

Issues in hidden sector dark matter

Seungwon Baek (KIAS)
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based on JHEP1202; JHEP1211; JHEP1305
in collaboration with Pyungwon Ko, Wan-Il Park, Eibun Senaha

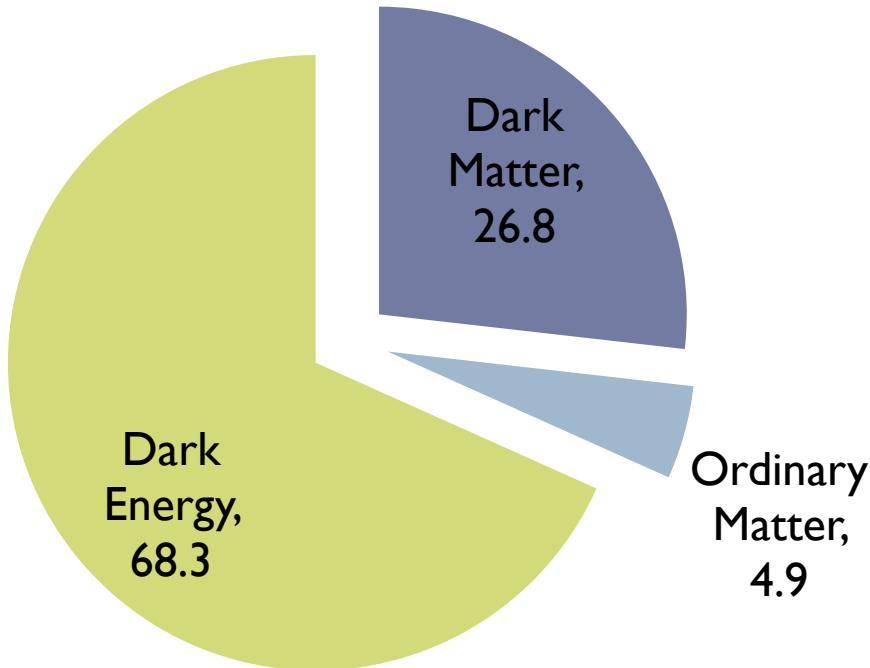
Outline

- ▶ Hidden sector dark matter with Higgs portal interaction
 - ▶ Relic density and direct detection
 - ▶ Higgs phenomenology
 - ▶ EW precision test
 - ▶ Vacuum stability, perturbativity, unitarity bound
 - ▶ LHC searches
- ▶ Conclusions



Dark Matter

- ▶ 27% of the universe is DM

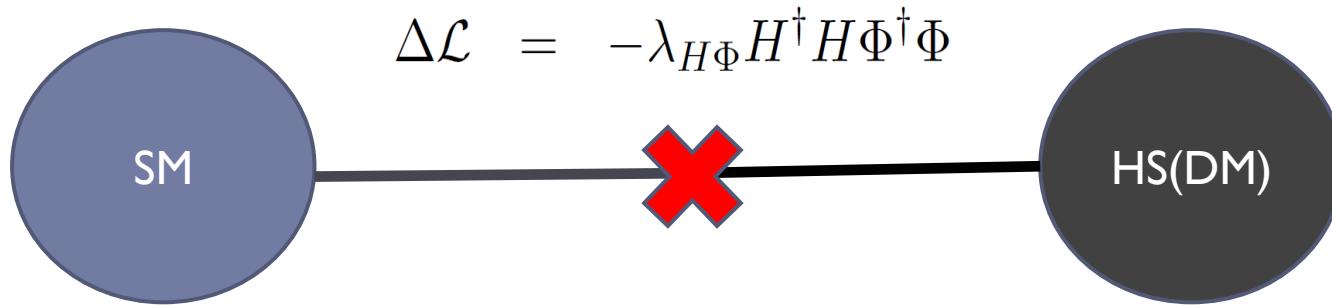


- ▶ We do not know the nature of DM
- ▶ WIMP allows the particle physics explanation of DM and its creation and detection at LHC
- ▶ One possible WIMP DM scenario is the framework of “**Hidden Sector**” DM



Hidden Sector DM and Higgs Portal

- ▶ DM is singlet under the SM gauge group → hidden
- ▶ Higgs and a singlet scalar can mediate between the SM and hidden sector through renormalizable interaction



Other portals

- ▶ **Z'-portal** Babu, Kolda, March-Russel, hep-ph/9710441

$$\mathcal{L}_{\text{mix}} = - \frac{\sin \chi}{2} \hat{Z}'_{\mu\nu} \hat{B}^{\mu\nu}$$

- ▶ **N_R -portal** Adam Falkowski , Joshua T. Ruderman , Tomer Volansky, arXiv:1101.4936

$$\mathcal{L}_{\text{RHN-portal}} = \lambda^i \overline{N_{Ri}} \psi X^\dagger + \text{H.c.}$$

- ▶ **fermion-portal** Yang Bai, Joshua Berger, arXiv:1308.0612

$$\mathcal{L}_{\text{fermion}} \supset \lambda_{u_i} \phi_{u_i} \overline{\chi}_L u_R^i + \lambda_{d_i} \phi_{d_i} \overline{\chi}_L d_R^i + \text{h.c.}$$



Hidden sector DM models with Higgs portal

- ▶ Singlet Fermionic DM

$$\mathcal{L}_{\text{dark}} = \overline{\psi}(i\cancel{\partial} - m_{\psi_0})\psi - \lambda S\overline{\psi}\psi .$$

