

# Invisible Higgs decay width vs. Direct detection cross section in Higgs portal DM models

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Based on arXiv:1403.3530, and on earlier works  
arXiv:1112.1847, JHEP (2012); 1209.4163, JHEP (2012); 1212.2131, JHEP (2013) (also with Eibun Senaha)

# Higgs portal DM models

All invariant under (ad hoc)  $Z_2$

$$\mathcal{L}_{SSDM} = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{HS}}{2} S^2 H^\dagger H$$

$$\mathcal{L}_{SDFM} = \bar{\psi}(i \not{\partial} - m_\psi) \psi - \frac{\lambda_{\psi H}}{\Lambda} \bar{\psi} \psi H^\dagger H$$

Non-renormalizable or not gauge-invariant, not unitary!

$$\mathcal{L}_{VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{2} V_\mu V^\mu H^\dagger H - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

$m_H$ (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(H \rightarrow \text{inv}) / \sigma_{SM}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—

[arXiv:1404.1344]

$$\sigma_{\text{inv}}^{\text{SI}} = \frac{4f_{\text{inv}}}{m_{\text{inv}}^2 \beta} \frac{m_h^2 f_S^2}{(M_h + m_{\text{inv}})^2}$$

$$\sigma_{\text{inv}}^{\text{SI}} = \frac{16f_{\text{inv}} M_h^4}{m_{\text{inv}}^2 \beta (m_{\text{inv}}^2 - 4M_h^2 m_{\text{inv}}^2 + 12M_h^4)} \frac{m_h^2 f_S^2}{(M_h + m_{\text{inv}})^2}$$

$$\sigma_{\text{inv}}^{\text{SI}} = \frac{8f_{\text{inv}} M_h^2}{m_{\text{inv}}^2 \beta^2} \frac{m_h^2 f_S^2}{(M_h + m_{\text{inv}})^2}$$

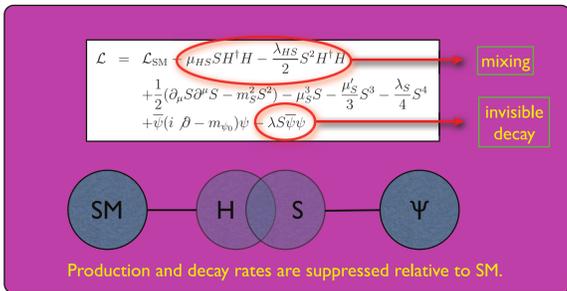
$\Gamma_{\text{inv}}$  is constrained  $\Rightarrow$  So is  $\sigma^{\text{SI}}$

# Usual story within EFT

- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters. Therefore the invisible Higgs decay is suppressed. And Vice Versa.
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in UV completions (renormalizable) however

# Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847



# Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \text{Br}(H_i \rightarrow \text{SM})}{\sigma_h \text{Br}(h \rightarrow \text{SM})} = \frac{\cos^4 \alpha \Gamma_{H_1}^{\text{SM}}}{\cos^2 \alpha \Gamma_{H_1}^{\text{SM}} + \sin^2 \alpha \Gamma_{H_1}^{\text{hid}}}$$

$$r_1 = \frac{\sin^4 \alpha \Gamma_{H_2}^{\text{SM}}}{\sin^2 \alpha \Gamma_{H_2}^{\text{SM}} + \cos^2 \alpha \Gamma_{H_2}^{\text{hid}} + \Gamma_{H_2 \rightarrow H_1 H_1}}$$

$$r_2 = \frac{\sin^4 \alpha \Gamma_{H_2}^{\text{SM}}}{\sin^2 \alpha \Gamma_{H_2}^{\text{SM}} + \cos^2 \alpha \Gamma_{H_2}^{\text{hid}} + \Gamma_{H_2 \rightarrow H_1 H_1}}$$

Mixing of the SM Higgs with a singlet scalar

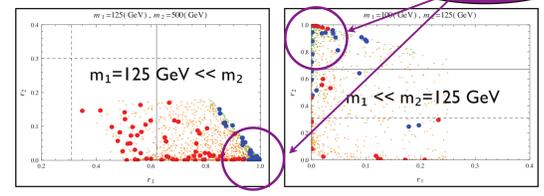
$$H_1 = h \cos \alpha - s \sin \alpha, H_2 = h \sin \alpha + s \cos \alpha.$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$   
Invisible decay mode is not necessary!

If  $r_i > 1$  for any single channel, this model will be excluded !!

# Discovery possibility

- Signal strength ( $r_2$  vs  $r_1$ )



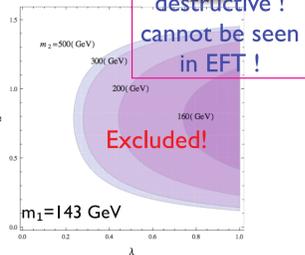
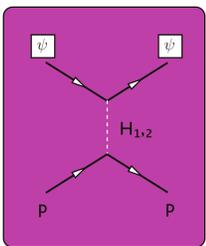
$L = 5 \text{ fb}^{-1}$  for  $3\sigma$  Sig.  
 $L = 10 \text{ fb}^{-1}$  for  $3\sigma$  Sig.

