Dark Matter signals at the LHC from a 3HDM

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Abstract

We analyse new signals of Dark Matter (DM) at the Large Hadron Collider (LHC) in the Z_2 I(2+1)HDM. An interesting signal to study is the loop induced decay of the next-to-lightest scalar, $H_2 \to H_1 f\bar{f}$ ($f = u, d, c, s, b, e, \mu, \tau$). This is a smoking-gun signal of the 3HDM since it is not allowed in the IDM and is expected to be important when H_2 and H_1 are close in mass. In practice, this signature can be observed in the cascade decay of the SM-like Higgs boson, $h \to H_1 H_2 \to H_1 H_1 f\bar{f}$ into two DM particles and di-leptons/di-jets, where h is produced from either gluon-gluon Fusion (ggF) or Vector Boson Fusion (VBF). However, this signal competes with the tree-level channel $q\bar{q} \to H_1 H_1 Z^* \to H_1 H_1 f\bar{f}$.

1 The model

The CPC scalar potential

The potential can be written as:

$$V = V_0 + V_{Z_2}, \tag{1}$$

$$\begin{aligned} V_0 = & -\mu_1^2(\phi_1^\dagger\phi_1) - \mu_2^2(\phi_2^\dagger\phi_2) - \mu_3^2(\phi_3^\dagger\phi_3) + \lambda_{11}(\phi_1^\dagger\phi_1)^2 + \lambda_{22}(\phi_2^\dagger\phi_2)^2 + \lambda_{33}(\phi_3^\dagger\phi_3)^2 \\ & + \lambda_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_{23}(\phi_2^\dagger\phi_2)(\phi_3^\dagger\phi_3) + \lambda_{31}(\phi_3^\dagger\phi_3)(\phi_1^\dagger\phi_1) \\ & + \lambda'_{12}(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda'_{23}(\phi_2^\dagger\phi_3)(\phi_3^\dagger\phi_2) + \lambda'_{31}(\phi_3^\dagger\phi_1)(\phi_1^\dagger\phi_3), \end{aligned} \tag{2}$$

$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_2)^2 + \lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + \text{h.c.}. \tag{3}$$

We shall no consider CPV here, therefore we require all parameters of the potential to be real.

The minimum of the potential is realised for the following point:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}, \tag{4}$$

with $v^2 = \mu_3^2/\lambda_{33}$. ϕ_1 and ϕ_2 are the inert doublets (charge -1 under Z_2). ϕ_3 is the active (SM) doublet (charge 1 under Z_2, same as SM particles), with $m_h^2 = 2\mu_3^2 = (125\text{GeV})^2$.

We choose our parameters so that

$$m_{H_1} < m_{H_2}, m_{A_{1,2}}, m_{H_{1,2}^\pm},$$

then H_1 is our DM candidate.

Simplified couplings

We focus on a simplified case in where:

$$\mu_1^2 = n\mu_2^2, \quad \lambda_3 = n\lambda_2, \quad \lambda_{31} = n\lambda_{23}, \quad \lambda'_{31} = n\lambda'_{23}, \tag{5}$$

$n \to 0$, model reduces to the IDM.

Input parameters:

$$m_{H_1}, m_{H_2}, g_{H_1 H_1 h}, \theta_a, \theta_c, n \tag{6}$$

$g_{H_1 H_1 h}$ Higgs-DM coupling. $\theta_{a,c}$ angles that diagonalise pseudoscalar and charged sectors. n is related to θ_h:

$$\tan^2\theta_h = \frac{m_{H_1}^2 - n m_{H_2}^2}{n m_{H_1}^2 - m_{H_2}^2}. \tag{7}$$

$n \to 1$ equalise both inerts, $\theta_h = \pi/4$. We need: $m_{H_1}^2 < n m_{H_2}^2$ and $m_{H_1}^2 < \frac{1}{n} m_{H_2}^2$. We take $n < 1 \Rightarrow \tan 2\theta > 0$ for $\theta_h < \pi/4$.

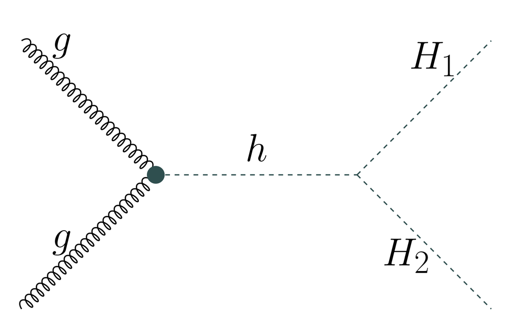
Other values of n is a matter of reparametrisation of the potential.