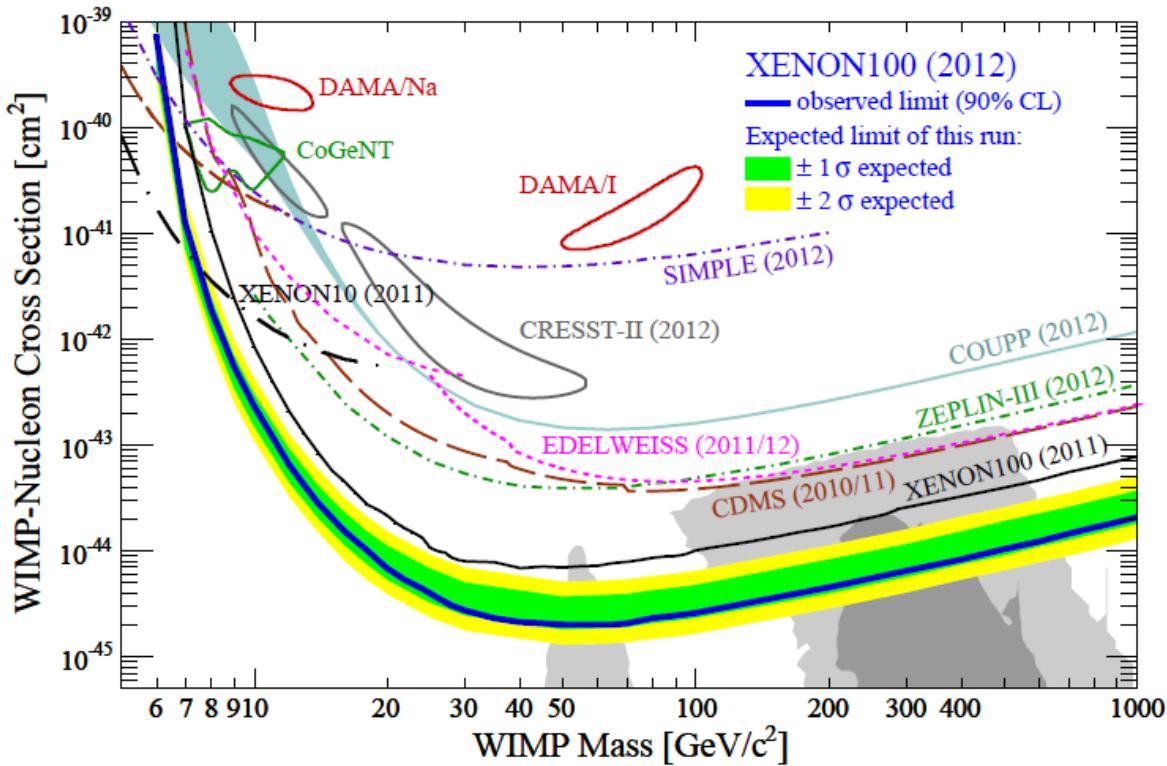
- ▶ Vector DM

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



Direct detection

► XENON100(2012)

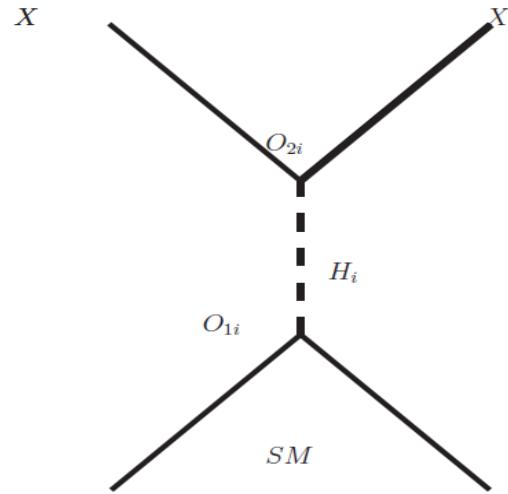


$$\sigma = 2.0 \times 10^{-45} \text{ cm}^2 \text{ at } m_\chi = 55 \text{ GeV}/c^2$$



Direct detection

$$\begin{pmatrix} h \\ \varphi \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \equiv O \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$



- ▶ GIM-type cancellation occurs in direct detection cross section

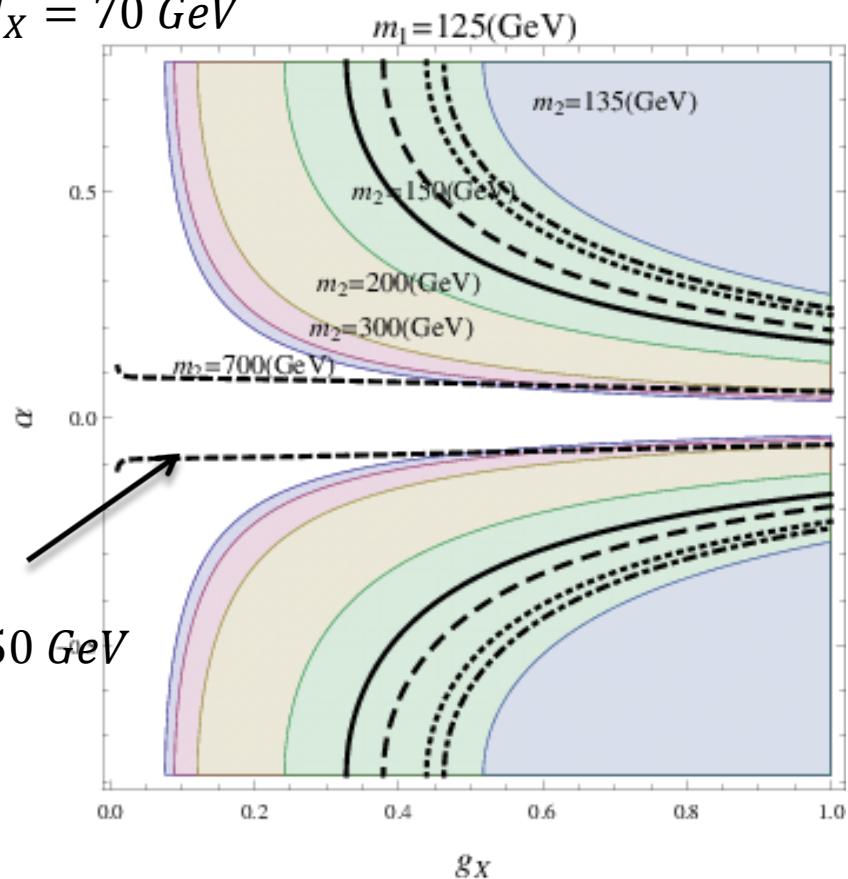
$$\sigma_{\text{ann,el}} \propto \left| \sum_i \frac{O_{1i} O_{2i}}{q^2 - m_i^2} \right|^2 \rightarrow 0 \text{ for degenerate Higgs}$$

