A Simplified Model for H to Invisibles Searches with 2 Scalars

Valentin V. Khoze and Gunnar Ro

December 29, 2014

1 Defining of the simplified model

The use of simplified models [1] for jets + Missing Energy signatures at colliders is well motivated. They are a better way of characterising LHC searches then effective field theories, which are only valid when the energies probed are much smaller than the masses of the mediators which have been integrated out. Simplified models with active mediators have been recently used for studies of mono-jet plus missing energy search for dark matter at the LHC, see e.g [2–5].

References [4, 5] investigated simplified models with scalar and pseudo-scalar mediators produced in the gluon fusion channel and decaying to fermionic dark matter. Similar simplified models would be useful to characterise the Higgs to invisible searches but now using the vector boson fusion production mechanism. Instead of coupling the SM Higgs directly to 'invisible' particles from the dark sector (this would require giving the dark sector degrees of freedom electroweak charges) we will construct a simplified model based on a more economical scenario where the Higgs mixes with the neutral singlet ϕ which in turn can decay into dark sector degrees of freedom – all now neutral under the SM gauge charges. Hence, apart from the Higgs-ϕ mixing and interactions, the SM Higgs interacts only with the SM fields and ϕ interacts only with the invisible matter, e.g. dark matter fermions, χ.

In the unitary gauge the Standard Model (SM) contains just a single scalar-field degree of freedom, the neutral scalar Higgs h. At tree level h interacts with the massive vector bosons, $W^{\pm}$ and Z^0, and all the SM fermions. The linear in h interactions are,

$$\mathcal{L}_h^{SM} \supset \left(\frac{2M_W^2}{v} W_\mu^+ W^{-\,\mu} + \frac{2M_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right) h \,. \tag{1.1}$$

W now introduce a neutral scalar ϕ which is a Standard Model singlet. Out of all SM degrees of freedom, the singlet ϕ can mix and interact only with the neutral Higgs h, but not with the SM vectors and fermions as it carries no SM charges. On the other hand ϕ can interact with the 'invisible' dark sector, for example it can decay into dark sector fermions,

$$\mathcal{L}_\phi \supset -g_\chi \bar{\chi}\chi \, \phi \,. \tag{1.2}$$

The visible SM sector and the 'invisible' χ sector are coupled to each other via the mixing between the two neutral scalars. The states of definite masses are h_1 and h_2, and the neutral scalars h and ϕ can be experessed in terms of their linear combinations,

$$h = \cos(\theta) h_1 + \sin(\theta) h_2 \,, \qquad \phi = -\sin(\theta) h_1 + \cos(\theta) h_2 \,, \tag{1.3}$$

where θ is the mixing angle (in the limit $\theta \to 0$ the mixing disappears and the two sectors decouple). Combining Eqs. (1.1)-(1.3) we obtain a Simplified Model for invisible Higgs decays involving two Higgs-like neutral scalars h_1 and h_2:

$$\begin{aligned}\mathcal{L}_{h_1,h_2} &= \left(\frac{2M_W^2}{v}\,W_\mu^+W^{-\,\mu} + \frac{2M_Z^2}{v}\,Z_\mu Z^\mu - \sum_f \frac{m_f}{v}\,\bar{f}f\right)\Big(\cos(\theta)h_1 + \sin(\theta)h_2\Big) \\ &- g_\chi\,\bar{\chi}\chi\Big(\cos(\theta)h_2 - \sin(\theta)h_1\Big) - \frac{1}{2}m_{h_1}^2h_1^2 - \frac{1}{2}m_{h_2}^2h_2^2 - m_\chi\bar{\chi}\chi\,. \qquad (1.4)\end{aligned}$$

The first scalar mass eignstate h_1 plays the role of the observed SM Higgs boson with $m_{h_1} = 125$ GeV. The electroweak VEV $v = 246$ GeV is another known parameter. As the result, the Eq. (1.4) contains four free parameters: θ, g_χ, m_{h_2} and m_χ.

With this Lagrangian we can produce h_2 as in the SM via both gluon fusion and vector boson fusion mechanisms, with the corresponding SM cross sections rescaled by $\sin^2(\theta)$. Similarly the 125 GeV Higgs scalar h_1 production rates are rescaled relative to the SM by the factor of $\cos^2(\theta)$ which is $\simeq 1$ for sufficiently small values of the mixing angle. We will refer to the h_1 mass eigenstate as the SM Higgs, and both of the scalar states h_1 and h_2 play the role of scalar mediators to invisible decays into $\bar{\chi}\chi$. The SM Higgs decay is suppressed by $\sin^2(\theta)$. We note that θ and g_χ will always just rescale the DM production cross sections, while m_{h_2} and m_{dm} will change the kinematics.