2 Decays at the LHC

Inert decays lead to the resulting detector signature $E_T f\bar{f}$ ($f = u, d, c, s, b, e, \mu, \tau$). Access to the inert sector can be obtained through the SM-like h or $Z/W^\pm$.

ggF production

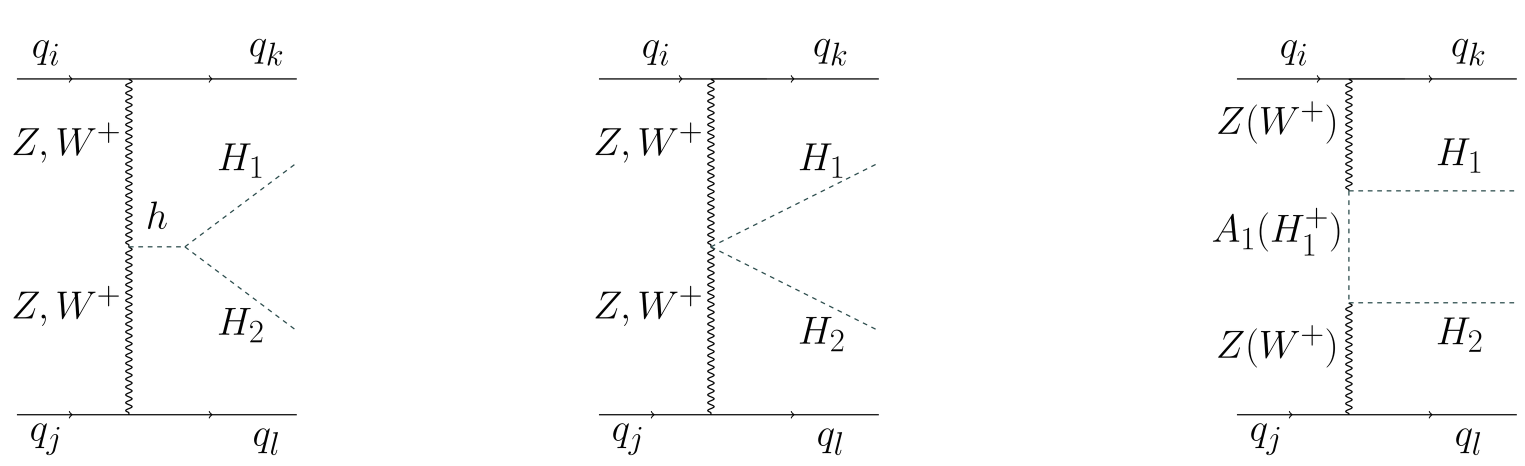
$$gg \to h \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$$



- Benchmarks are designed to increase this signature
- We try larger $g_{hH_1H_1}$ if it is consistent with DM constraints
- Promissing signature if others decays are suppressed and $m_{H_1} + m_{H_2} \approx m_h$

VBF production

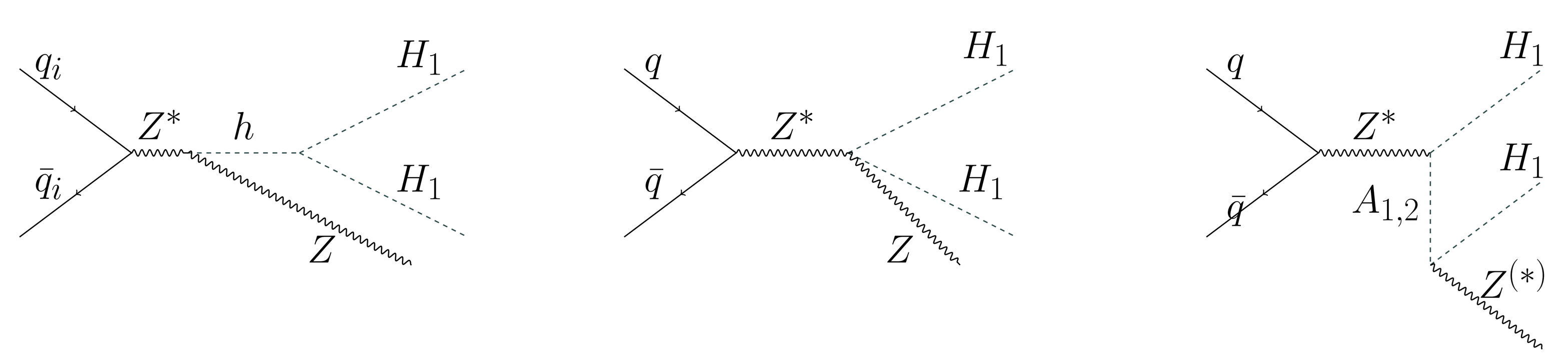
$$q_i q_j \to q_k q_l H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$$



