General Aspects of Higgs Portal Dark Matter

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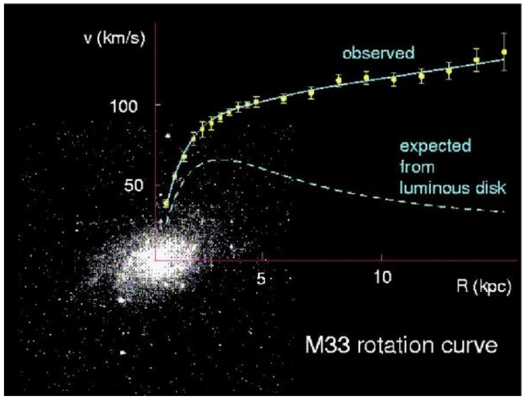
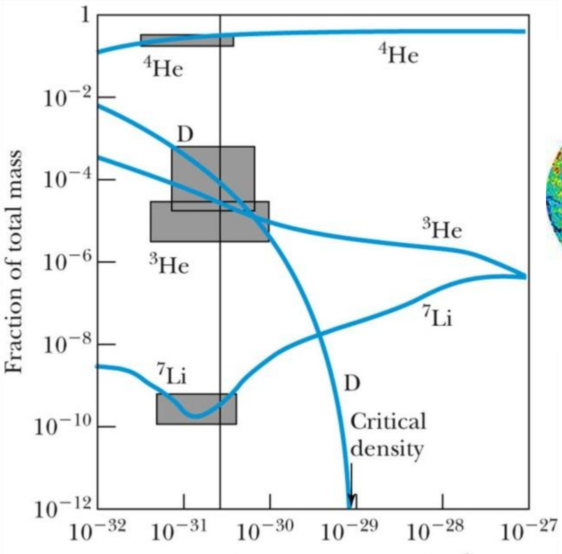
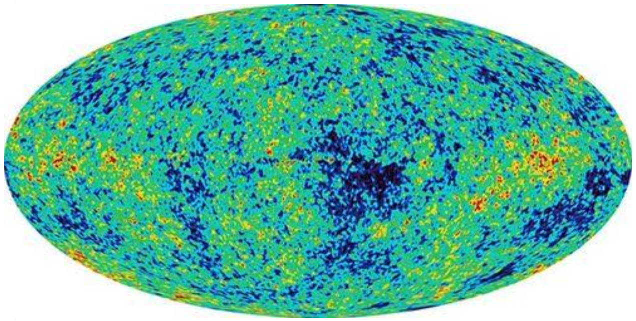
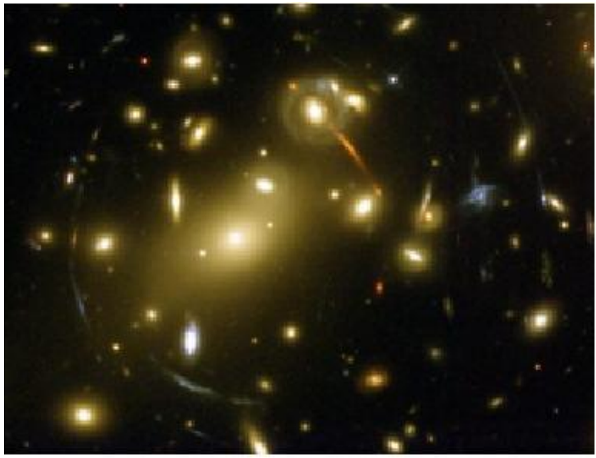
based on 1112.1847, 1209.4163, work in progress
in collaboration with P. Ko, W.I. Park, E. Senaha

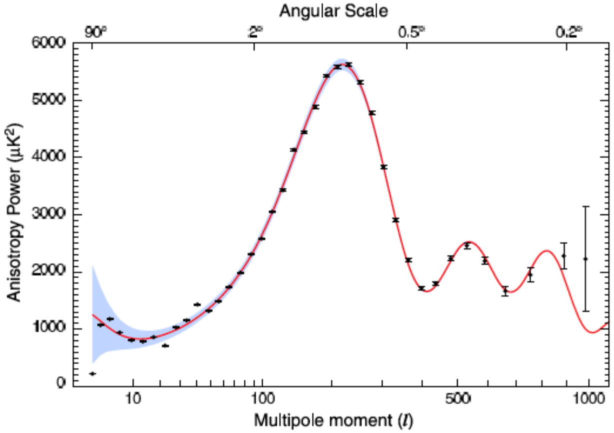
Dark Matter


v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve


1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Fraction of total mass
^{4}He
^{4}He
D
^{3}He
^{3}He
^{7}Li
^{7}Li
D
Critical
density
10^{-32}
10^{-31}
10^{-30}
10^{-29}
10^{-28}
10^{-27}
Current baryon density (g/cm^3)