Direct detection

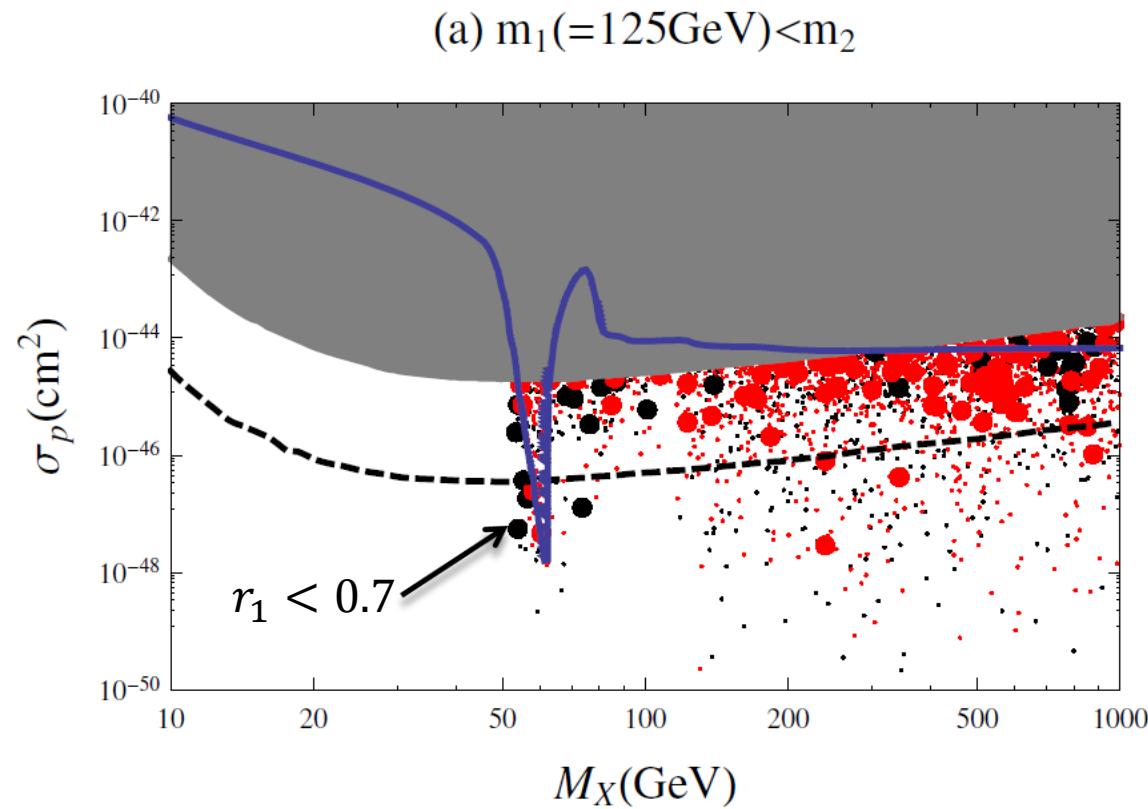
- ▶ Exclusion plot by XENON100
- ▶ g_X : DM- Φ coupling
- ▶ Cancellation mechanism works quite efficiently and larger region is allowed by direct detection experiments

SB, P. Ko, W.I. Park(2011) $m_2 = 150 \text{ GeV}$

$$M_X = 70 \text{ GeV}$$



Comparison with the EFT approach



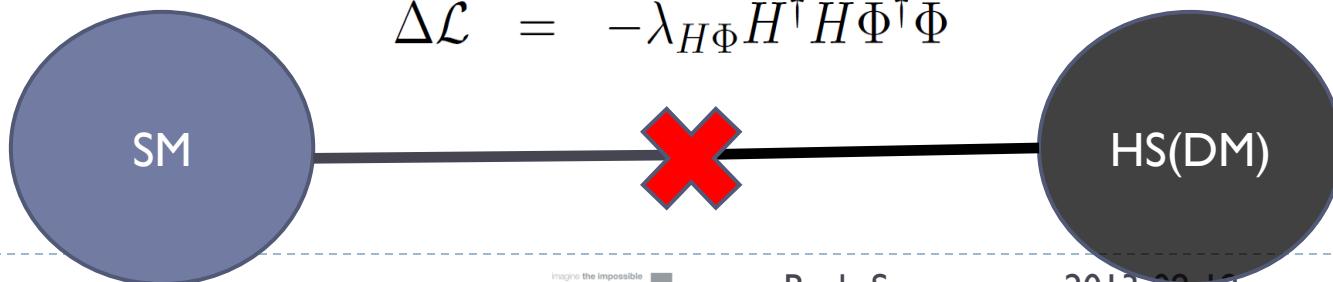
SB, P. Ko, W-I. Park, E. Senaha, JHEP(2013)

Higgs Phenomenology

- ▶ Higgs sector is extended → Higgs phenomenology is different from the SM one

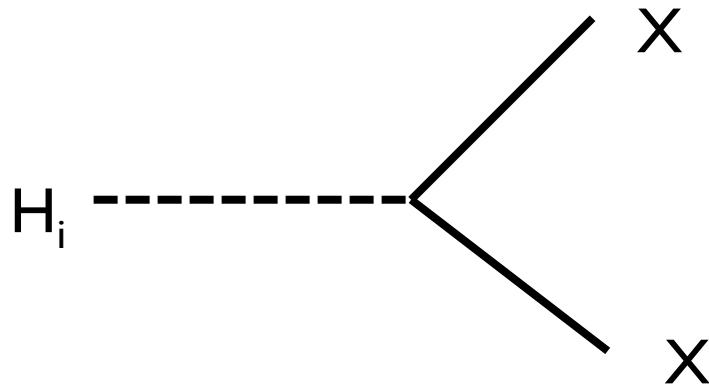
$$\Delta\mathcal{L}_{\text{Higgs}} = -\frac{\lambda_H}{4} \left(H^\dagger H - \frac{v_H^2}{2} \right)^2 - \frac{\lambda_\Phi}{4} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2 - \lambda_{H\Phi} \left(H^\dagger H - \frac{v_H^2}{2} \right) \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)$$

$$M_{\text{Higgs}}^2 = \begin{pmatrix} \lambda_H v_H^2 & \lambda_{H\Phi} v_H v_\Phi \\ \lambda_{H\Phi} v_H v_\Phi & \lambda_\Phi v_\Phi^2 \end{pmatrix} \boxed{\begin{pmatrix} h \\ \varphi \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \equiv O \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}}$$

