Updated HAHM MadGraph Model

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Contents

1 Introduction

Here we outline all the derivations necessary to construct a fully self-consistent MadGraph model for the Hidden Abelian Higgs Model (HAHM) using FeynRules 2.0.23. The notation for the construction of the HAHM model follows [1], but apart from a single parameter redefinition it is identical to the Dark Vector simplified model we defined in our Exotic Higgs Survey [2].

This is based on the HAHM MG model by C. Duhr from the FeynRules website, but has been extensively modified to correct typos, implement self-consistent derivation of mixing angles from M_Z, M_{Z_D}, M_h, M_{h_s} *mass eigenvalue* inputs. Mixing angles have also been defined in such a way that for small kinetic or higgs mixing $\ll 1$, the corresponding mixing angle will also be $\ll 1$ regardless of whether the dark or SM higgs/Z is heavier or lighter. (Not the case in the original HAHM MG model.)

We also outline how the model was tested against analytical expressions, and how to use the model for collider studies.

The fully self-consistent nature of the MG model means it can be trusted to correctly simulate any aspect of higgs decay into dark sector states, including interference terms for off-shell production or decay (e.g. $h \to Z\ell\ell$ with off-shell Z and Z_D). The model also includes the effective ggh and $\gamma\gamma h$ vertices from the HiggsEffective FeynRules model to enable the simulation of gluon-initiated production, but production cross sections should be rescaled to the correct NLO values, and the partial decay width for $h \to gg, \gamma\gamma$ should not be trusted. Similarly, all higgs or vector decays are LO, so $\mathcal{O}(1)$ QCD corrections for quark final states are not taken into account.

Note that this model can also be used to simulate only the SM + Singlet Scalar mixing with the higgs (e.g. for $h \to 2a \to 4b$ decays) by setting the kinetic mixing to zero. Similarly, higgs mixing can be set to zero to allow for purely kinetic-mixing dominated phenomenology.

2 Model Definition

We mostly follow the notation of [1]. In addition to the normal SM Lagrangian there is a $U(1)_X$ gauge symmetry with gauge boson $\hat{X}_\mu$ which kinetically mixes with hypercharge:

$$\mathcal{L}_X = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}. \tag{1}$$

The mixing χ should be small $\ll 1$ to be in agreement with electroweak precision constraints. There is an additional SM-singlet 'dark higgs' Φ_H with $U(1)_X$ charge q_X. Φ_{SM} is the SM higgs doublet.

$$\begin{aligned}\mathcal{L}_\Phi &= |D_\mu\Phi_{SM}|^2+|D_\mu\Phi_H|^2+\mu^2_{\Phi_H}|\Phi_H|^2+\mu^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ &\quad -\lambda|\Phi_{SM}|^4-\rho|\Phi_H|^4-\kappa|\Phi_{SM}|^2|\Phi_H|^2,\end{aligned} \tag{2}$$

The $U(1)_X$ is broken spontaneously by $\langle\Phi_H\rangle = \xi/\sqrt{2}$, and electroweak symmetry is broken spontaneously by $\langle\Phi_{SM}\rangle = (0, v/\sqrt{2})$.

Note that this model definition is identical to the SM + Vector simplified model of [2], with the parameter substitution

$$\chi \to \frac{\epsilon}{\cos\theta_W} \quad , \qquad \kappa \to \zeta. \tag{3}$$

3 Gauge Boson Spectrum

The 'hatted' gauge bosons do not have canonical kinetic terms. The gauge bosons can be made canonical via the transformation

$$\begin{pmatrix} X_\mu \\ Y_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\chi^2} & 0 \\ -\chi & 1 \end{pmatrix} \begin{pmatrix} \hat{X}_\mu \\ \hat{Y}_\mu \end{pmatrix}.$$