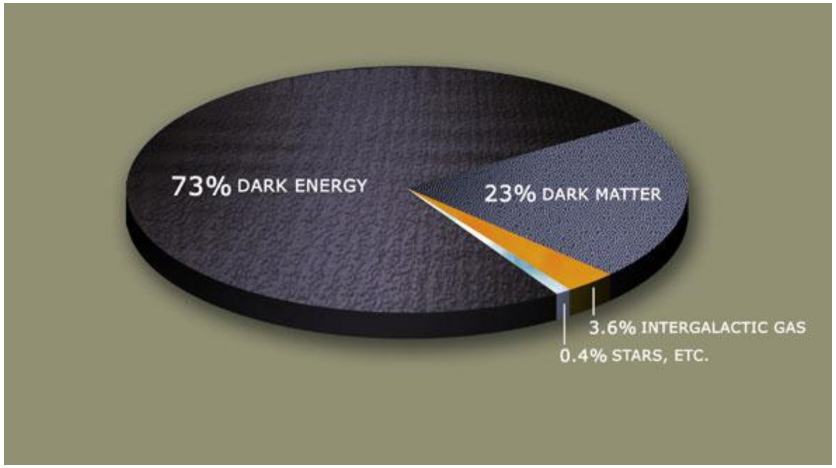



le - Thomson


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (l)

Dark Matter

- 23% of the universe is DM

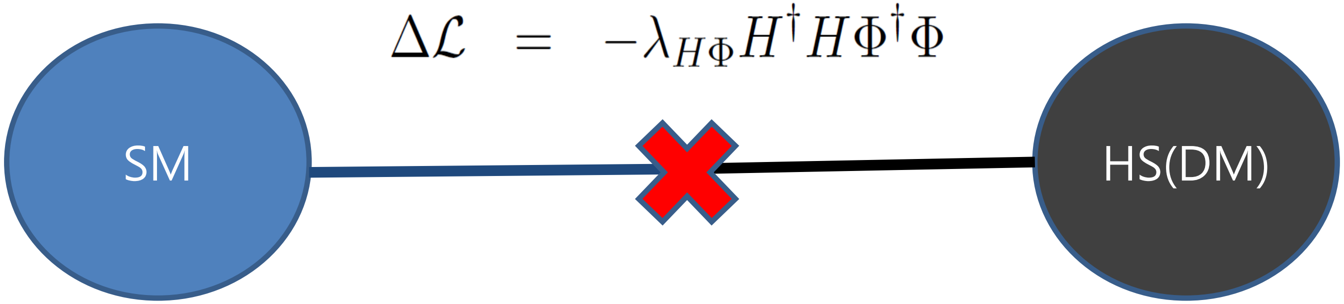


- We do not know the nature of DM
- WIMP allows the particle physics explanation of DM and its creation and detection at LHC
- One possible WIMP DM scenario is the framework of "Hidden Sector" DM

Hidden Sector DM and Higgs Portal

- DM may be singlet under the SM gauge group→hidden
- Hidden sector is generic in SUSY or superstring models
- The renormalizable Higgs can mediate the interaction between the SM and hidden sector

