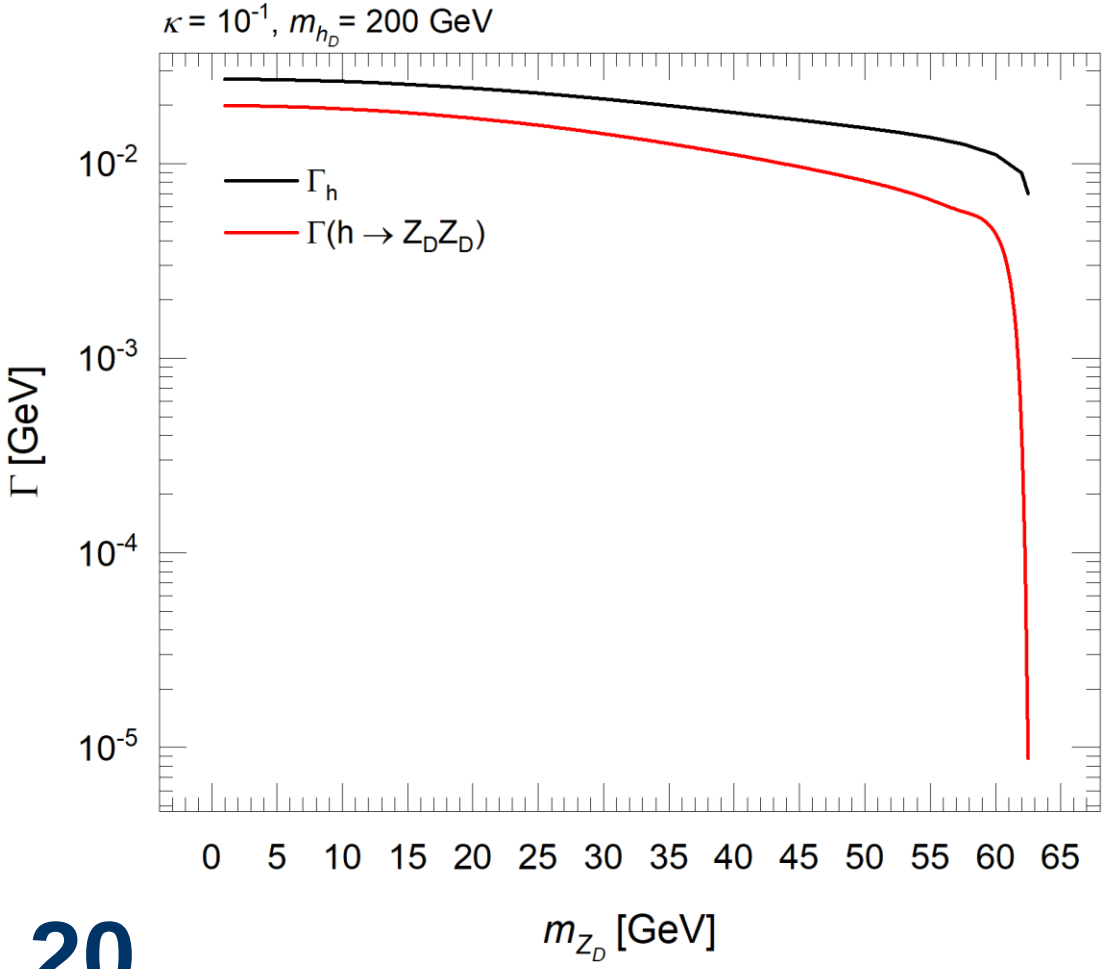
How branching fractions change with the Z_D mass?



$B(h \rightarrow Z_D Z_D)$ is unchanged for all expected masses of Z_D and decreases abruptly in the vicinity of the threshold of 62.5 GeV.

$B(Z_D \rightarrow \mu^+\mu^-)$ is unchanged for all expected masses of Z_D except for the range of m_{ZD} < 4 GeV where it decreases slightly with the increase of m_{ZD}.

By what factor will the current decay width of SM Higgs increase if it is found to decay to Z_DZ_D?