This gives a covariant derivative

$$D_\mu = \partial_\mu + i(g_X Q_X + g'\eta Q_Y)X_\mu + ig'Q_Y B_\mu + igT^3 W^3_\mu\ . \tag{4}$$

where $\eta \equiv \chi/\sqrt{1-\chi^2}$, and a factor of $\sqrt{1-\chi^2}$ has been absorbed into the $U(1)_X$ gauge coupling:

$$g_X = \frac{\hat{g}_X}{\sqrt{1-\chi^2}}. \tag{5}$$

The photon stays massless, but the SM-Z-boson (which we call Z_0) and the $U(1)_X$ gauge boson have a small mass mixing as a consequence of making the kinetic term canonical. In the (Z_0, X) basis:

$$M^2_{Z_0 X} = M^2_{Z_0} \begin{pmatrix} 1 & -s_w \eta \\ -s_w \eta & \Delta_Z + sw^2 \eta \end{pmatrix}, \tag{6}$$

where $\Delta_Z = M_X^2/M_{Z_0}^2$. $M_{Z_0}^2$ is as in the SM, and $M_X^2 = \xi^2 g_X^2 q_X^2$. The product $g_X q_X$ only matters for determining M_X in terms of the vev ξ and is arbitrary.

Adopting precisely the mixing angle definitions of [1], we define mass eigenstates Z, Z_D by

$$\begin{pmatrix} Z \\ Z_D \end{pmatrix} = \begin{pmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{pmatrix} \begin{pmatrix} Z_0 \\ X \end{pmatrix} \tag{7}$$

. The gauge boson mixing angle is given by

$$\tan\theta_a = \frac{1 - s_w^2\eta^2 - \Delta_Z - \mathrm{Sign}(1-\Delta_Z)\sqrt{4 s_w^2 \eta^2 + (1 - s_w^2\eta^2 - \Delta_Z)^2}}{2 s_w \eta}. \tag{8}$$

This reproduces the expression in [1]

$$\tan(2\theta_\alpha) = \frac{-2 s_W \eta}{1 - s_W^2 \eta^2 - \Delta_Z}. \tag{9}$$

and reduces to $\tan\theta_a \approx s_w\eta/(-1+\Delta_Z)$ in the $\eta \ll 1$ limit. The mass eigenvalues are

$$M^2_{Z,Z_D} = \frac{1}{2} M^2_{Z_0} \left(1 + s_w^2\eta^2 + \Delta_Z \ \pm \mathrm{Sign}(1-\Delta_Z)\sqrt{4 s_w^2\eta^2 + (1 - s_w^2\eta^2 - \Delta_Z)^2}\right) \tag{10}$$

Note that the mass eigenvalues can't be arbitrarily close to each other for nonzero η due to level splitting, more on that below.

4 Higgs Spectrum

$\langle \Phi_H \rangle = \xi/\sqrt{2}$ and $\langle \Phi_{SM} \rangle = (0, v/\sqrt{2})$ requires

$$\mu^2_{\Phi_{SM}} = v^2\lambda + \frac{1}{2}\kappa\xi^2 \quad , \qquad \mu^2_{\Phi_H} = \xi^2\rho + \frac{1}{2}\kappa v^2 \tag{11}$$

Expanding in small fluctiations $\phi_{SM,H}$ around the vacuum, the higgs mass matrix in the (ϕ_{SM}, ϕ_H) basis is

$$M^2_{\phi_{SM}\phi_H} = \begin{pmatrix} 2v^2\lambda & v\xi\kappa \\ v\xi\kappa & 2\xi^2\rho \end{pmatrix}, \tag{12}$$

Again adopting precisely the mixing angle definitions in [1], we define mass eigenstates (h, h_s)

$$\begin{pmatrix} h \\ h_s \end{pmatrix} = \begin{pmatrix} \cos\theta_a & -\sin\theta_a \\ \sin\theta_a & \cos\theta_a \end{pmatrix} \begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix}. \tag{13}$$

(Notice the minus sign.) For small mixing angle, h is dominantly SM-higgs-like and h_s is dominantly singlet-higgs like. The mixing angle is given by

$$\tan\theta_h = \frac{v^2\lambda - \xi^2\rho - \mathrm{Sign}(v^2\lambda - \xi^2\rho)\sqrt{v^4\lambda^2 + \xi^4\rho^2 + v^2\xi^2(\kappa^2 - 2\lambda\rho)}}{v\xi\kappa} \tag{14}$$

This reproduces the expression in [1]

$$\tan 2\theta_h = \frac{\kappa v\xi}{\rho\xi^2 - \lambda v^2} \tag{15}$$

and reduces to $\tan\theta_h \approx v\xi\kappa/(-2v^2\lambda + 2\xi^2\rho)$ in the $\kappa \ll 1$ limit. The mass eigenvalues are

$$M^2_{h,h_s} = v^2\lambda + \xi^2\rho \pm \mathrm{Sign}(v^2\lambda - \xi^2\rho)\sqrt{v^4\lambda^2 + \xi^4\rho^2 + v^2\xi^2(\kappa^2 - 2\lambda\rho)} \tag{16}$$

Note that in both the higgs and gauge boson case it is important to define the mixing angle directly from the $\tan\theta$ with the Sign(...) expression included. Defining it from $\tan 2\theta$ does not specify which of the two possible solutions for $\tan\theta$ give small ($\ll 1$) mixing angles in the κ or $\xi \ll 1$ limit.