$$\Delta\mathcal{L} = -\lambda_{H\Phi} H^\dagger H \Phi^\dagger \Phi$$



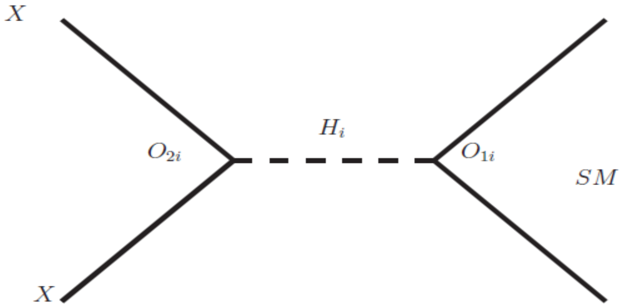
General Aspects of Higgs Portal DM

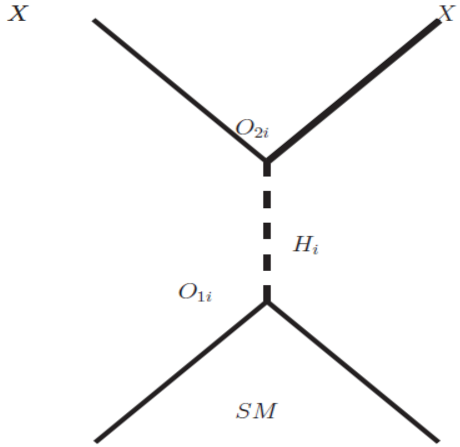
- Dark matter physics
- Collider phenomenology (Higgs search)
- EW precision tests
- Vacuum stability
- Perturbativity

DM physics

- GIM-type cancellation occurs in the DM annihilation and scattering cross section

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



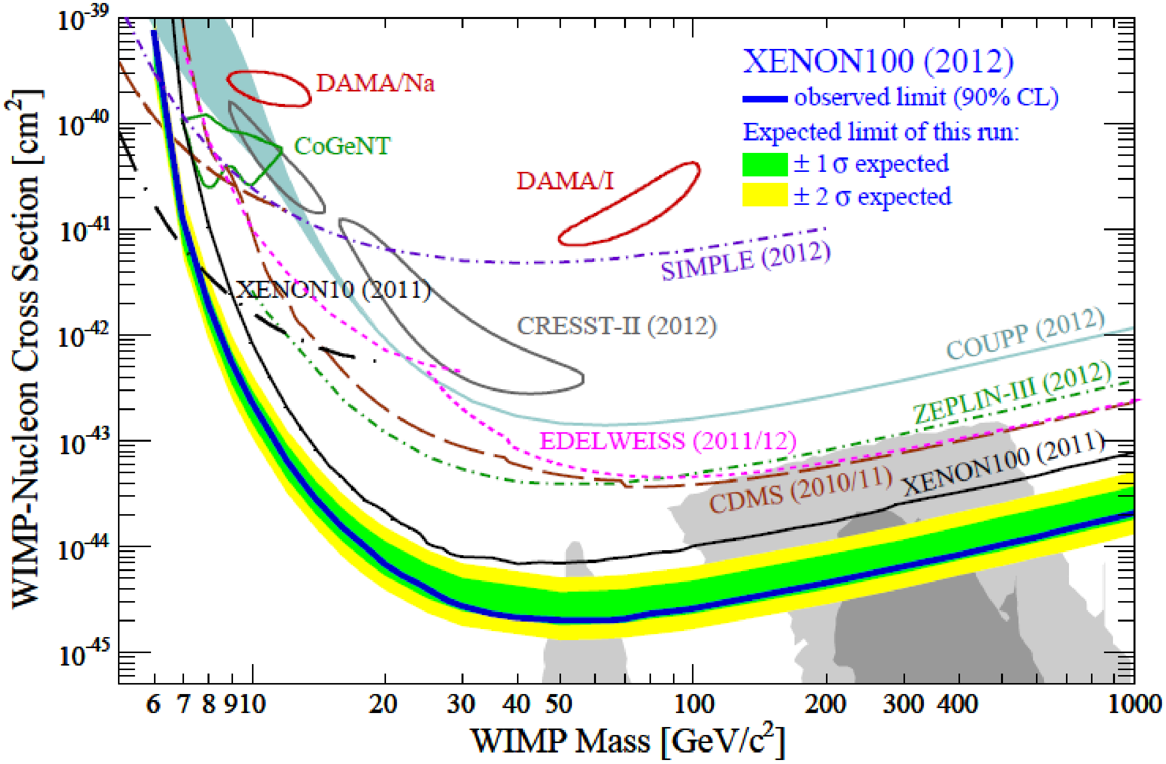


$$\boxed{\sigma_{\mathrm{ann,el}} \propto \left| \sum_i \frac{O_{1i} O_{2i}}{q^2 - m_i^2} \right|^2}$$