Background signature (significant)

$$q\bar{q} \to Z^* \to H_1 H_1 Z^{(*)} \to H_1 H_1 f\bar{f}$$

and $$q\bar{q} \to Z^* \to H_1 A_i \to H_1 H_1 Z^{(*)} \to H_1 H_1 f\bar{f}$$



3 Calculation

The general structure for the amplitude is:

$$\mathcal{M} = ie\bar{v}(k_1)\gamma^\nu u(k_2)\frac{ig_{\mu\nu}}{(p_3 - p_2)^2}[A(p_3 + p_2)^\mu] \tag{8}$$

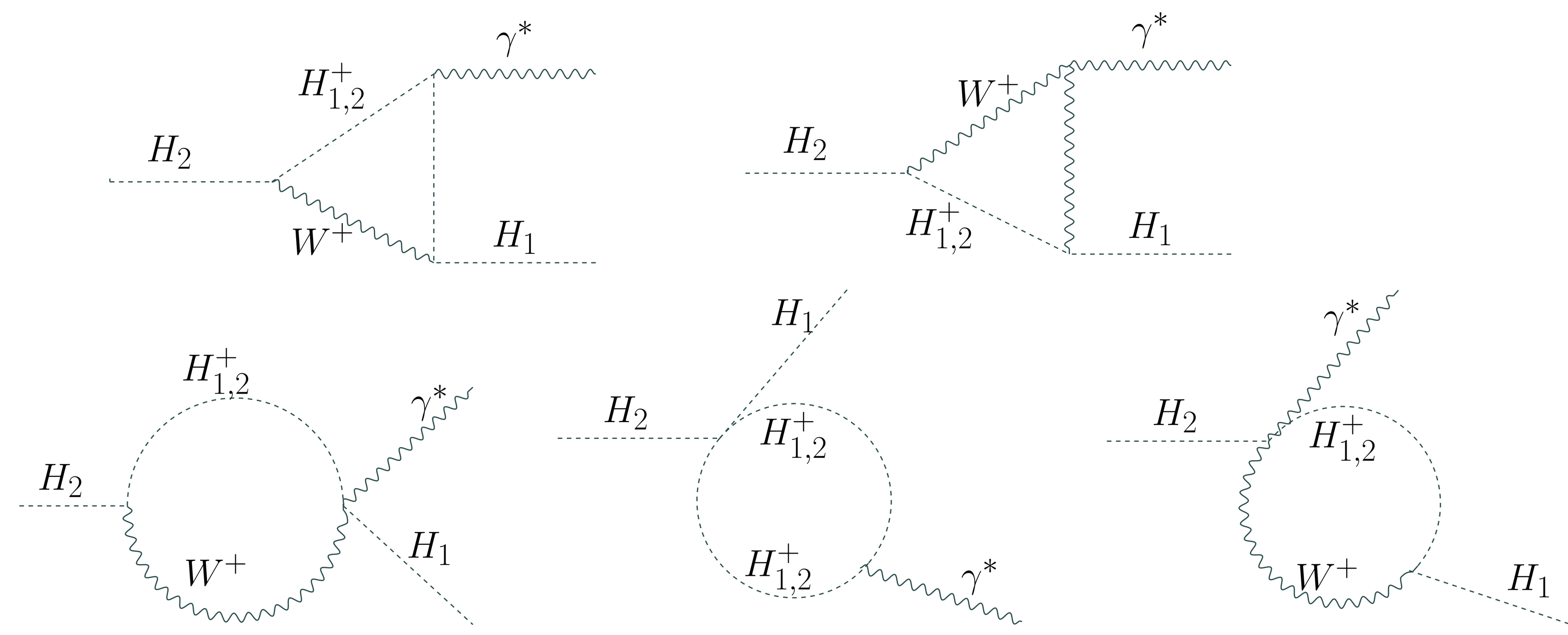


Figure 1: Triangle and bubble diagrams contributing to the $H_2 \to H_1\gamma^*$ decay, where the lightest inert particle is absolutely stable and hence invisible, while γ^* is a virtual photon that couples to fermion-antifermion pairs.