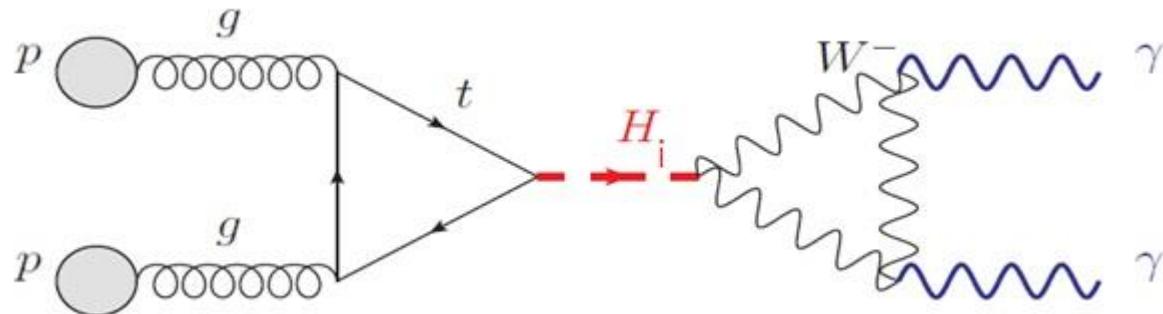


Higgs Phenomenology

- ▶ Invisible decay of Higgs at tree is allowed



- ▶ Reduction of Higgs signal strength



Higgs Phenomenology

▶ Signal strength

$$r_i \equiv \frac{\sigma_{H_i} B_{H_i \rightarrow X_{\text{SM}}}}{\sigma_{H_i}^{\text{SM}} B_{H_i \rightarrow X_{\text{SM}}}^{\text{SM}}} \quad (i = 1, 2)$$

$$r_1 = \frac{c_\alpha^4 \Gamma_{H_1}^{\text{SM}}}{c_\alpha^2 \Gamma_{H_1}^{\text{SM}} + s_\alpha^2 \Gamma_{H_1}^{\text{hid}}},$$
$$r_2 = \frac{s_\alpha^4 \Gamma_{H_2}^{\text{SM}}}{s_\alpha^2 \Gamma_{H_2}^{\text{SM}} + c_\alpha^2 \Gamma_{H_2}^{\text{hid}} + \Gamma_{H_2 \rightarrow H_1 H_1}},$$

- ▶ $r_i < 1$ ($i = 1, 2$). If some $r_i > 1$, our scenario will be excluded

Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \rightarrow bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \rightarrow \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \rightarrow \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \rightarrow WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \rightarrow ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	1.30 ± 0.20	0.80 ± 0.14

EW precision tests

- ▶ New contribution to the EW precision obs.

Barger, et.al. 2008

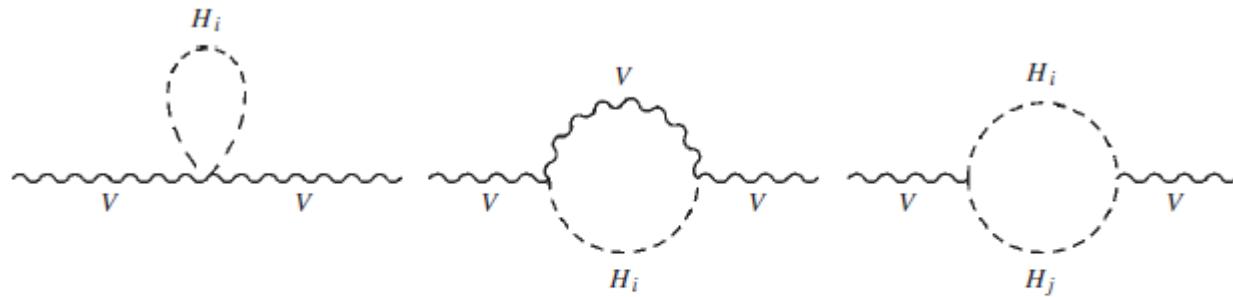
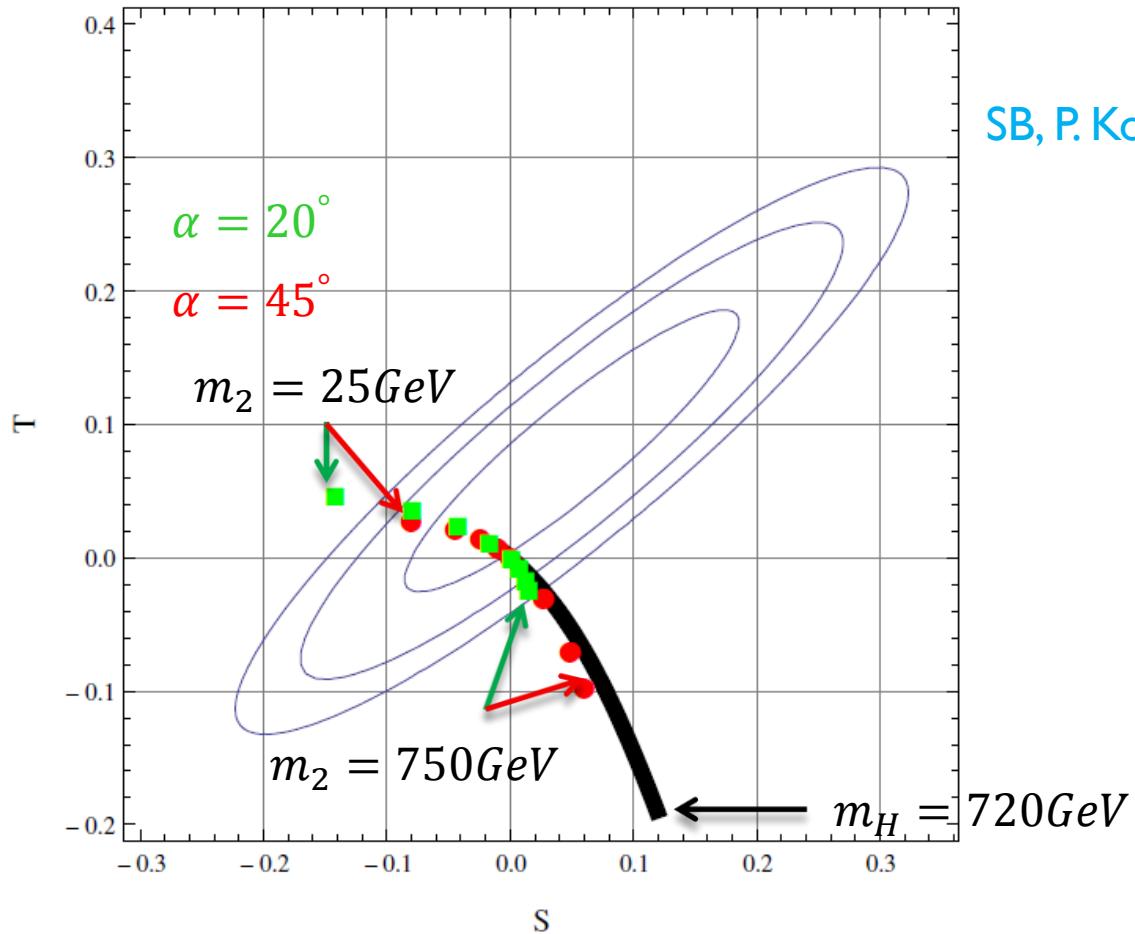