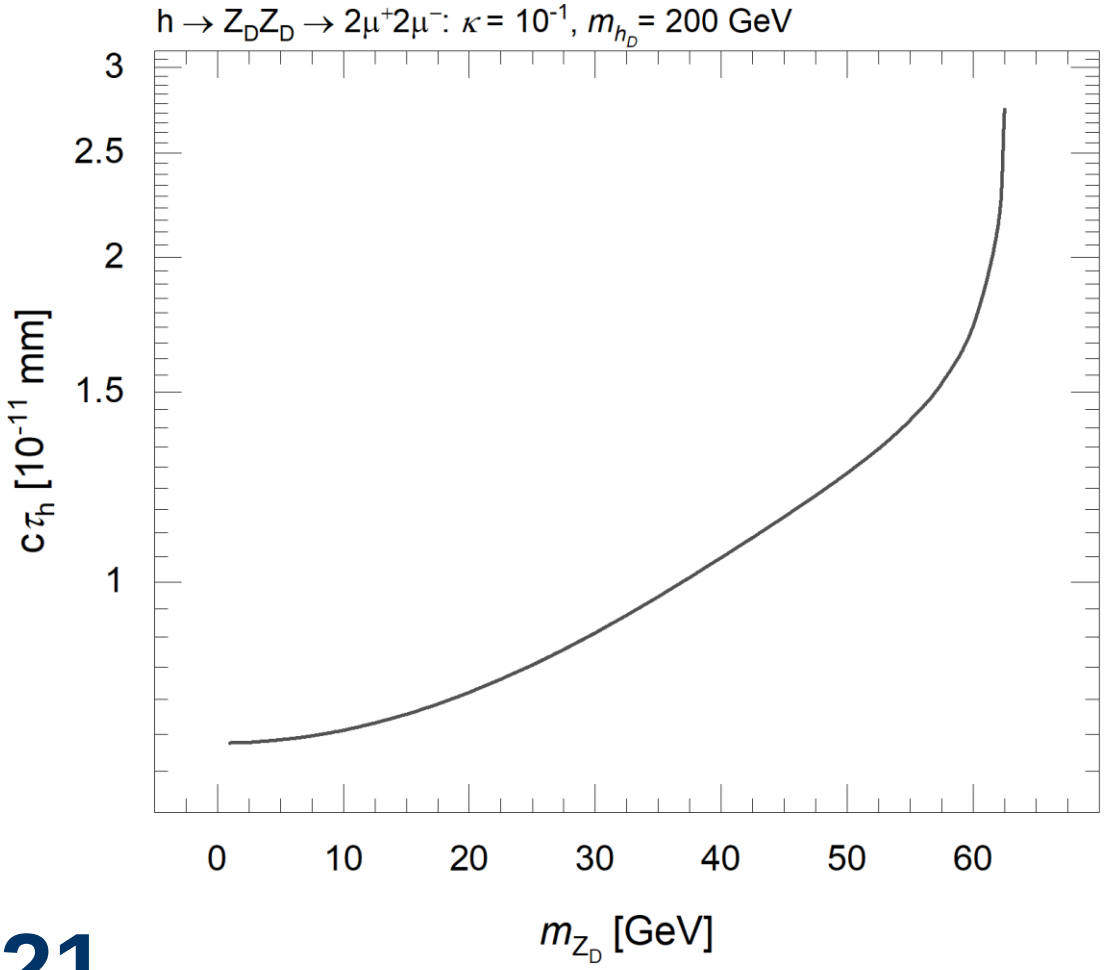


The total and partial (i.e., h➔Z_DZ_D) decay widths of SM Higgs are inversely proportional to the mass of Z_D.

The total decay width of SM Higgs is expected to increase by about one order of magnitude if it is found to decay to Z_DZ_D.

The partial decay width Γ(h➔Z_DZ_D) of SM Higgs decreases abruptly in the vicinity of the threshold of 62.5 GeV.

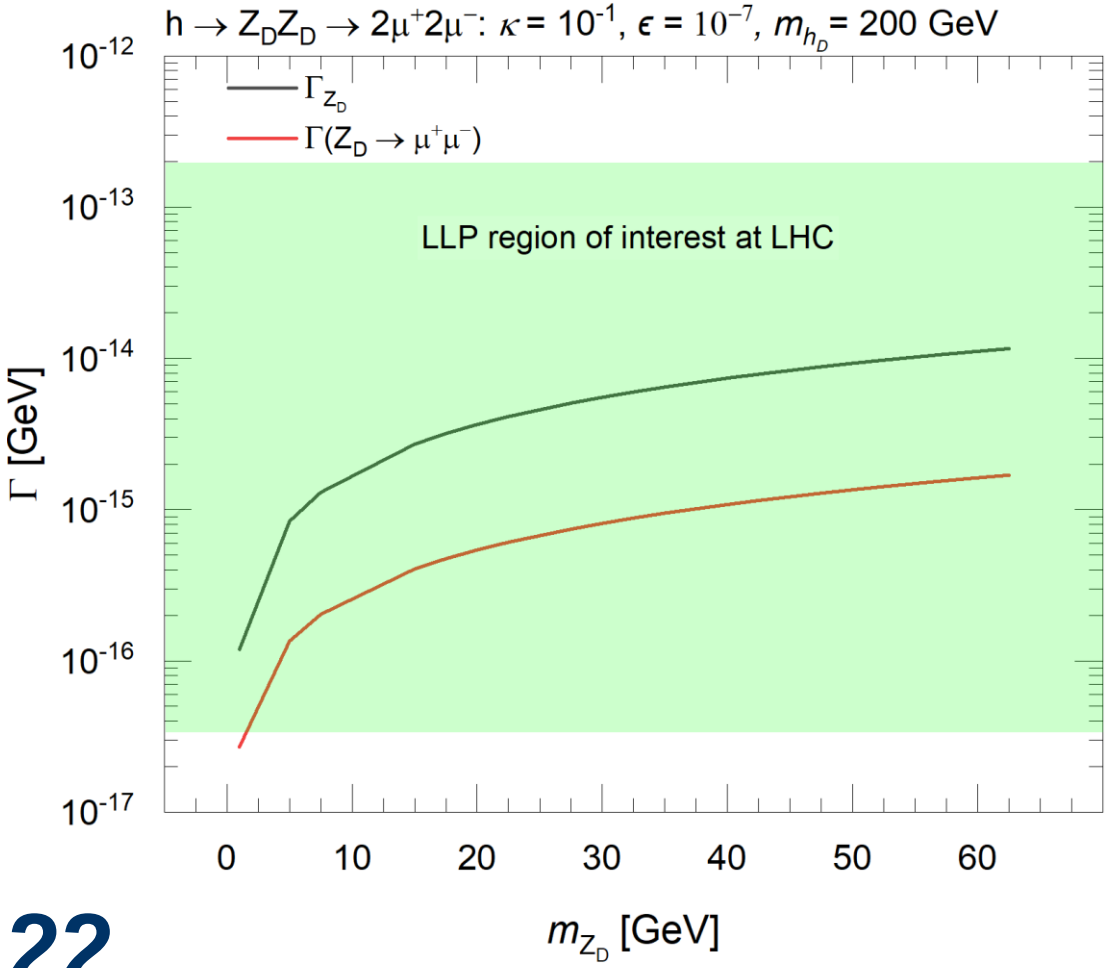
What is the expected new lifetime of SM Higgs if it is found to decay to $Z_D Z_D$?