- $\Omega(x), \sigma_{\text{p}(x)}$
- $\Omega(x), \sigma_{\text{p}(o)}$
- $\Omega(o), \sigma_{\text{p}(x)}$
- $\Omega(o), \sigma_{\text{p}(o)}$

# Constraints

- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi} \mu^2 \lambda_p^2 \approx 2.7 \times 10^{-2} \frac{m_p^2}{\pi} \left( \frac{m_p}{v} \right) \lambda \sin \alpha \cos \alpha \left( \frac{1}{m_1^2} - \frac{1}{m_2^2} \right)$$



- We can't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

$$\mathcal{L}_{\text{eff}} = \bar{\psi} \left( m_0 + \frac{H^\dagger H}{\Lambda} \right) \psi. \quad \text{or} \quad \lambda \bar{\psi} \psi$$

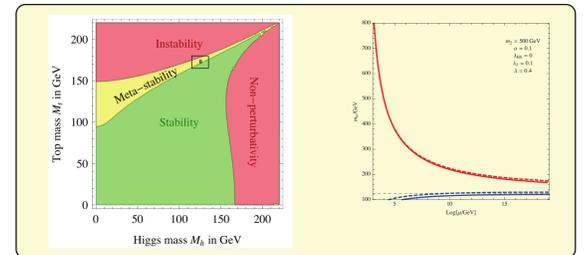
Breaks SM gauge sym

- Only one Higgs boson ( $\alpha = 0$ )

We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

No definite correlation between the upper bound on DD cross section and the invisible Higgs decay

# Vacuum Stability Improved by the singlet scalar S



A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

# Similar for Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- Stueckelberg mechanism : nonrenormalizable
- A complete model should be something like this:

$$\mathcal{L}_{VDM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{\lambda_\Phi}{4} \left( \Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{H\Phi} \left( H^\dagger H - \frac{v_H^2}{2} \right) \left( \Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)$$

$$\langle 0 | \phi_X | 0 \rangle = v_X + h_X(x)$$

- There appear a new singlet scalar  $h_X$  from  $\phi_X$ , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model
- Important to consider a minimal renormalizable model to discuss physics correctly
- Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)

# New scalar improves EW vacuum stability

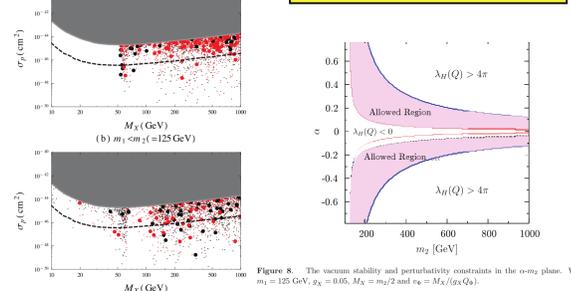
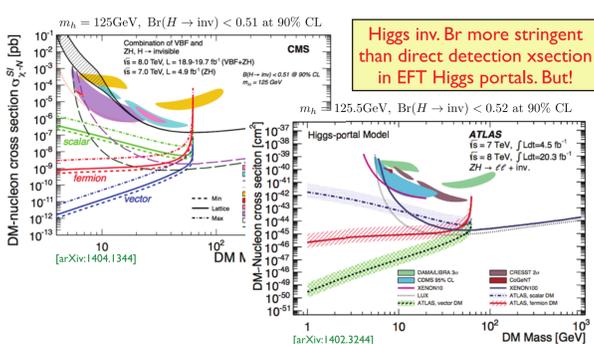


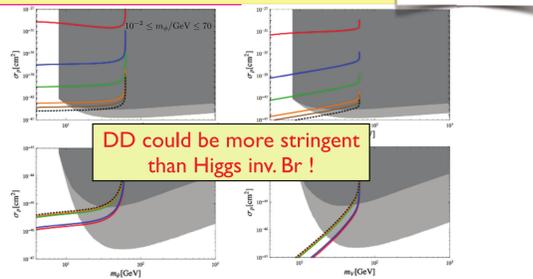
Figure 8. The vacuum stability and perturbativity constraints in the  $\alpha$ - $m_2$  plane. We take  $m_1 = 125$  GeV,  $\alpha_1 = 0.05$ ,  $M_X = m_2/2$  and  $v_\Phi = M_X / (\alpha \sqrt{2})$ .

- DM-nucleon scattering in EFT Higgs portals

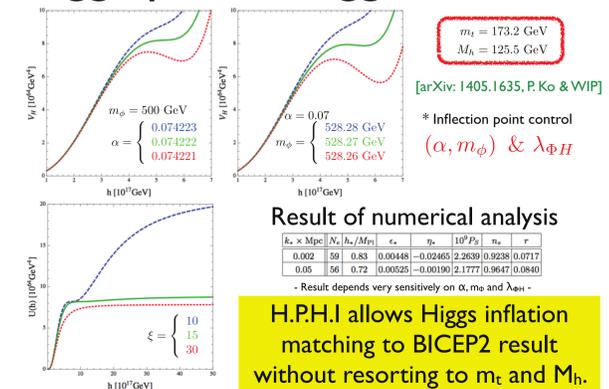


Higgs inv. Br more stringent than direct detection section in EFT Higgs portals. But!

- However in renormalizable unitary models, Additional dependence on the dark Higgs mass and the scalar mixing angle, and cancellation mechanism works! And no definite correlation!



# Higgs-portal Higgs inflation



H.P.H.I allows Higgs inflation matching to BICEP2 result without resorting to  $m_t$  and  $M_h$ .