So far we have taken into account only the mass-eignestates mixing effects between h and ϕ. A more realistic/complete model will also contain the three-point and four-point renormaliseable interactions of the two scalars. In the regime where $m_{h_2} > 2m_{h_1}$, it becomes kinematically possible for h_2 to decay into two h_1's. These 2-body decays can be described by the interaction

$$\mathcal{L}_{h_2\to h_1h_1} = -2\lambda_p v\, h_2h_1^2\,, \qquad (1.5)$$

involving a new dimensionless coupling λ_p. In the alternative regime of light second scalar, $m_{h_1} > 2m_{h_2}$, the 2-body scalar decays are described by

$$\mathcal{L}_{h_1\to h_2h_2} = -2\lambda_p v\, h_1h_2^2\,. \qquad (1.6)$$

In the simplest version of the model we can fix the width of h_2 to the minimum width (which only includes tree-level on-shell decays)

$$\Gamma_{h_2} = \cos^2(\theta)\,\Gamma_{\bar{\chi}\chi} + \sin^2(\theta)\,\Gamma_{SM} + \Gamma_{h_1h_1}\,, \qquad (1.7)$$

where Γ_{SM} is the Higgs decay width calculated in the SM for a Higgs of mass m_{h_2}. In particular when m_{h_2} rises above the $t\bar{t}$ threshold, is includes the kinematically allowed $h_2 \to t\bar{t}$ channel as in Refs. [4, 5]. The contribution $\Gamma_{\bar{\chi}\chi}$ is the decay width of h_2 to dark matter

$$\Gamma_{\bar{\chi}\chi} = \frac{g_\chi^2 m_{h_2}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{h_2}^2}\right)^{\frac{3}{2}}\,, \qquad (1.8)$$

and for $m_{h_2} > 2m_{h_1}$, we have also included the contribution $\Gamma_{h_1h_1}$ arising from (1.5),

$$\Gamma_{h_1h_1} = \frac{\lambda_p^2 v^2}{32\pi m_{h_2}}\left(1 - \frac{4m_{h_1}^2}{m_{h_2}^2}\right)^{\frac{1}{2}}\,, \qquad (1.9)$$

which scales with the fifth parameter λ_p^2.

Instead of varying λ_p, it will be more efficient to just vary the entire width of h_2 and treat Γ_{h_2} as a free parameter. This would also take into account possible additional unknown interactions and decays of h_2 into the hidden sector.

The minimal width of the Higgs scalar h_1 takes the form:

$$\Gamma_{h_1} \;=\; \cos^2(\theta)\,\Gamma_{SM} \;+\; \sin^2(\theta)\,\Gamma_{\bar{\chi}\chi}\,, \tag{1.10}$$

where Γ_{SM} is computed for the measured Higgs mass $m_{h_1} = 125$ GeV, and in the case of the light second scalar, $m_{h_1} > 2m_{h_2}$, one should also include on the right hand side the contribution:

$$\Gamma_{h_2h_2} \;=\; \frac{\lambda_p^2 v^2}{32\pi m_{h_1}} \left(1 - \frac{4m_{h_2}^2}{m_{h_1}^2}\right)^{\frac{1}{2}} \,. \tag{1.11}$$

As with the width of h_2 this width could change if there was more matter in the hidden sector, but since such decays will always be suppressed by $\sin^2(\theta)$ they will be less relevant. We therefore propose that in the regime of not too light second scalar, $m_{h_2} > 113$ GeV, to simply use the calculated minimal width for the Higgs Boson as given by Eq. (1.10).

In Summary: our simplified model is given by the Lagrangian (1.4) and involves two singlet scalar mediators, h_1 and h_2. The first scalar is the 125 GeV SM Higgs, while the second one is an additional Higgs-like scalar. In general, this simplified model is characterised by five parameters: the mass and the widths of the second scalar, m_{h_2} and Γ_{h_2}, the DM (or invisible fermion's) mass, m_χ, the mixing angle θ and the DM coupling g_χ.

We note that these five parameters are in one-to-one correspondence with the five parameters characterising the scalar and pseudo-scalar mediated simplified models for DM searches at colliders studied in Refs. [4, 5].