5 Couplings and Partial Widths

5.1 Couplings

Copying this straight from [1]. This has been verified in [2].

Fermion couplings: Couplings to SM fermions are

$$\begin{aligned} \bar\psi\psi Z &: \frac{ig}{c_W}\left[c_\alpha(1 - s_W t_\alpha \eta)\right]\left[T^3_L - \frac{(1 - t_\alpha\eta/s_W)}{(1 - s_W t_\alpha\eta)} s^2_W Q\right] \\ \bar\psi\psi Z_D &: \frac{-ig}{c_W}\left[c_\alpha(t_\alpha + \eta s_W)\right]\left[T^3_L - \frac{(t_\alpha + \eta/s_W)}{(t_\alpha + \eta s_W)} s^2_W Q\right] \end{aligned} \tag{17}$$

where $Q = T^3_L + Q_Y$ and $t_\alpha \equiv s_\alpha/c_\alpha$. The photon coupling is as in the SM and is not shifted.

Triple gauge boson couplings: With $\mathcal{R}$ being the coupling relative to the corresponding SM, one finds $\mathcal{R}_{AW^+W^-} = 1$, $\mathcal{R}_{ZW^+W^-} = c_\alpha$ and $\mathcal{R}_{Z_D W^+W^-} = -s_\alpha$ (the last is compared to the SM ZW^+W^- coupling).

Higgs couplings: The Higgs couplings are

$$\begin{aligned}
hff &: -ic_h\frac{m_f}{v}\ , \qquad hWW : 2ic_h\frac{M_W^2}{v}\ , \\
hZZ &: 2ic_h\frac{M_{Z_0}^2}{v}(-c_\alpha+\eta s_W s_\alpha)^2 - 2is_h\frac{M_X^2}{\xi}s_\alpha^2\ , \\
hZ_DZ_D &: 2ic_h\frac{M_{Z_0}^2}{v}(s_\alpha+\eta s_W c_\alpha)^2 - 2is_h\frac{M_X^2}{\xi}c_\alpha^2\ , \\
hZ_DZ &: 2ic_h\frac{M_{Z_0}^2}{v}(-c_\alpha+\eta s_W s_\alpha)(s_\alpha+\eta s_w c_\alpha) - 2is_h\frac{M_X^2}{\xi}s_\alpha c_\alpha\ .
\end{aligned} \tag{18}$$

5.2 Partial Widths

Here we collect analytical expressions for some exotic decay widths, at lowest order in χ or κ.

To first order in kinetic mixing χ, the coupling of Z_D to fermions is given by

$$g_{Z_D f\bar{f}} = \frac{\chi g'\left(c_w^2 M_Z^2(\mathrm{T3}+Y) - YM_{Z_D}^2\right)}{M_Z^2 - M_{Z_D}^2} \tag{19}$$

Y is the hypercharge of the fermion. This gives

$$\Gamma(Z_D \to f\bar{f}) = \frac{N_c}{24\pi M_{Z_D}}\sqrt{1-\frac{4m_f^2}{M_{Z_D}^2}}\left(M_{Z_D}^2\left(g_L^2+g_R^2\right) - m_f^2\left(-6g_Lg_R+g_L^2+g_R^2\right)\right) \tag{20}$$

where $g_{L,R} = g_{Z_D f_{L,R}\bar{f}_{L,R}}$.