➔0 for degenerate Higgs

Direct detection

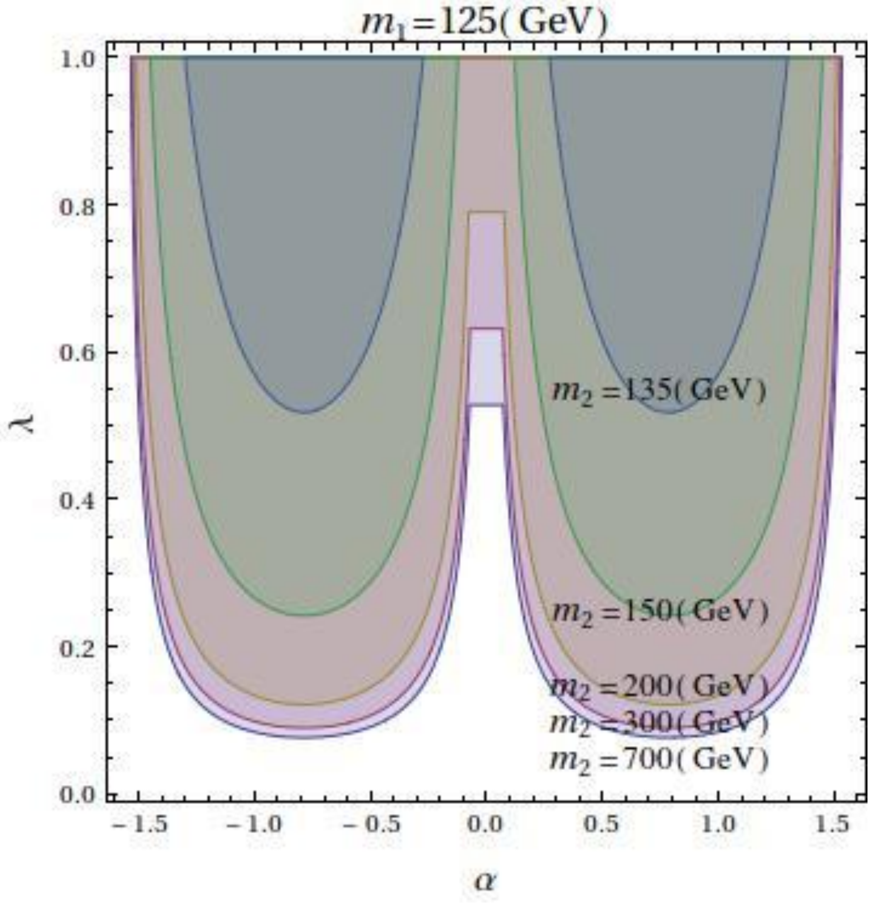
- XENON100(2012)



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

Direct detection

- Exclusion plot by XENON100
- λ: DM-S coupling
- Cancellation is quite effective
- SB, P. Ko, W.I. Park(2011)



DM relic density

- Thermal relic density $\Omega_{\mathrm{CDM}}h^2 \simeq 0.1123 \pm 0.0035$

$$\Omega_{\mathrm{CDM}}h^2 \approx \frac{3 \times 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{fz}}}.$$

- Singlet Fermionic DM

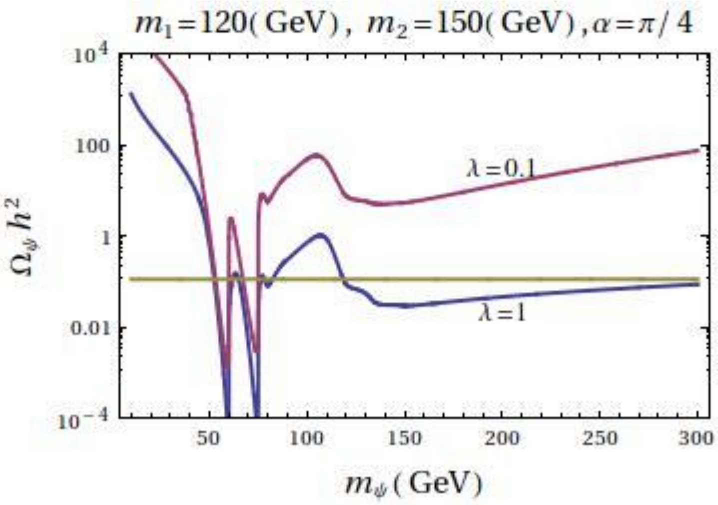
$$\mathcal{L}_{\mathrm{dark}} = \overline{\psi}(i\partial\!\!\!/ - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi \ .$$