FIG. 2. Feynman diagrams of gauge boson propagators that are affected by Higgs bosons.

EW precision tests



SB, P. Ko, W-I. Park, E. Senaha, JHEP(2013)



Vacuum stability (EW)

- ▶ Requiring the global min. of the Higgs potential is at the EW vacua constrains the parameters of the Higgs portal

EW : $v_H = 246 \text{ GeV}, \quad v_S = v_S^{\text{in}},$

SYM : $v_H = v_S = 0,$

I : $v_H = 0, \quad v_S \neq 0,$

II : $v_H \neq 0, \quad v_S = 0,$

III : $v_H \neq 246 \text{ GeV}, \quad v_S \neq v_S^{\text{in}},$



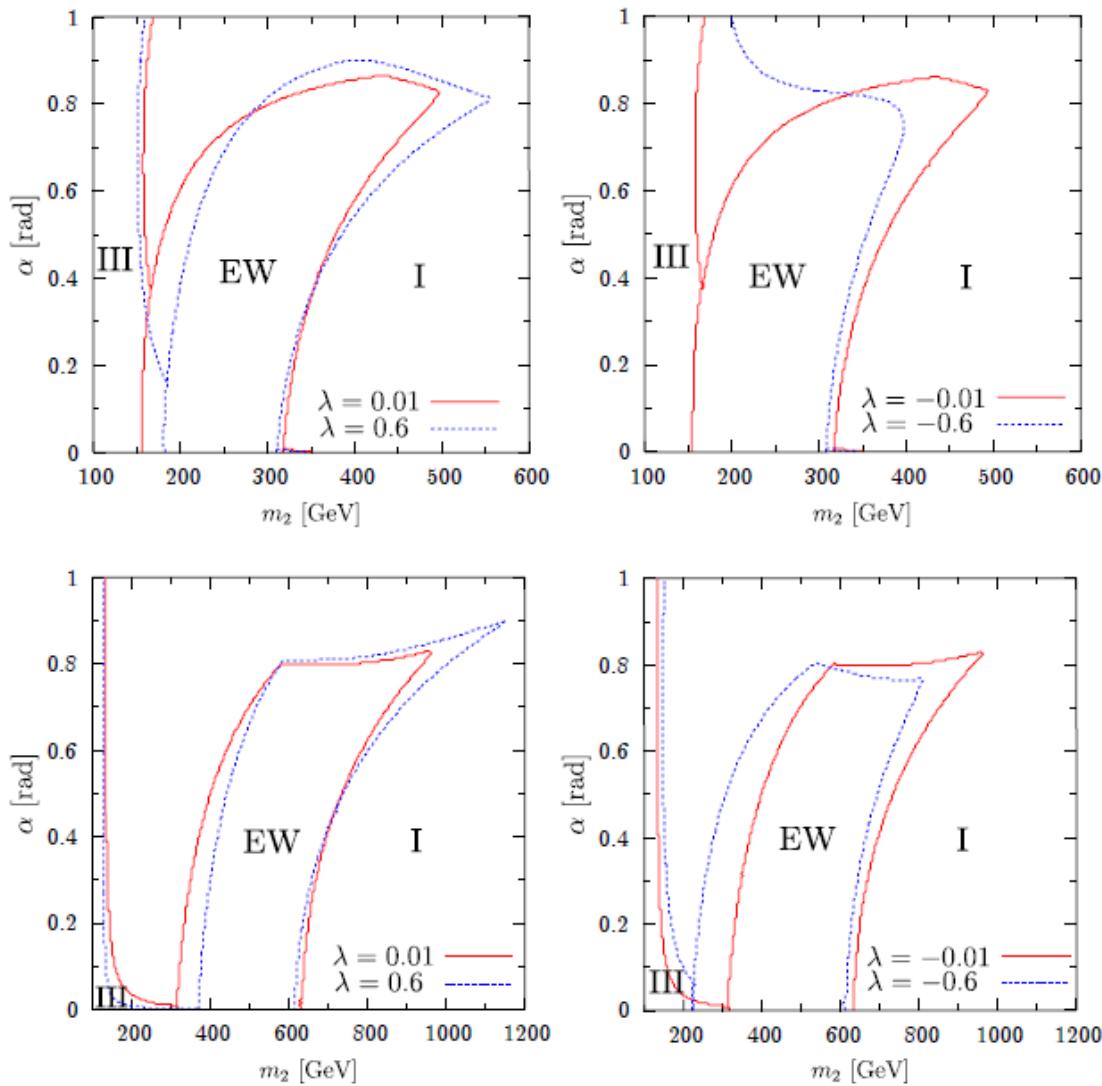
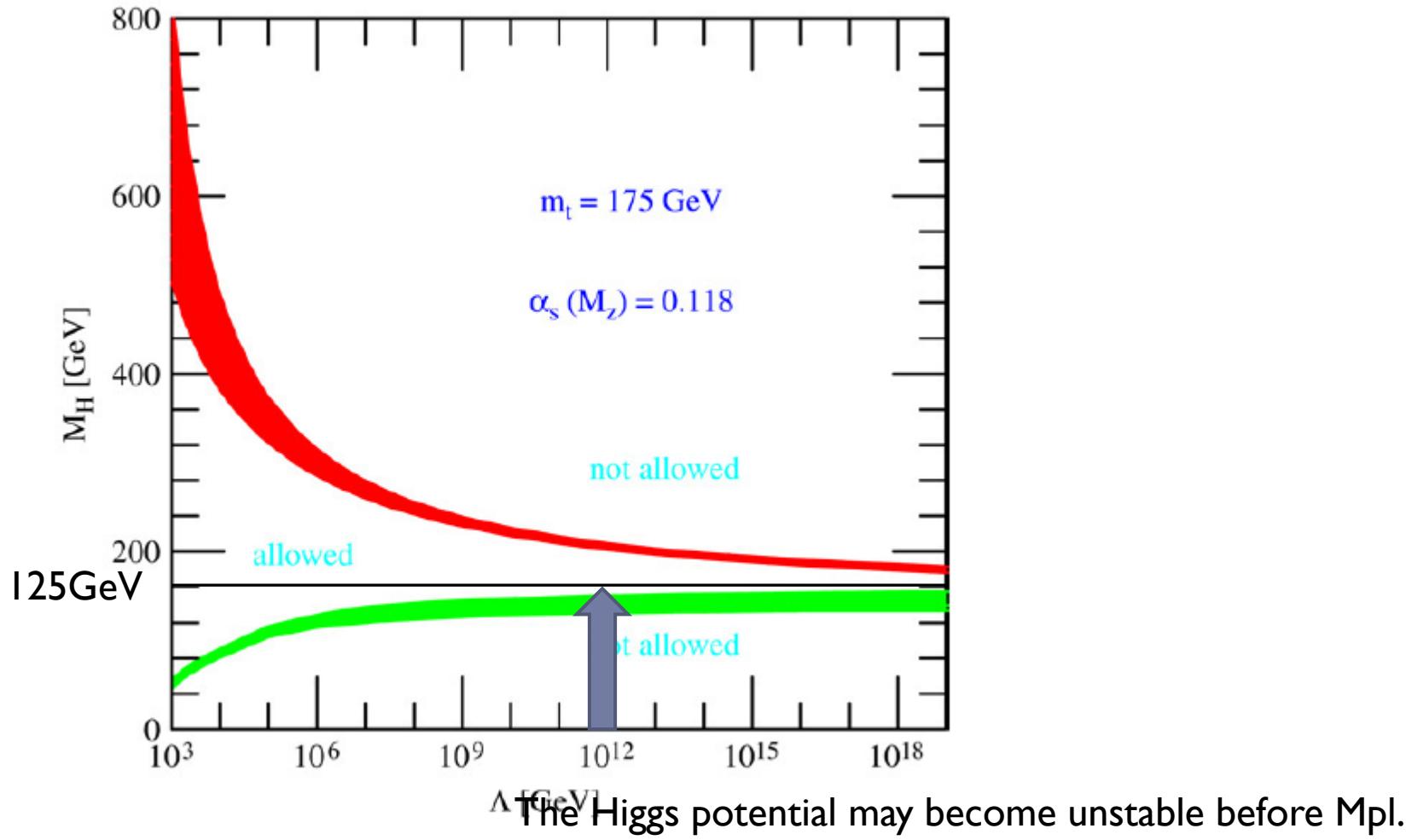