Expected new lifetime of SM Higgs increases with the increase of the expected mass of Z_D.

Expected maximal lifetime of SM Higgs is found to be higher than the expected minimal lifetime by a factor of ~5 in the scan over a range of Z_D mass of 1 – <62.5 GeV.

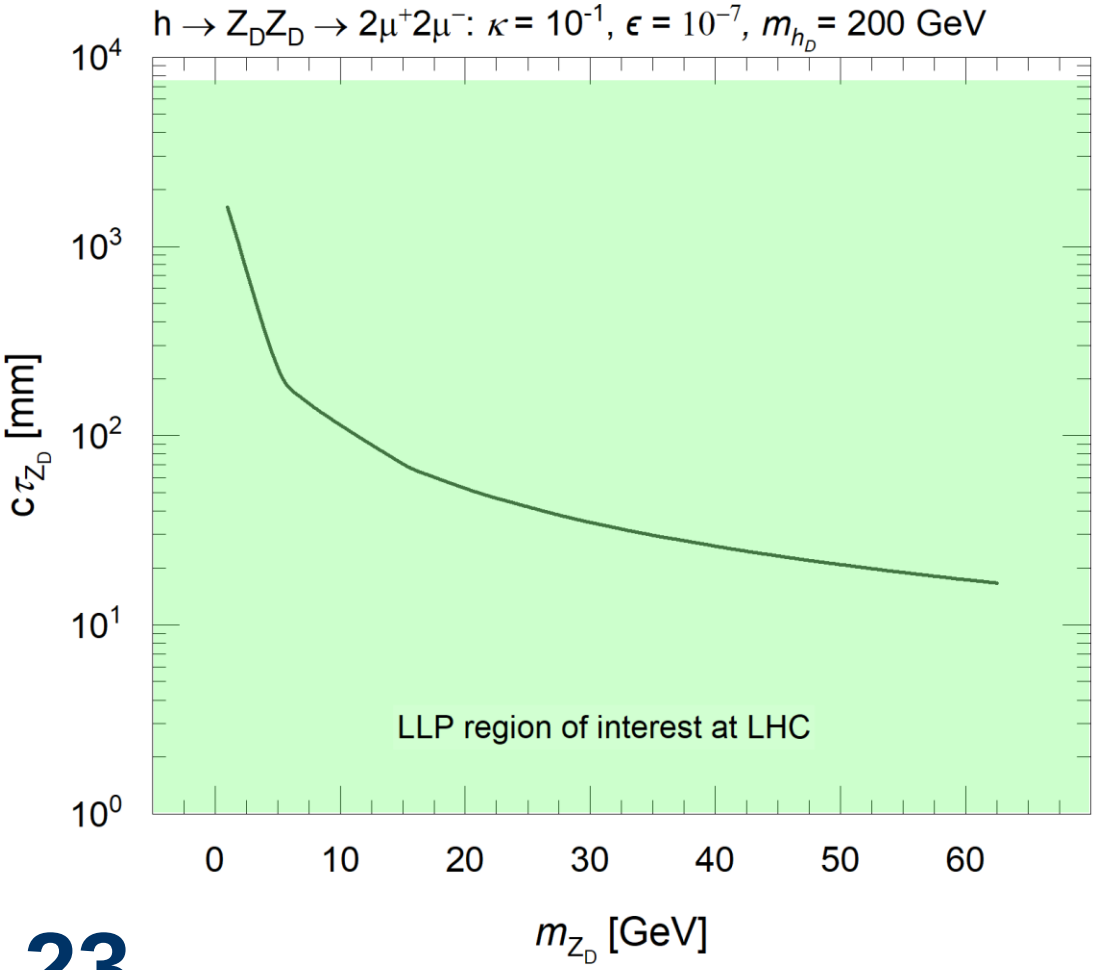
What is the contribution of the partial decay width of $Z_D \rightarrow \mu^+\mu^-$ to the total decay width of Z_D?



The partial decay width of $Z_D \rightarrow \mu^+\mu^-$ is lower by about one order of magnitude than the total decay width of Z_D.

Referring to Slide 9, the value of $\epsilon = 10^{-7}$ is selected to produce Z_D of measurable decay length within the geometrical size of the CMS detector.