- We add an effective term $H_2 \to H_1 f\bar{f}$:

$$L_{\text{eff}} = L_{\text{I(2+1)HDM}} + iK_f(H_1\partial_\mu H_2 - H_2\partial_\mu H_1)\bar{f}\gamma^\mu f$$

- Amplitude:

$$\mathcal{M} = iK_f\bar{v}(k_1)\gamma^\mu(p_3 + p_2)_\mu u(k_2) \Rightarrow |\mathcal{M}|^2 \sim K_f^2 \tag{9}$$

- Calculate $\Gamma(H_2 \to H_1\gamma^* \to H_1 f\bar{f})$ with `LoopTools` then compare (8) with (9):

$$K_f^2 = \frac{16\pi^3 m_{H_2}^3 \Gamma(H_2 \to H_1 f\bar{f})}{I_3}, \tag{10}$$

  where I_3 is a phase space integral
- We can use L_{eff} for numerical scans in `CalcHEP`

4 Results

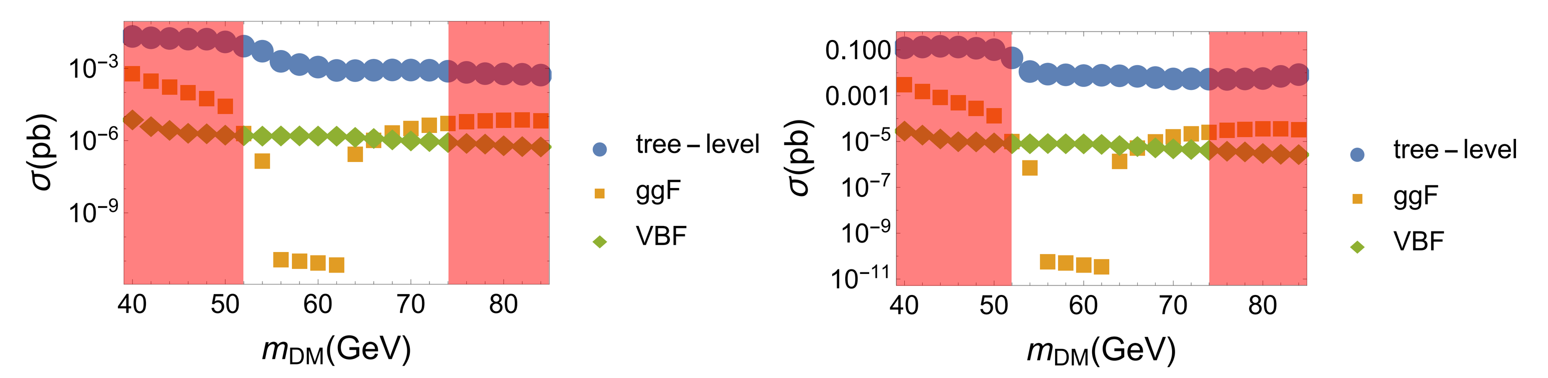


Figure 2: The anatomy of scenario A50. The plots show the cross sections with leptonic (left) and hadronic (right) final states. The red regions are ruled out by LHC ($m_{DM} < 53$ GeV) and by direct detection ($m_{DM} > 73$ GeV).