Figure 6. The effects of λ on the vacuum structures. The red straight curves corresponds to the case of $|\lambda| = 0.01$ and the blue dotted curves denotes to the case of $|\lambda| = 0.6$. (Upper) $v_S = -500$ GeV; $\lambda = 0.01, 0.6$ (left) and $\lambda = -0.01, -0.6$ (right). (Lower) $v_S = -1000$ GeV; $\lambda = 0.01, 0.6$ (left) and $\lambda = -0.01, -0.6$ (right).

Triviality and vacuum stability bound on m_H



- ▶ Higgs portal model can provide negative contribution to the SM-like Higgs.
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Lebedev 2012, Joan Elias-Miro, Jose R. Espinosa, Gian F. Giudice, Hyun Min Lee, Alessandro Strumia, 2012

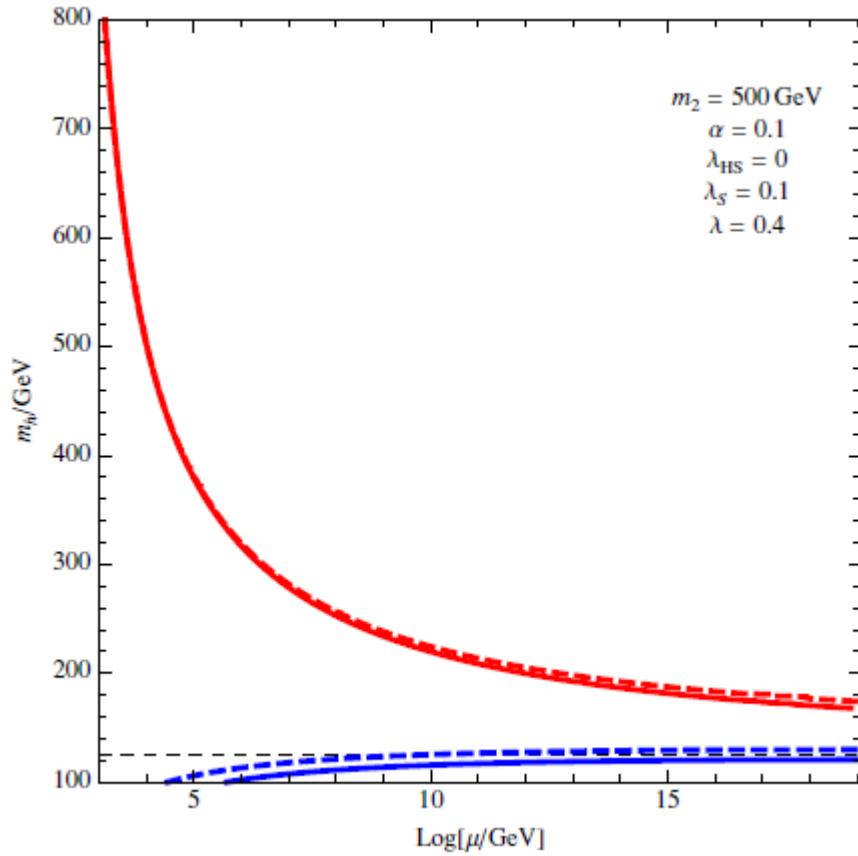
$$m_1^2 \simeq 2 \left(\lambda_h - \frac{\lambda_{hs}^2}{4\lambda_s} \right) v^2 ,$$