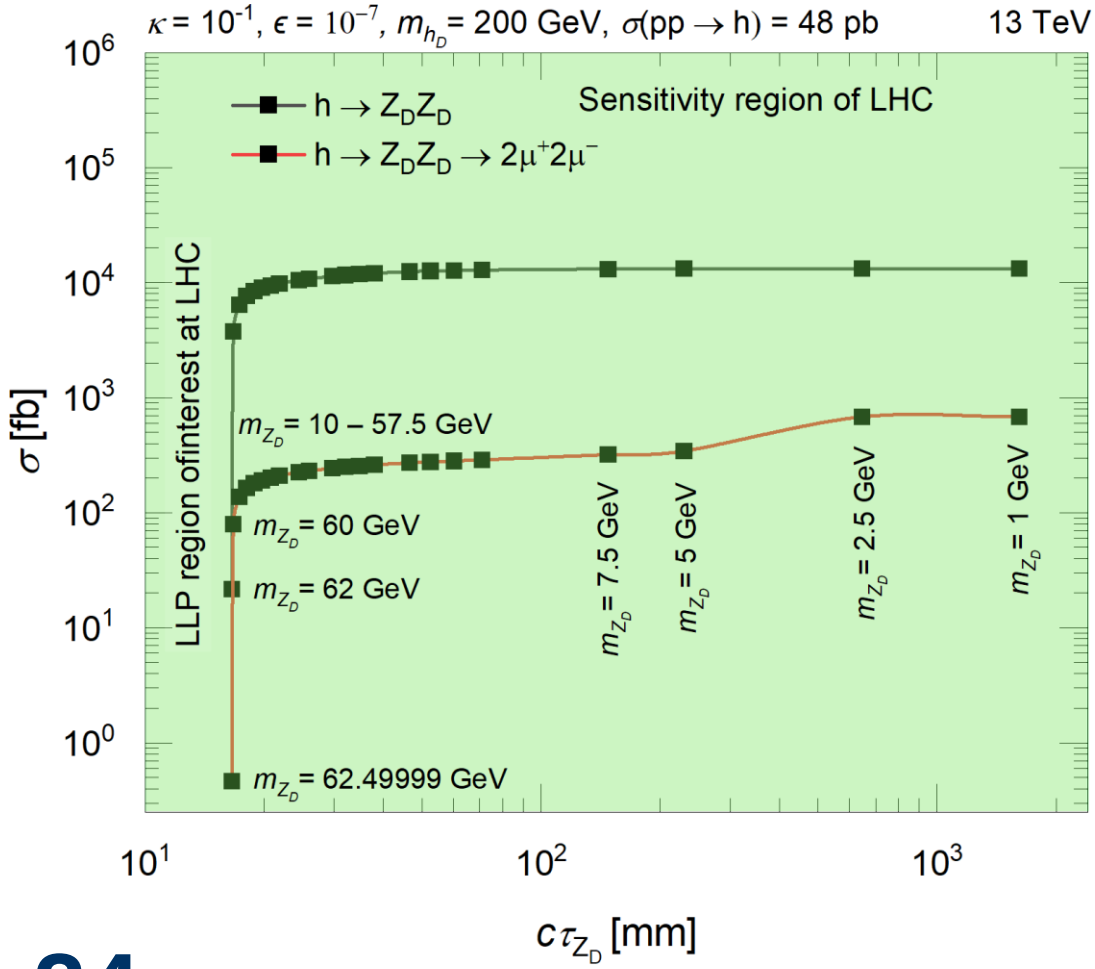
How is the Z_D lifetime impacted by its mass?



Z_D is expected to be an excellent LLP candidate if HM is ON, and KM is selected carefully (See Slide 9) for any expected mass of Z_D in the range of 1 – <62.5 GeV.

Referring to Slide 9, the value of $\epsilon = 10^{-7}$ is selected to produce long-lived Z_D of measurable decay length (here, it gives 11–2000 mm) within the geometrical size of the CMS detector.

How is the cross section related to the Z_D lifetime?



It is shown how the decay length and production/total cross section of Z_D are expected to change with each other if HM is ON.

If kinetic mixing parameter is fixed at $\epsilon = 10^{-7}$, $c\tau$ of Z_D can change slightly based on its mass, but it will still be LLP.

All decay lengths of Z_D correspond to a measurable total cross section of Z_D in Run 2 of the LHC (an acceptance of 100% is assumed).

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO QCD + NLO EW.

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
$h \rightarrow Z Z_D \rightarrow 2\mu^+ 2\mu^-$ 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
$h \rightarrow Z Z_D \rightarrow 2\mu^+ 2\mu^-$ 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) The current presentation of APS April Meeting can be downloaded from: (https://absuploads.aps.org/presentation.cfm?pid=19067).
4) "Modeling exotic Higgs decays to vector bosons with displaced dimuons in the final states", Tamer Elkafrawy and Marcus Hohlmann, Searching for long-lived particles at the LHC and beyond: Ninth workshop of the LLP Community, May 25–28, 2021. (upcoming) (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/).

Conclusion

(1) For Z_D to be measured via the exotic decay $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ at the LHC in Run 2, HM has to be dominant ($k \geq 6\times10^{-4}$) [See Slide 9], and for Z_D to be long-lived with $c\tau \geq 1$ mm, KM must be negligible ($\epsilon < 5\times10^{-7}$) [See Slide 15]. However, the smaller KM strength is, the longer-lived Z_D is produced.

(2) Assuming an acceptance of 100%, the LHC in Run 2 is sensitive to measure Z_D with any mass in the range of 1 – <62.5 GeV (We did not scan masses of Z_D < 1 GeV) and with any expected lifetime (i.e., prompt or long-lived) based on the value of kinetic mixing parameter and its mass.

(3) The predicted lifetime of SM Higgs is seen to be slightly impacted by the masses of h_D and Z_D and unchanged with the change of KM and HM strengths.

(4) If Z_D is to be measured indirectly via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$, the lifetime of SM Higgs is predicted to be decreased to about half of the current known predicted value.

(5) Lifetime of Z_D is tuned mainly by the KM strength and slightly by Z_D mass.

(6) The branching fraction $B(h \rightarrow Z_D Z_D)$ is largely impacted by the scan over the entire range of HM parameter and slightly impacted by the scan over m_{ZD} in the vicinity of the threshold of 62.5 GeV, while $B(Z_D \rightarrow \mu^+\mu^-)$ is unchanged in all scans.

