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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 $h \rightarrow Z_DZ_D \rightarrow 2\mu^+2\mu^-$. We are interested in the final state of two dimuons, displaced by 1–7500 mm.

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

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

**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

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

$H =$ SM Higgs real scalar doublet
$S =$ dark Higgs real scalar singlet
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
Scan over Higgs mixing parameter $k$
Scan over Higgs mixing parameter \( k \)

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

\[ Z_D \] 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 \( (k \geq 6 \times 10^{-4}) \) where an acceptance of 100% is assumed.

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

The LHC is assumed to be sensitive down to 0.073 fb based on 10 events to be measured for \( L_{\text{int}} = 137 \text{ fb}^{-1} \).
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.
Scan over Higgs mixing parameter $k$

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

$B(h \rightarrow Z_D Z_D)$ 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 $B(h \rightarrow Z_D Z_D)$ starts to vary with $\epsilon^4$.

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

**Graph:**

- $\epsilon = 10^{-7}$, $m_{Z_D} = 30$ GeV, $m_{h_D} = 200$ GeV
Scan over Higgs mixing parameter $k$

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

The partial decay width of $h \rightarrow Z_DZ_D$ 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 $h \rightarrow Z_DZ_D$ starts to vary with $\epsilon^4$.

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

$\epsilon = 10^{-7}$, $m_{Z_D} = 30$ GeV, $m_{h_D} = 200$ GeV

$\Gamma_h$, $\Gamma(h \rightarrow Z_DZ_D)$

$\kappa$
Scan over Higgs mixing parameter $k$

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 ($k \geq 6 \times 10^{-4}$) and it is unchanged otherwise ($k < 6 \times 10^{-4}$).

Expected maximal lifetime of SM Higgs is found to be higher than the expected minimal lifetime by a factor of $\sim 3$ in the scan over a range of HM parameter of $10^{-12}–10^{-1}$. 
Scan over Higgs mixing parameter \( k \)

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 (\( k \geq 6 \times 10^{-4} \)).

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

The LHC is assumed to be sensitive down to 0.073 fb based on 10 events to be measured for \( L_{int} = 137 \text{ fb}^{-1} \).
Scan over kinetic mixing parameter $\epsilon$
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 $\epsilon^4$) 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 $N^3LO$ 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 mixing parameter $\epsilon$
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 \( \epsilon^4 \).

10 events are assumed to be the least number for a resonance to be measured at the LHC.
The branching fraction $B(h \rightarrow Z_D^+ Z_D^-)$ is maximized and unchanged in the scan over $K_M$ parameter in the range of $10^{-12}$–$10^{-1}$ if $H_M$ is ON.

If $H_M$ is OFF, $B(h \rightarrow Z_D^+ Z_D^-)$ is “drastically” impacted by $K_M$ (it varies as $\epsilon^4$), 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 $H_M$ is OFF.

What causes the total cross section to be highly impacted by $K_M$ if $H_M$ 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 $\sim 4.68 \times 10^{-11}$ 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 $\epsilon^2$, 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.
Scan over kinetic mixing parameter $\epsilon$

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 $h \rightarrow Z_D Z_D$ and measured indirectly via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ at the LHC in Run 2 if HM is ON.

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

$\sigma(pp \rightarrow h) = 48$ 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$^{-1}$. 
For HM being OFF, although prompt $Z_D$ could have been produced via $h \rightarrow Z_D Z_D$ for $\epsilon \geq 0.06$, the LHC in Run 2 is insensitive to the indirect measurement of $Z_D$ via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ for $\epsilon \leq 0.1$.

$\sigma_{ZD}$ is inversely proportional to $\epsilon^2$, while production/total cross section of $Z_D$ is directly proportional to $\epsilon^4$ if HM is OFF, which causes that production/total cross section of $Z_D$ is inversely proportional to $\sigma_{ZD}^2$ if HM is OFF.

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

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 $h \rightarrow Z_D Z_D$ and measured indirectly via $h \rightarrow Z_D Z_D \rightarrow 2\mu^+ 2\mu^-$ 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.

$\sigma(pp \rightarrow h) = 48$ 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.

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

10 events are assumed to be the least number for a resonance to be measured at the LHC.
Scan over dark vector boson $Z_D$ mass

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 $m_{Z_D} < 4$ GeV where it decreases slightly with the increase of $m_{Z_D}$.
By what factor will the current decay width of SM Higgs increase if it is found to decay to $Z_D Z_D$?

The total and partial (i.e., $h \rightarrow Z_D Z_D$) 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 $Z_D Z_D$.

The partial decay width $\Gamma(h \rightarrow Z_D Z_D)$ 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 $Z_DZ_D$?

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 $\sim 5$ 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?

$h \rightarrow Z_DZ_D \rightarrow 2\mu^+2\mu^-; \kappa = 10^{-1}, \epsilon = 10^{-7}, m_{h_D} = 200$ GeV

$Z_D$ 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 $\epsilon = 10^{-7}$, $\text{ct}$ 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).

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

\[\kappa = 10^{-1}, \epsilon = 10^{-7}, m_{h_D} = 200 \text{ GeV}, \sigma(pp \rightarrow h) = 48 \text{ pb}\]
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:


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 ($k \geq 6 \times 10^{-4}$) [See Slide 9], and for $Z_D$ to be long-lived with $c\tau \geq 1$ mm, KM must be negligible ($\epsilon < 5 \times 10^{-7}$) [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.
Backup Slides
Scan over $h_D$ mass
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 $N^3LO$ 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.

$$\sigma(pp \rightarrow h) = 48 \text{ pb}$$ for ggF production channel, calculated to $N^3LO$ 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 $B(h \rightarrow Z_DZ_D)$ shows a major dip at a mass of $h_D$ of 125 GeV.

The branching fraction $B(Z_D \rightarrow \mu^+\mu^-)$ 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 $Z_DZ_D$ if $h_D$ has a mass of 125 GeV, and in substitution $h_D$ in this case decays only to $Z_DZ_D$. 
By what factor will the decay width of SM Higgs increase if it is found to decay to $Z_D Z_D$?

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 $h \rightarrow Z_D Z_D$ for $h_D$ masses $<65$ GeV, while they are almost equal for $h_D$ masses $>65$ GeV.

Partial decay width of $h \rightarrow Z_D Z_D$ 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?

![Graph showing the expected new lifetime of SM Higgs variations within one order of magnitude for the $h_D$ mass range of 1–200 GeV.](image-url)

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.

$\sigma(pp \rightarrow h) = 48$ 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$^{-1}$. 