Decays of the SM-like higgs to dark vectors.

$$\Gamma(h \to Z_DZ_D) = \frac{\kappa^2\sqrt{M_h^2-4M_{Z_D}^2}\left(-4M_h^2M_{Z_D}^2+12M_{Z_D}^4+M_h^4\right)}{64\pi\lambda\left(M_h^2-M_{h_s}^2\right)^2} \tag{21}$$

$$\begin{aligned}
\Gamma(h \to ZZ_D) \quad = \quad & \frac{\chi^2 s_w^2 M_Z^2 M_{Z_D}^2}{16\pi v^2 M_h^3\left(M_Z^2-M_{Z_D}^2\right)^2}\times \\
& \left(-2M_{Z_D}^2\left(M_h^2-5M_Z^2\right)+M_{Z_D}^4+\left(M_h^2-M_Z^2\right)^2\right)\times \\
& \sqrt{-2M_h^2\left(M_{Z_D}^2+M_Z^2\right)+\left(M_Z^2-M_{Z_D}^2\right)^2+M_h^4}
\end{aligned} \tag{22}$$

Decay of SM-like higgs to singlet higgs:

$$\Gamma(h \to h_sh_s) = \frac{\kappa^2 v^2}{32\pi M_h}\frac{(M_h^2+2M_{h_s}^2)^2}{(M_h^2-M_{h_s}^2)^2}\sqrt{1-\frac{4M_{h_s}^2}{M_h}} \tag{23}$$

The decay widths of the singlet higgs are the same as for a SM higgs of that mass, rescaled by the mixing angle. At LO,

$$\Gamma(h_s \to f\bar{f}) = s_{\theta_h}^2\frac{N_c}{8\pi}M_{h_s}\frac{m_f^2}{v^2}\left(1-\frac{4m_f^2}{M_{h_s}}\right)^{3/2} \tag{24}$$

6 HAHM MG Model

This is based on the HAHM MG model by C. Duhr from the FeynRules website, but has been extensively modified to correct typos, implement self-consistent derivation of mixing angles from M_Z, M_{Z_D}, M_h, M_{h_s} *mass eigenvalue* inputs. Mixing angles have also been defined in such a way that for small kinetic or higgs mixing $\ll 1$, the corresponding mixing angle will also be $\ll 1$ regardless of whether the dark or SM higgs/Z is heavier or lighter. (Not the case in the original HAHM MG model.)

If we do everything consistently then the tree-level SM relation

$$\cos\theta_w = \frac{g}{\sqrt{g^2 + g'^2}} = \frac{M_W}{M_Z} \tag{25}$$

has to be modified in the presence of $Z - Z_D$ mixing. Below we show how to self-consistently do this in two ways, by shifting either the W pole mass or the measured Weinberg mixing angle from its SM value.

6.1 Mass Eigenvalue inputs, varying M_W

This is implemented in the FeynRules MadGraph model `HAHM_final_variableMW.fr`.

6.1.1 Gauge Sector

If we keep s_w fixed at its SM value and take the Z pole mass as an input, then the *pre-kinetic-mixing* Z-mass M_{Z_0} will be slightly different from M_Z, giving a slight shift to M_W.

Solving for M_{Z_0} and Δ_Z for fixed mass eigenvalues M_Z, M_{Z_D} yields[1]

$$M_{Z_0} = \sqrt{\frac{-\mathrm{Sign}\left(M_{Z_D} - M_Z\right)\sqrt{-2M_Z^2 M_{Z_D}^2\left(2\eta^2 s_w^2 + 1\right) + M_{Z_D}^4 + M_Z^4} + M_{Z_D}^2 + M_Z^2}{2\eta^2 s_w^2 + 2}} \tag{26}$$

$$\begin{aligned}\Delta_Z \;=\; & \frac{1}{2M_{Z_D}^2 M_Z^2}\Bigg[M_Z^2\,\mathrm{Sign}\left(M_{Z_D} - M_Z\right)\sqrt{-2M_Z^2 M_{Z_D}^2\left(2\eta^2 s_w^2 + 1\right) + M_{Z_D}^4 + M_Z^4} \\ & + M_{Z_D}^2\left(\mathrm{Sign}\left(M_{Z_D} - M_Z\right)\sqrt{-2M_Z^2 M_{Z_D}^2\left(2\eta^2 s_w^2 + 1\right) + M_{Z_D}^4 + M_Z^4} - 2\eta^2 M_Z^2 s_w^2\right) \\ & + M_{Z_D}^4 + M_Z^4\Bigg]\end{aligned} \tag{27}$$

This solution exists as long as the following condition is satisfied:

$$\left|\frac{M_{Z_D}}{M_Z} - \sqrt{1 + s_w^2\eta^2}\right| > s_w|\eta| \tag{28}$$

otherwise level splitting prevents such mass eigenvalues from being possible for the given kinetic mixing η.