FLORIDA TECH

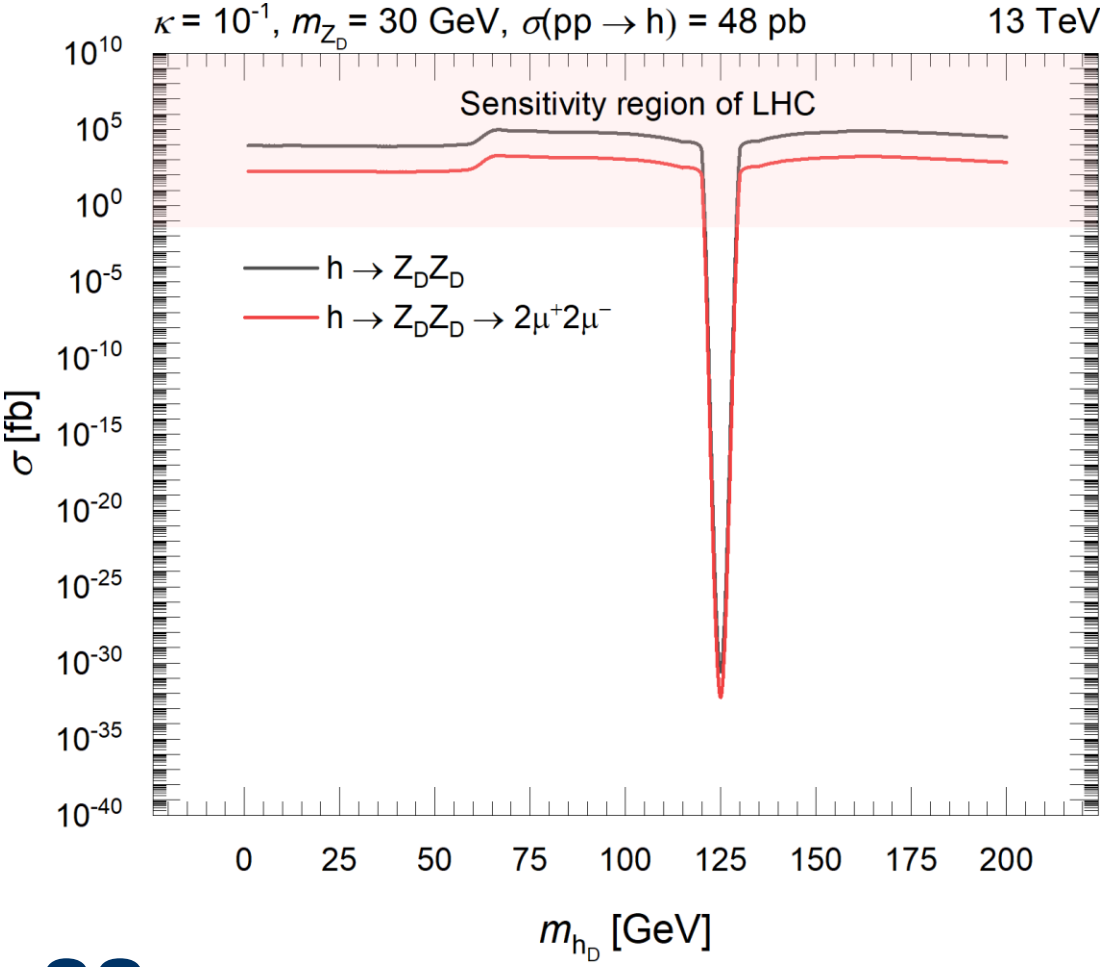
Backup Slides

FLORIDA TECH

Scan over h_D mass

FLORIDA TECH

Is the LHC sensitive to measure Z_D for any expected mass of h_D?



Z_D could have been produced and measured indirectly via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ at the LHC for any expected mass of h_D in the range of 1–200 GeV where an acceptance of 100% is assumed.

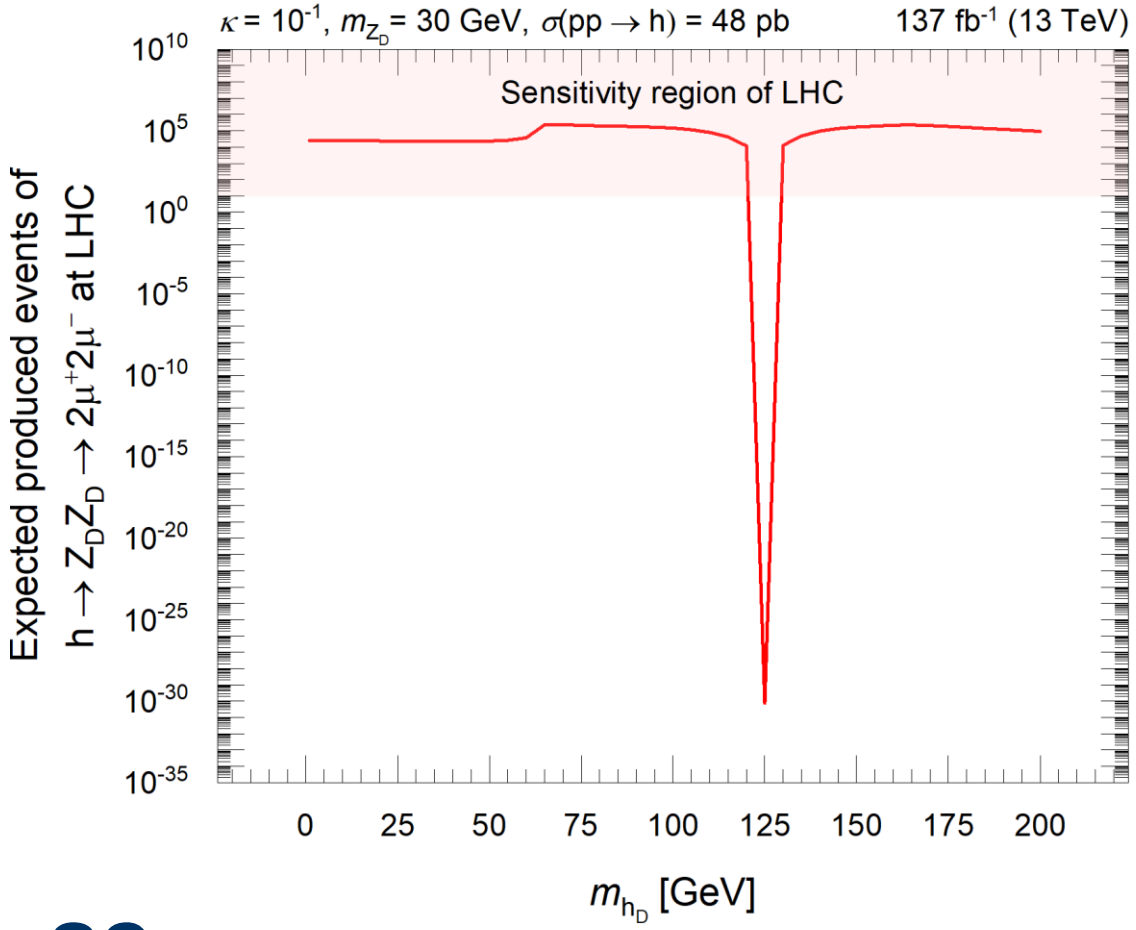
The mass of h_D has a negligible impact on production and total cross sections of Z_D except for the mass of 125 GeV where the total cross section shows an abrupt major dip.