- Vector DM

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

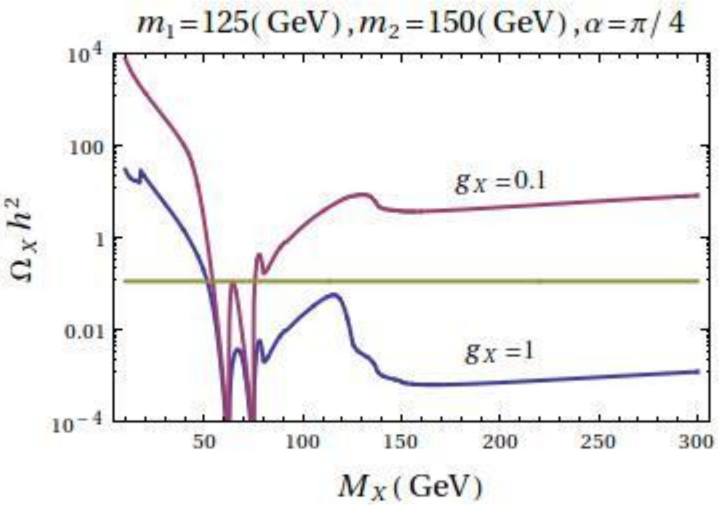
DM relic density

SFDM



P-wave annihilation

VDM



S-wave annihilation

Comparison with the EFT approach

- For heavy m2, H2 can be integrated out. And 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-Hororez, Schwetz, Zupan 2012

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

Comparison with the EFT approach

- SFDM scenario is ruled out in the EFT
- We may lose imformation in DM pheno.

A. Djouadi, et.al. 2011

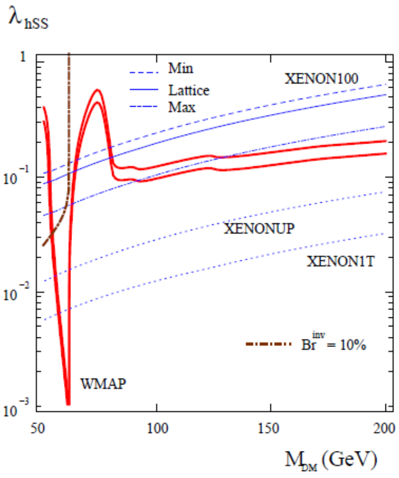


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

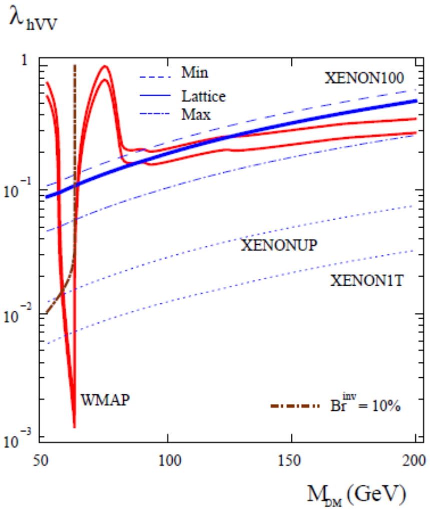


FIG. 2. Same as Fig. 1 for vector DM particles.