[1] Note that turning on mixing in a 2×2 mass matrix can only *increase* mass splitting, so $\mathrm{Sign}(M_{Z_D} - M_Z) = \mathrm{Sign}(M_{Z_0} - M_X)$ etc, similarly in the higgs sector.

6.1.2 Higgs Sector

The SM higgs VEV is given by the Fermi constant

$$v = \frac{1}{\sqrt{\sqrt{2}G_F}} \tag{29}$$

while the singlet higgs VEV is given by the desired dark vector gauge boson mass before mixing (determined above)

$$\xi = \frac{M_X}{q_X g_X} \tag{30}$$

One then has to solve for the quartic couplings λ, ρ in terms of the desired mass eigenvalues M_h, M_{h_s}:

$$\lambda, \rho = \frac{\pm \operatorname{Sign}(M_h - M_{h_S}) \sqrt{\left(M_h^2 - M_{h_S}^2\right)^2 - 4\kappa^2\xi^2v^2} + M_{h_S}^2 + M_h^2}{4v^2} \tag{31}$$

This solution exists as long as the following condition is satisfied

$$(M_h^2 - M_{h_s}^2)^2 - 4v^2\xi^2\kappa^2 > 0 \tag{32}$$

In terms of these inputs, the mixing angle is

$$\tan\theta_h = \frac{\operatorname{Sign}(M_h - M_{h_s}) \sqrt{\left(M_h^2 - M_{h_s}^2\right)^2 - 4\kappa^2\xi^2v^2} + M_{h_s}^2 - M_h^2}{2\kappa\xi v} \tag{33}$$

6.2 Mass Eigenvalue inputs, varying $\sin^2\theta_w$

This is implemented in the FeynRules MadGraph model `HAHM_final_variablesw.fr`.

6.2.1 Gauge Sector

Now we set the SM value of M_W as an input and let $c_w = M_W/M_{Z_0}$ as an output of the calculation. This means s_w has to be replaced everywhere by $\sqrt{1 - M_W^2/M_{Z_0}^2}$, and then we have to solve for M_{Z_0}.

Solving for M_{Z_0} and Δ_Z for fixed mass eigenvalues M_Z, M_{Z_D} yields

$$M_{Z_0} = \sqrt{\frac{\operatorname{Sign}(M_Z - M_{Z_D}) \sqrt{A^2 - 4(\eta^2+1) M_Z^2 M_{Z_D}^2} + A}{2(\eta^2+1)}} \tag{34}$$

$$\Delta_Z = \frac{(\eta^2+1)\left(\operatorname{Sign}(M_{Z_D} - M_Z) \sqrt{A^2 - 4(\eta^2+1) M_Z^2 M_{Z_D}^2} + A\right)}{\operatorname{Sign}(M_Z - M_{Z_D}) \sqrt{A^2 - 4(\eta^2+1) M_Z^2 M_{Z_D}^2} + A} \tag{35}$$

where

$$A = M_{Z_D}^2 + M_Z^2 + \eta^2 M_W^2. \tag{36}$$

This solution exists as long as the following condition is satisfied:

$$\frac{A^2 M_Z^2}{M_Z^4 M_{Z_D}^4} > 4(1+\eta^2). \tag{37}$$

6.2.2 Higgs Sector

This is identical to the previous case.

6.3 Verification & Limits of Applicability

We numerically evaluated the following partial widths in MadGraph (in both versions of this model)

- $\Gamma(h \to ff, Vff, gg, \gamma\gamma)$
- $\Gamma(h \to h_s h_s)$
- $\Gamma(h \to Z Z_D)$
- $\Gamma(h \to Z_D Z_D)$
- $\Gamma(h_s \to ff, Vff, gg, \gamma\gamma)$,
- $\Gamma(Z_D \to ff)$

In all cases, the results agree with LO analytical expressions of the partial widths given in Section 5. This means it is *incorrect* for $gg, \gamma\gamma$ final states, and also does not include the important $\mathcal{O}(1)$ QCD corrections for quark final states. *The higgs decays to vector bosons and leptons can be trusted.*

The HAHM MG model is now verified to be correct within its level of approximation. The HEFT operators are only there to enable the respective production and decays to be used in event generation, but in those cases the cross sections and partial widths have to be manually rescaled.[2]

For calculations where interference effects in decays might important (e.g. $h \to \ell\ell\ell'\ell'$ where Z and Z_D can interfere with each other) the HEFT vertices should be switched off in the decay.