h_D is found to decay only to $Z_D Z_D$ if its mass is 125 GeV.

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

10 events are assumed to be the least number for a resonance to be measured at the LHC.

How many produced events are expected in Run 2 of the LHC as impacted by h_D mass?

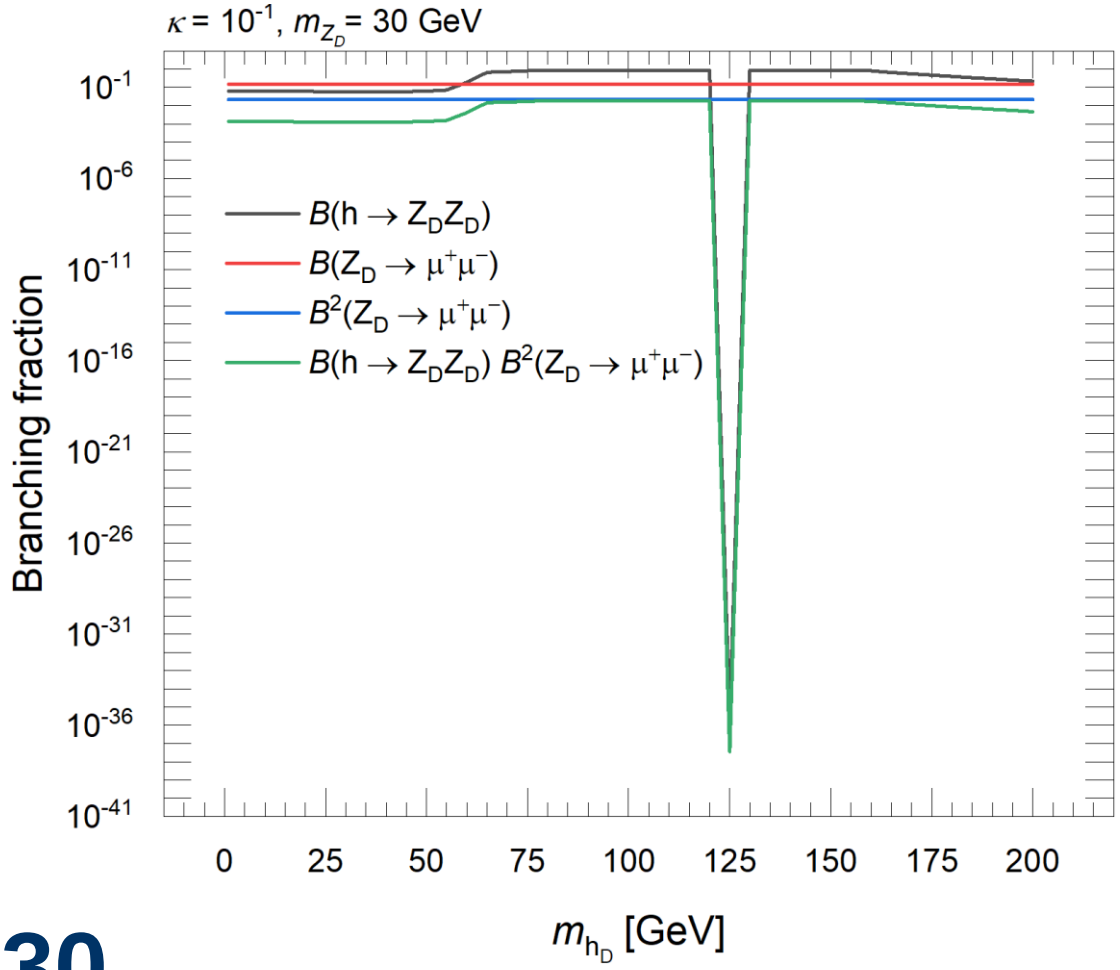


A large number (up to 10^5 events) could have been produced for indirect measurement of Z_D at the LHC during Run 2 for any expected mass of h_D in the range of 1–200 GeV except for the mass of 125 GeV where an acceptance of 100% is assumed.

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO QCD + NLO EW.

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 h_D mass?