$$m_2^2 \simeq 2\lambda_s u^2 + \frac{\lambda_{hs}^2}{2\lambda_s} v^2 ,$$

$$\tan 2\theta \simeq -\frac{\lambda_{hs}v}{\lambda_s u} ,$$



Triviality and vacuum stability bound



Unitarity bound

► Sin Kyu Kang, Jubin Park, arXiv:1306.6713

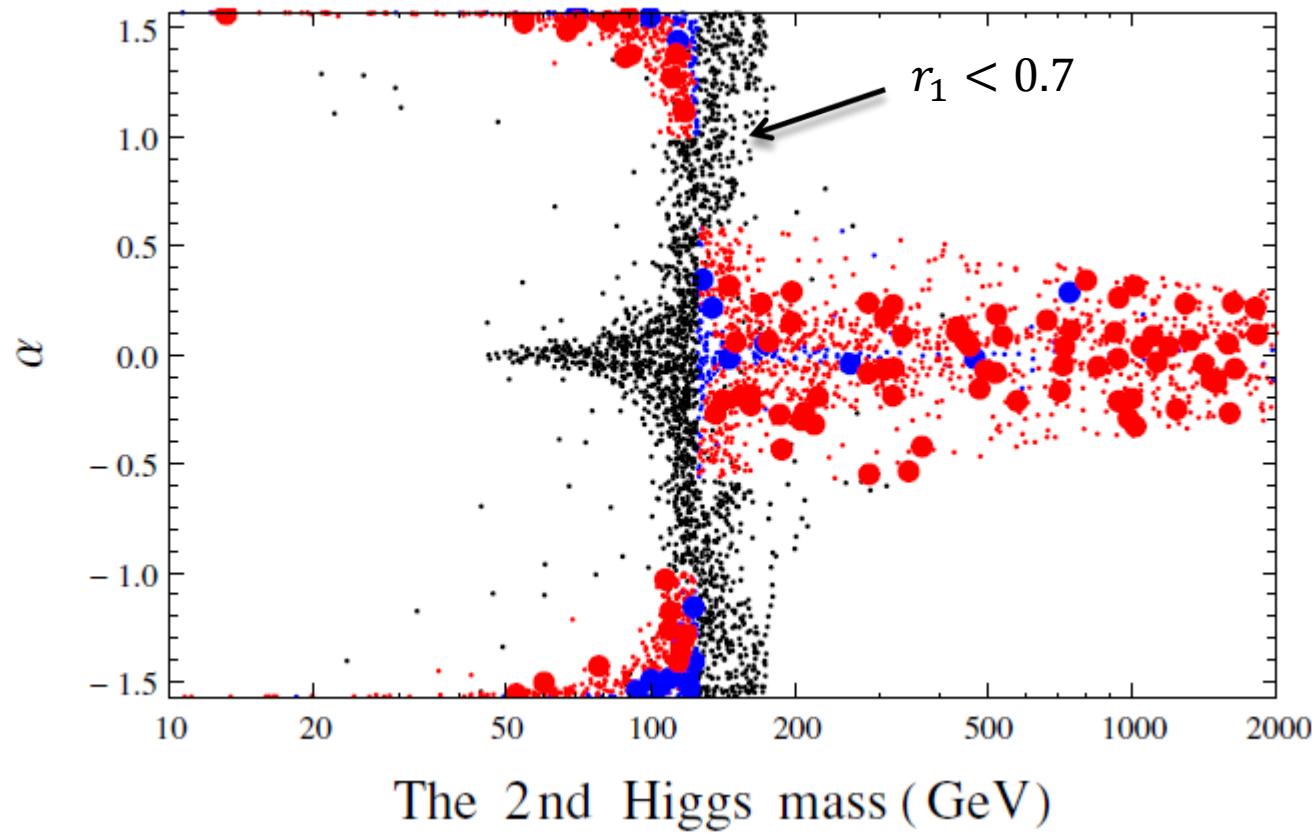
$$\mathcal{M}(s, t, u) = 16\pi \sum_{J=0}^{\infty} (2J+1) P_J(\cos\theta) a_J(s)$$

$$|a_0| \leq \frac{1}{2}$$

$$\langle m^2 \rangle \equiv m_1^2 \cos^2 \alpha + m_2^2 \sin^2 \alpha \leq \frac{4\pi\sqrt{2}}{3G_F} \approx (700\text{GeV})^2$$