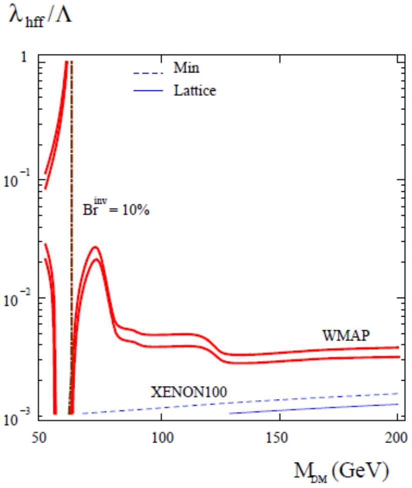


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

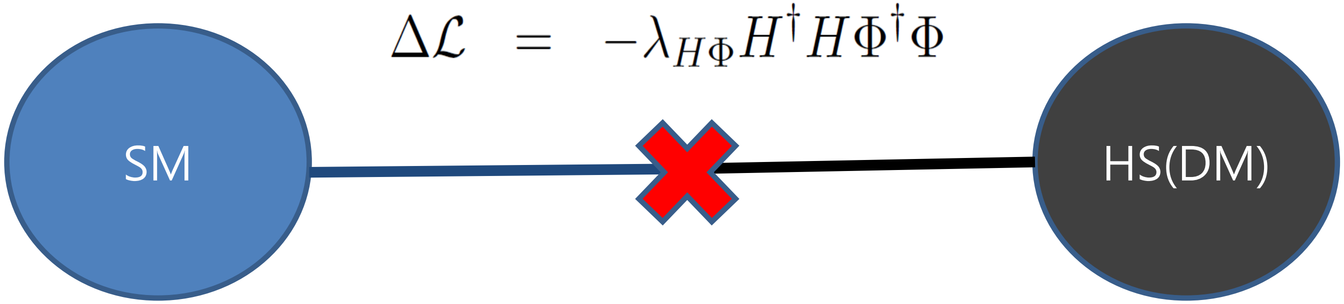
Higgs Phenomenology

- Higgs sector is extended➔Higgs phenomenology is different from the SM one

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

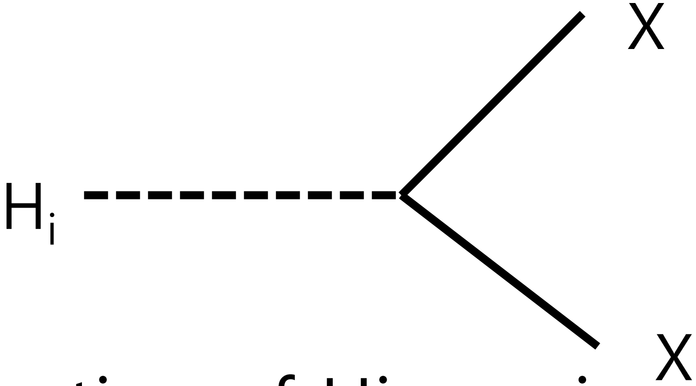
$$M_{\rm Higgs}^2 = \begin{pmatrix} \lambda_H v_H^2 & \lambda_{H\Phi} v_H v_\Phi \\ \lambda_{H\Phi} v_H v_\Phi & \lambda_\Phi v_\Phi^2 \end{pmatrix} \boxed{\begin{pmatrix} h \\ \varphi \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix} H_1 \\ H_2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