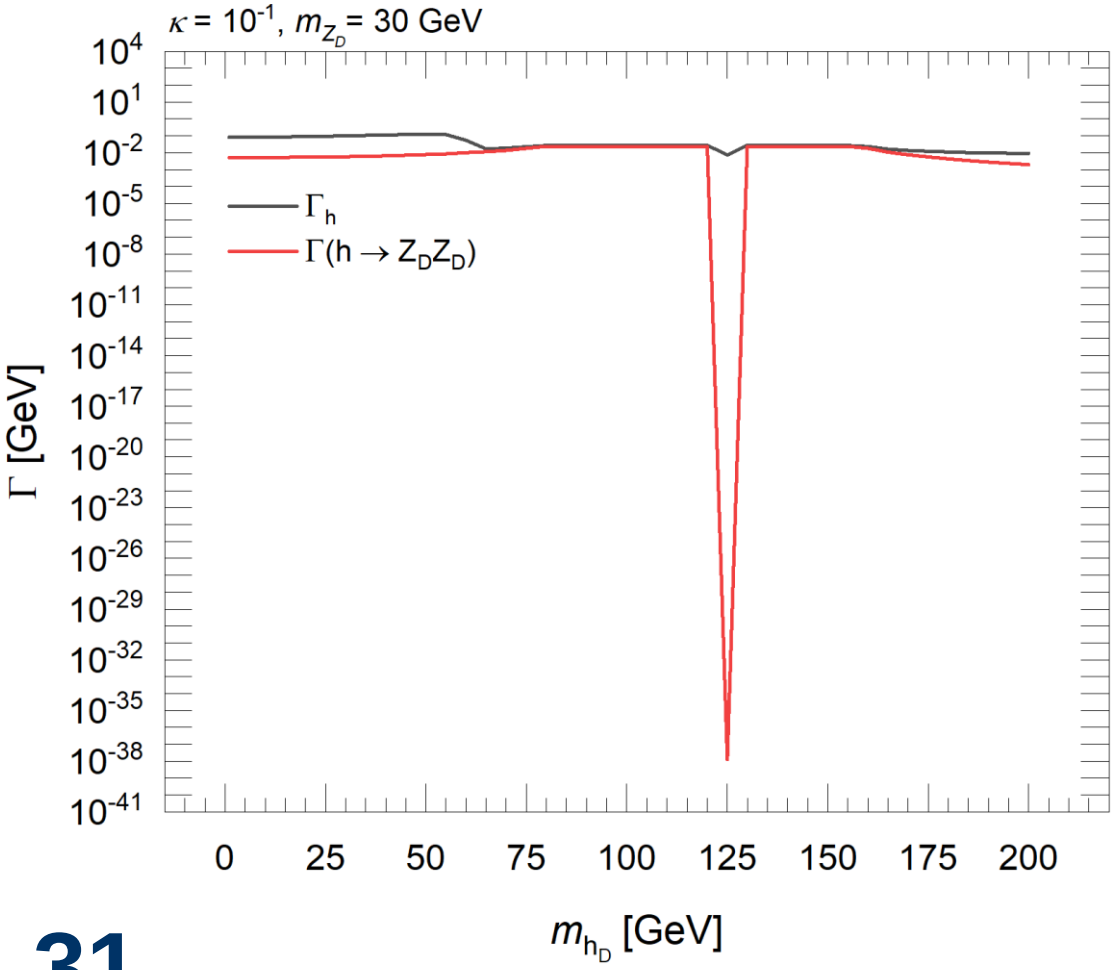


The branching fraction $B(h \to Z_D Z_D)$ shows a major dip at a mass of h_D of 125 GeV.

The branching fraction $B(Z_D \to \mu^+\mu^-)$ is unchanged for all expected masses of h_D in the range of 1–200 GeV.

It is very unlikely that SM Higgs decays to $Z_D Z_D$ if h_D has a mass of 125 GeV, and in substitution h_D in this case decays only to $Z_D Z_D$.

By what factor will the decay width of SM Higgs increase if it is found to decay to Z_DZ_D?