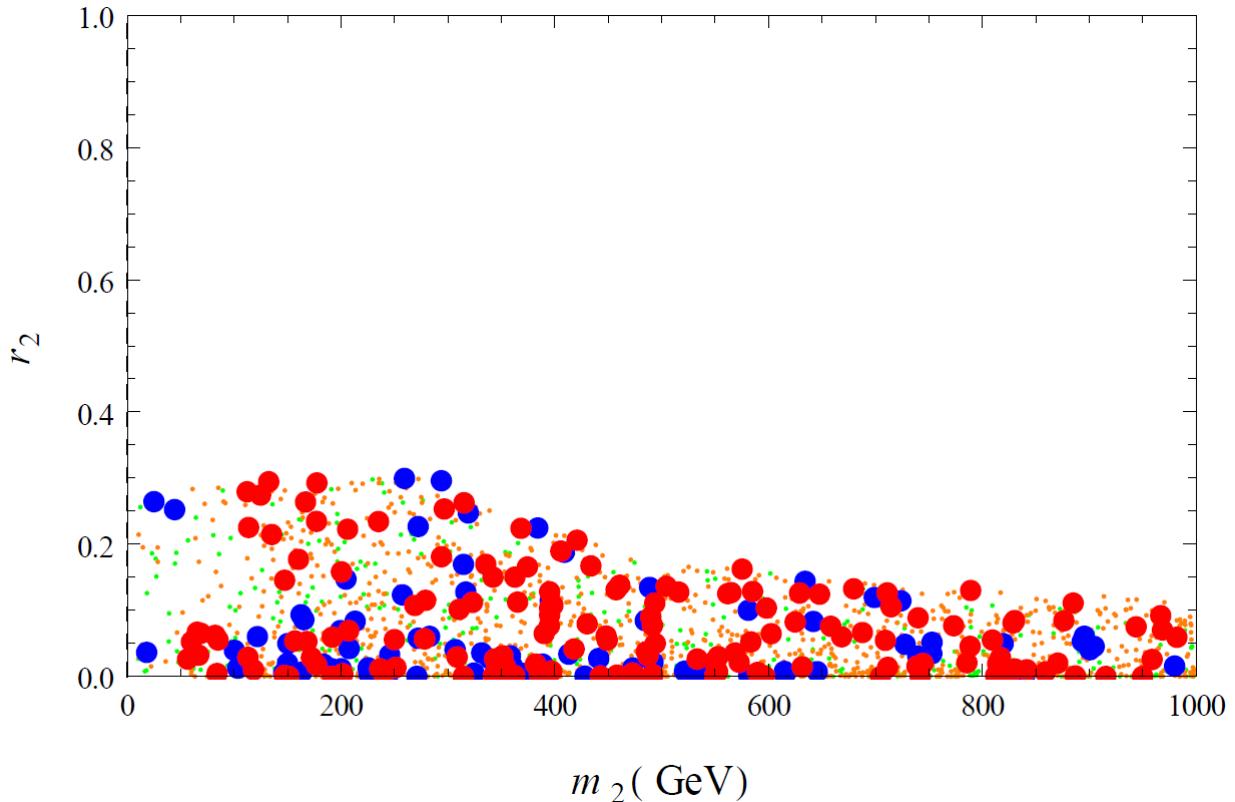


LHC tests



LHC tests

- ▶ $r_1 > 0.7$



It will be difficult to produce the 2nd Higgs at the LHC.

Conclusions

- ▶ DM with Higgs portal
 - ▶ provides cancellation to the direct search bound
 - ▶ improves the stability of Higgs potential
 - ▶ changes the Higgs search at colliders
 - ▶ is constrained by EWPT and the discovery of SM-Higgs boson
- ▶ It will be difficult to produce the 2nd Higgs.



Backups

Physics of Higgs Portal DM

- ▶ Dark matter relic density, direct & indirect detection

scalar: C.P. Burgess, Maxim Pospelov, Tonnis ter Veldhuis, hep-ph/0011135

fermion: Yeong Yun Kim, Kang Young Lee, Seodong Shin,
arXiv:0809.2745

vector: Yasaman Farzan, Amin Rezaei Akbarieh, arXiv:1207.4272

- ▶ Collider phenomenology

SB, P. Ko, W-I. Park, E. Senaha, 1112.1847, 1209.4163, 1212.2131

- ▶ EW precision tests

- ▶ Vacuum stability

- ▶ Perturbativity

- ▶ Unitarity

Comparison with the EFT approach

- ▶ For heavy H_2 , EFT is a good approximation.

S. Kanemura et.al 2010, A. Djouadi, et.al. 2011, O. Lebedev, H. M. Lee, Y. Mambrini, 2011, L. Lopez-Horoz, Schwetz, Zupan 2012

$$\begin{aligned}\Delta\mathcal{L}_S &= -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 , \\ \Delta\mathcal{L}_V &= \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu , \\ \Delta\mathcal{L}_f &= -\frac{1}{2}m_f \bar{\chi} \chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi} \chi .\end{aligned}\tag{1}$$



Comparison with the EFT approach

- ▶ SFDM scenario is ruled out in the EFT

A. Djouadi, et.al. 2011

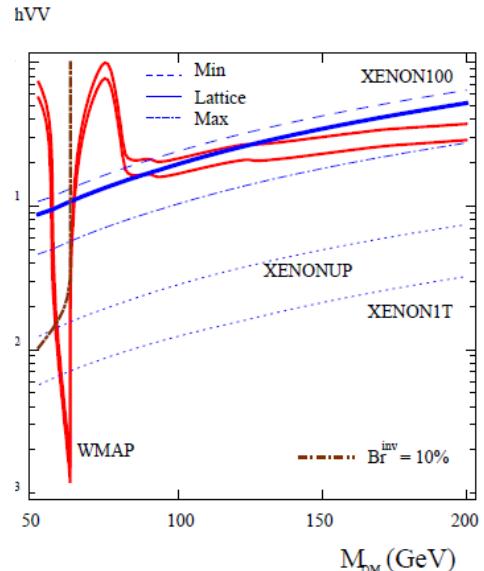
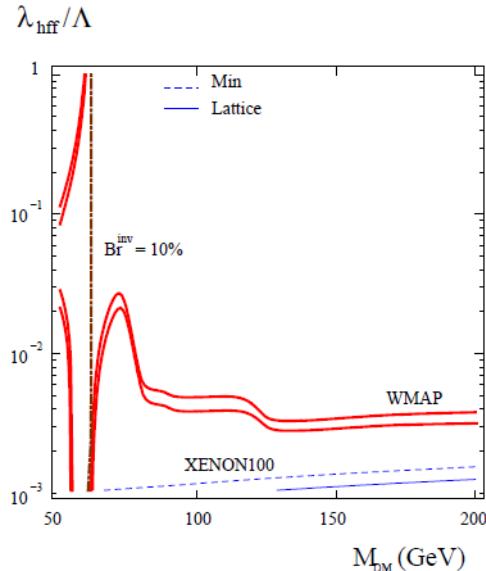
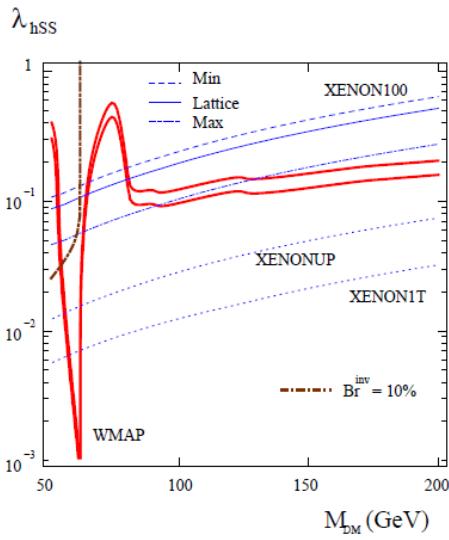


FIG. 1. Scalar Higgs-portal parameter space allowed (between the solid red curves), XENON100 and Br^{i} ($m_h = 125 \text{ GeV}$). Shown also are the prospects for XENON1T.

FIG. 2. Same as Fig. 1 for fermion DM; $\lambda_{\text{hff}}/\Lambda$ is in GeV^{-1} . FIG. 3. Same as in Fig. 1 for vector DM particles.



EW precision tests

- ▶ The S,T,U parameters give strong constraints on the mixing angle α