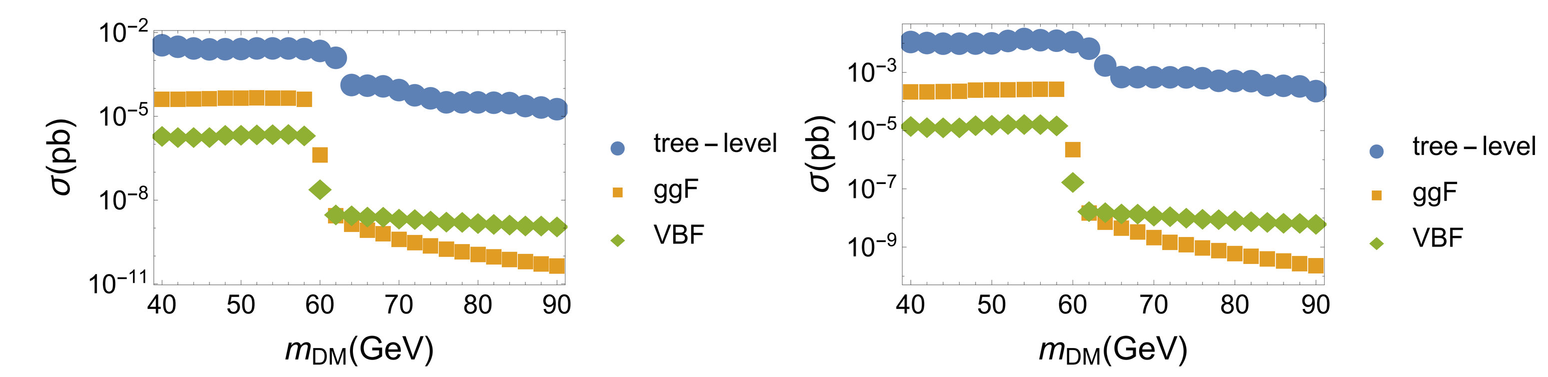


Figure 3: The anatomy of scenario I5. The plots show the cross sections with leptonic (left) and hadronic (right) final states.

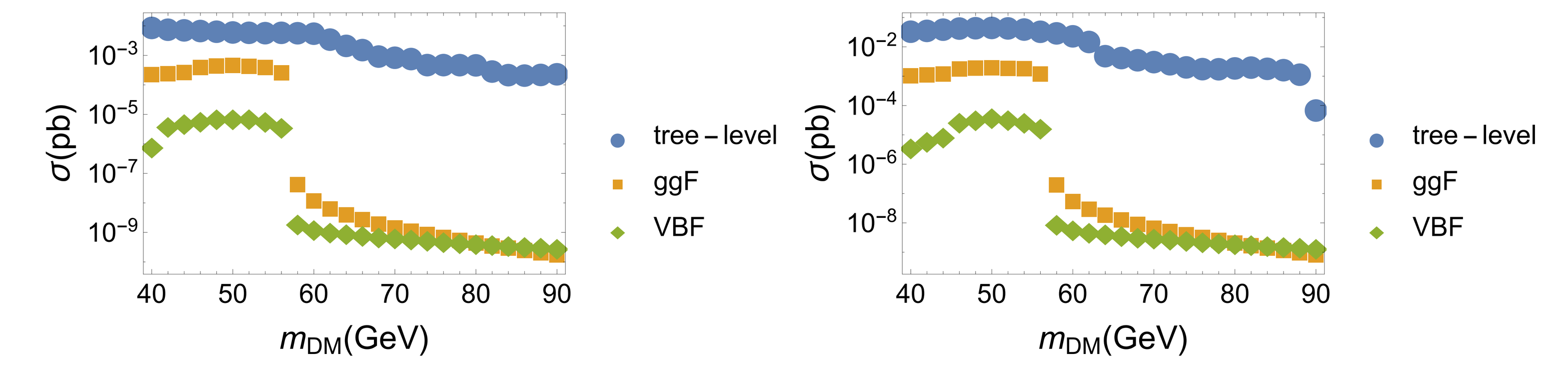


Figure 4: The anatomy of scenario I10. The plots show the cross sections with leptonic (left) and hadronic (right) final states.

Benchmark	$m_{H_2} - m_{H_1}$	$m_{A_1} - m_{H_1}$	$m_{A_2} - m_{H_1}$	$m_{H_1^\pm} - m_{H_1}$	$m_{H_2^\pm} - m_{H_1}$
A50	50	75	125	75	125
I5	5	10	15	90	95
I10	10	20	30	90	100

Table 1: Definition of benchmark scenarios with the mass splittings shown in GeV.

Conclusions

- A full calculation of the one-loop induced decay $H_2 \to H_1\gamma^* \to H_1 f\bar{f}$ was performed.
- This signature would emerge from SM-like Higgs boson production (ggF and VBF) and is distinctive of the I(2+1)HDM.
- With a small mass difference between the CP-even dark scalars the final state that would appear at detector level is a single EM shower plus a substantial E_T.
- The background process corresponds to a tree-level process which can also be present in the IDM. However, the cumulative signal of the VBF and ggF processes could be greater for DM mass $m_{DM} < m_h/2$, testable at Run 2 and 3.
- These searches included all up-to-date theoretical and experimental constraints.

Acknowledgements

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