In practice, there is no need to vary all these parameters throughout their whole domain. We propose:

1. First set the width of h_2 to the minimal width without allowing the possibility of $h_2 \to h_1h_1$ decays, i.e. to use Eq. (1.7) without the last term, and as the next step to allow for additional decays of h_2 by scaling this minimal width by an overall multiplicative factor, e.g. take $2\Gamma_{h_2}$ (the same procedure as the one adopted in Ref. [5]).

2. There is also no need to vary the DM mass m_χ indiscriminantly. There should be no strong dependence on m_χ in the regime where m_{h_1} and m_{h_2} are greater than $2m_\chi$, and both decays are kinematically allowed. Here it would be sufficient to choose just a single value of m_χ to find the location of the plato. Then one samples the kinematic boundaries of the h_1 and h_2 decays by putting more points near $m_{h_i} \sim 2m_\chi$.

Additional limits on this model would come from heavy Higgs searches applied to h_2, which is a Higgs-like state with decreased production cross section and different branching ratios. It could also be seen in $t\bar{t}$ events if h_2 is heavier than twice the top-mass.

This simplified model we described can naturally arise from a variety of Higgs portal models. The simplest would be a singlet fermion Dark Matter model, see e.g. [6, 7], which has the following Lagrangian if we impose a Z_2 symmetry for ϕ:

$$\mathcal{L} \supset m^2\phi^2 - \lambda_\phi\phi^4 - \lambda_p\phi^2|H|^2 + \mu^2|H|^2 + g_\chi\bar{\chi}\phi\chi + m_\chi\bar{\chi}\chi\,. \tag{1.12}$$

As both ϕ and H have wrong-sign mass terms they will both develop vevs. And after symmetry breaking the two scalars will mix and we will get two mass eigenstates h_1 and h_2 with a mixing angle θ.

The same simplified model (1.4) will also arise in Classically Scale Invariant Extensions of the Standard Model, see e.g. [8, 9]. These models have the following Lagrangian:

$$\mathcal{L} \supset -\lambda_\phi\phi^4 - \lambda_p|\phi|^2|H|^2 + \mu^2|H|^2 + g_{dm}\bar{\chi}\phi\chi\,, \tag{1.13}$$

where a complex scalar ϕ is charged under a dark sector gauge group. The effective potential in this hidden sector breaks the gauge invariance and gives ϕ a VEV. In addition it provides a relation between the gauge coupling constant and λ_ϕ. These models have a manifest Z_2 symmetry dictated by gauge invariance. After imposing the Higgs mass constraint there is only 3 parameters, which we can choose to be the hidden gauge coupling, the portal coupling and g_χ. These three parameters would be sufficient to calculate all masses and mixing angles.

References

[1] D. Alves *et al.* [LHC New Physics Working Group Collaboration], "Simplified Models for LHC New Physics Searches," J. Phys. G **39**, 105005 (2012) [arXiv:1105.2838 [hep-ph]].

[2] J. Abdallah, A. Ashkenazi, A. Boveia, G. Busoni, A. De Simone, C. Doglioni, A. Efrati and E. Etzion *et al.*, "Simplified Models for Dark Matter and Missing Energy Searches at the LHC," arXiv:1409.2893 [hep-ph].

[3] S. Malik, C. McCabe, H. Araujo, A. Belyaev, C. Boehm, J. Brooke, O. Buchmueller, G. Davies, *et al.*, "Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments," arXiv:1409.4075 [hep-ex].

[4] M. R. Buckley, D. Feld and D. Goncalves, "Scalar Simplified Models for Dark Matter," arXiv:1410.6497 [hep-ph].

[5] P. Harris, V. V. Khoze, M. Spannowsky and C. Williams, "Constraining Dark Sectors at Colliders: Beyond the Effective Theory Approach," arXiv:1411.0535 [hep-ph].

[6] S. Baek, P. Ko and W. I. Park, "Invisible Higgs Decay Width vs. Dark Matter Direct Detection Cross Section in Higgs Portal Dark Matter Models," Phys. Rev. D **90** (2014) 055014 [arXiv:1405.3530 [hep-ph]].

[7] S. Baek, P. Ko and W. I. Park, "Search for the Higgs portal to a singlet fermionic dark matter at the LHC," JHEP **1202** (2012) 047 [arXiv:1112.1847 [hep-ph]].

[8] C. Englert, J. Jaeckel, V. V. Khoze and M. Spannowsky, JHEP **1304** (2013) 060 [arXiv:1301.4224 [hep-ph]].

[9] V. V. Khoze, C. McCabe and G. Ro, JHEP **1408** (2014) 026 [arXiv:1403.4953 [hep-ph], arXiv:1403.4953].