6.4 Usage

Copy the folders `HAHM_variableMW_UFO`, `HAHM_variablesw_UFO` to the Madgraph5 models directory. Then after running `./bin/mg5_aMC` we can import these models by typing `import model --modelname HAHM_variableMW_UFO` etc.

The two models (variablesw and variableMW) represent genuinely different possibilities for modifying the SM tree-level relation Eq. (25). As long as the chosen ϵ are allowed by electroweak precision constraints, the differences for a collider analysis are minimal. In principle, however, both models should be used for an analysis if interference effects are important (e.g. off-shell Z_D).

The two new particle names are `hs` for the singlet-like higgs mass eigenstate, and `zp` for the dark-vector-like gauge boson eigenstate.

[2]Future versions of this model may include momentum-dependent form-factors to improve modelling of the hgg loop operator.

Once a process directory has been generated, edit the `param_card.dat`. The important part is this:

```
####################################
## INFORMATION FOR HIDDEN
####################################
Block hidden
    1 30.000000e+00 # mZDinput
    2 20.000000e+00 # MHSinput
    3 1.000000e-09 # epsilon
    4 1.000000e-02 # kap
    5 1.279000e+02 # aXM1
```

`aXM1` is α^{-1} of the dark gauge coupling, and need not be changed. The first two parameters are M_{Z_D}, M_{h_s} (mass eigenstates), `epsilon` is $\epsilon = c_w \chi$ (kinetic mixing in the basis of [2], and `kap` is κ (singlet-higgs coupling).

Note that this model can also be used to simulate only the SM+singlet mixing with the higgs (e.g. for $h \to 2a \to 4b$ decays) by setting `epsilon` $= \epsilon$ to zero. Similarly, higgs mixing `kap` $= \kappa$ can be set to zero to allow for purely kinetic-mixing dominated phenomenology.

Steps for using the model for a particular set of parameters:

1. Set parameters in `param_card`.

2. Compute partial width of $h \to Z f \bar{f}$ by running `generate h > Z f f` (where "f" is all fermions). Then set SM higgs width in `param_card` to $\Gamma_{NLO}(h \to \text{all except } Zff) + \Gamma_{Madgraph}(h \to Zff)$. (This is if we want to be totally consistent in taking slight change in overall h width due to kinetic mixing into account. If we want to be even more careful, include partial widths of exotic decays to Z_D, h_s, but this is unlikely to make a difference.)

3. Compute total width of Z_D in Madgraph by running

   ```
   import model --modelname HAHM_variableXX_UFO
   define f = u c d s u~ c~ d~ s~ b b~ e+ e- m+ m- tt+ tt- ve vm vt ve~ vm~ vt~
   generate zp > f f
   ```

   and put width in `param_card`.

4. If h_s can decay to Z_D, compute that width in MadGraph by running
   `generate hs > zp zp`
   and insert into `param_card`. If it can only decay to SM fermions then you need the width of a SM-like higgs with mass M_{h_s}, which our MG model cannot reliably compute at LO. It's therefore best to take NLO expressions of total higgs width as a function of m_h, evaluate for M_{h_s} and multiply $\sin^2 \theta_h$, see Eq. (33).

After following these steps the model should be completely internally consistent, and can be used to compute higgs production (after rescaling cross section to NLO result) and decay, both two- and three-body via off-shell gauge bosons. This is trustworthy as long as the final states are leptons. For other particles there will have to be some rescaling from NLO effects. (This assumes $\Gamma(Z_D \to qq)$ is reasonably trustworthy.)

Direct production of the singlet-like higgs and the dark vector (via Drell-Yan) can be simulated as well.

Note that you can control usage of the EFT vertices hgg and $h\gamma\gamma$ by setting `HIG = 0 HIW = 0` (or whatever) respectively.

References

[1] J. D. Wells, In *Kane, Gordon (ed.), Pierce, Aaron (ed.): Perspectives on LHC physics* 283-298 [arXiv:0803.1243 [hep-ph]].

[2] D. Curtin, R. Essig, S. Gori, P. Jaiswal, A. Katz, T. Liu, Z. Liu and D. McKeen *et al.*, arXiv:1312.4992 [hep-ph].