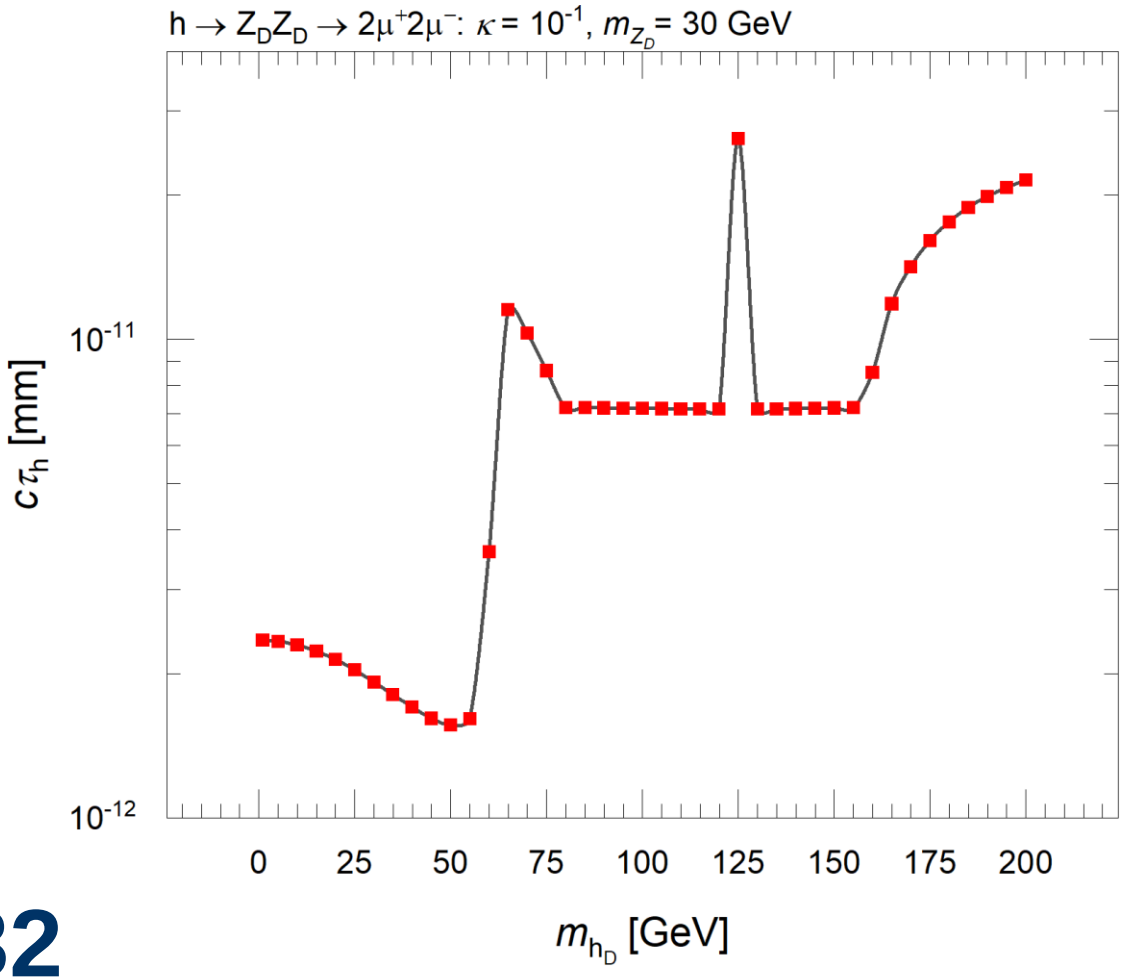


Total decay width of SM Higgs is higher by about one order of magnitude for h_D masses <65 GeV compared to h_D masses >65 GeV.

Total decay width of SM Higgs is expected to increase by about one order of magnitude than the partial decay width of h➔Z_DZ_D for h_D masses <65 GeV, while they are almost equal for h_D masses >65 GeV.

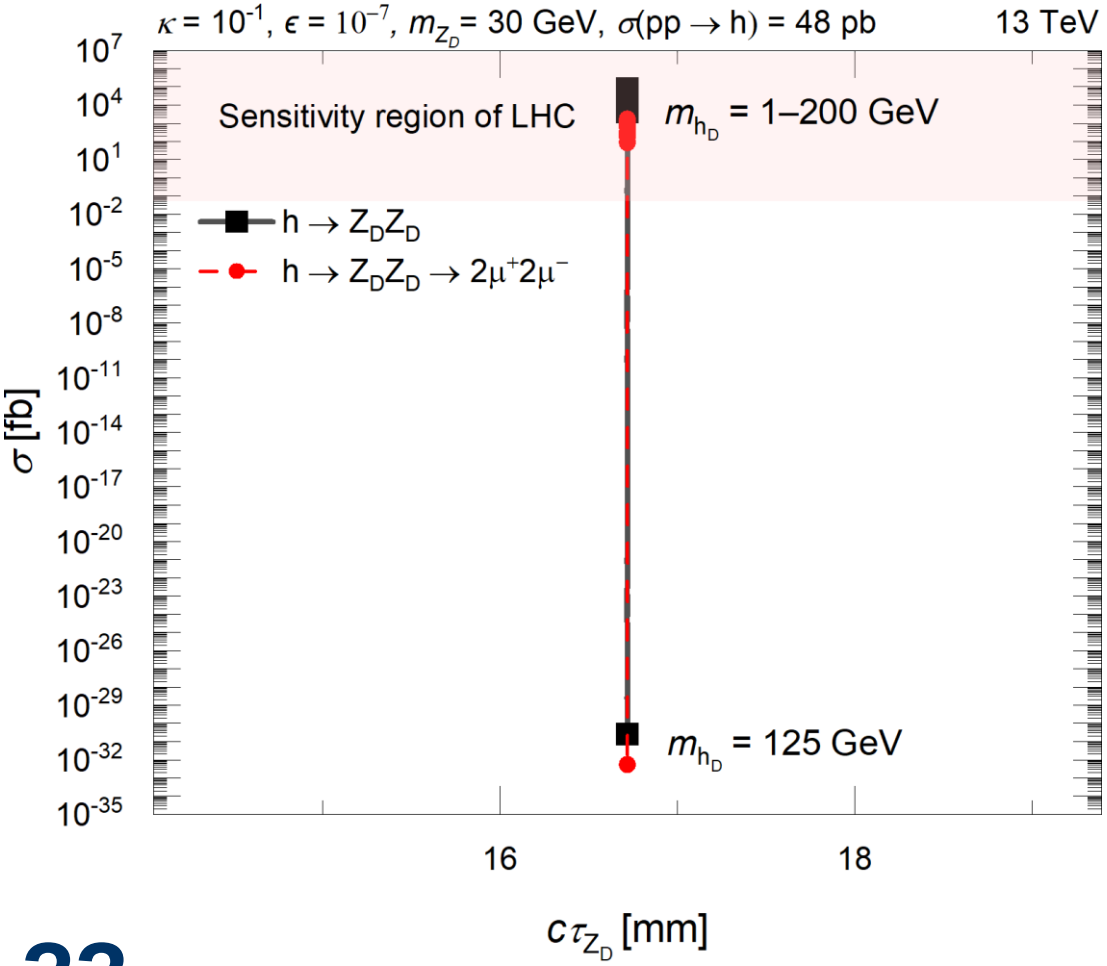
Partial decay width of h➔Z_DZ_D shows a major dip at h_D mass of 125 GeV.

How can the SM Higgs lifetime change with the scan over h_D mass?



Expected new lifetime of SM Higgs varies within one order of magnitude for the h_D mass range of 1–200 GeV.

How do cross section and decay length of Z_D change against each other in the scan over h_D mass?



Lifetime of Z_D is unchanged for all expected production and total cross sections for any mass of h_D in the range of 1–200 GeV.

The LHC is sensitive to the production of Z_D for any mass of h_D in the range of 1–200 GeV.

The LHC is sensitive to the indirect measurement of a long-lived Z_D with a decay length of ~100 m any mass of h_D in the range of 1–200 GeV except for the mass of 125 GeV.

σ(pp➔h) = 48 pb for ggF production channel, calculated to N^{3}LO 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}.