$$\Delta\mathcal{L} \;=\; -\lambda_{H\Phi} H^\dagger H \Phi^\dagger \Phi$$

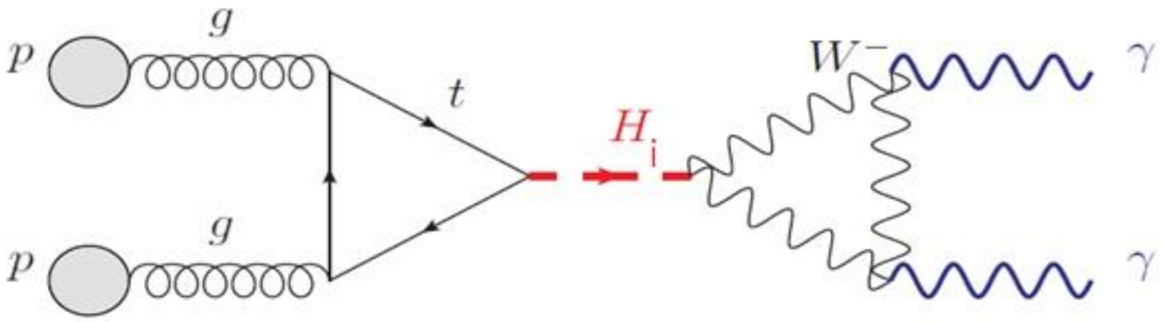


Higgs Phenomenology

- Invisible decay of Higgs at tree is allowed



- Reduction of Higgs signal strength



Higgs Phenomenology

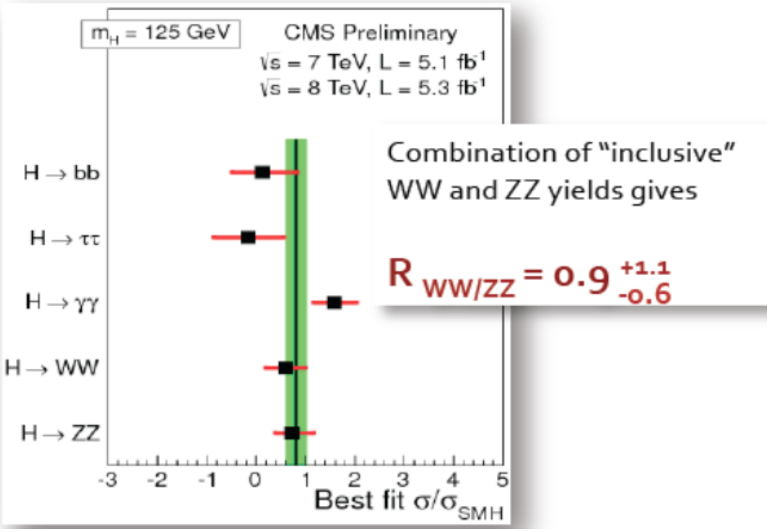
- Signal strength (reduction factor)

$$r_i \equiv \frac{\sigma_{H_i} B_{H_i \to X_{\rm SM}}}{\sigma^{\rm SM}_{H_i} B^{\rm SM}_{H_i \to X_{\rm SM}}} \quad (i = 1, 2)$$

$$r_1 = \frac{c_\alpha^4 \Gamma^{\rm SM}_{H_1}}{c_\alpha^2 \Gamma^{\rm SM}_{H_1} + s_\alpha^2 \Gamma^{\rm hid}_{H_1}},$$

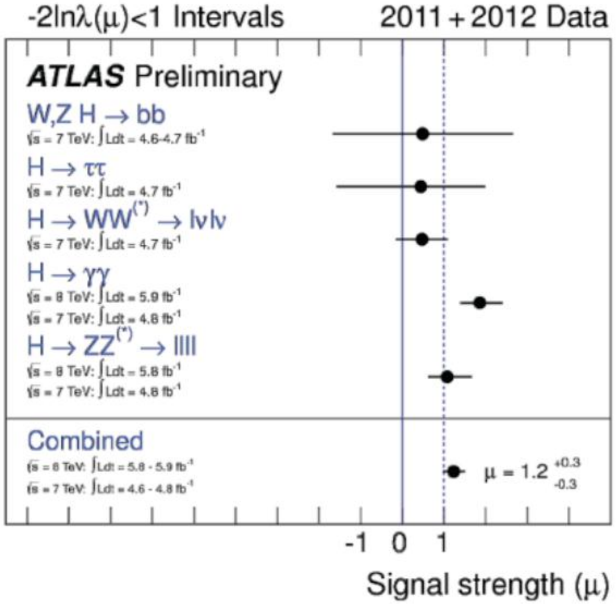
$$r_2 = \frac{s_\alpha^4 \Gamma^{\rm SM}_{H_2}}{s_\alpha^2 \Gamma^{\rm SM}_{H_2} + c_\alpha^2 \Gamma^{\rm hid}_{H_2} + \Gamma_{H_2 \to H_1 H_1}},$$

- ri<1. If some ri>1, our scenario is excluded



Combination of "inclusive" WW and ZZ yields gives

$R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$



EW precision tests

- New contribution to the EW precision obs. Barger, et.al. 2008

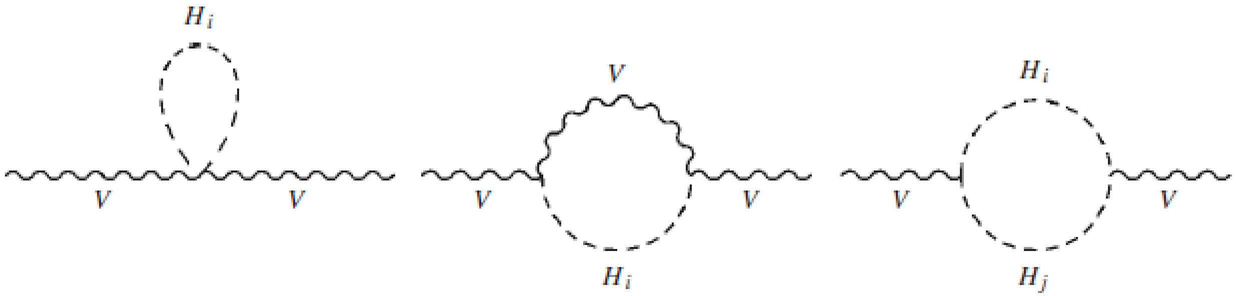
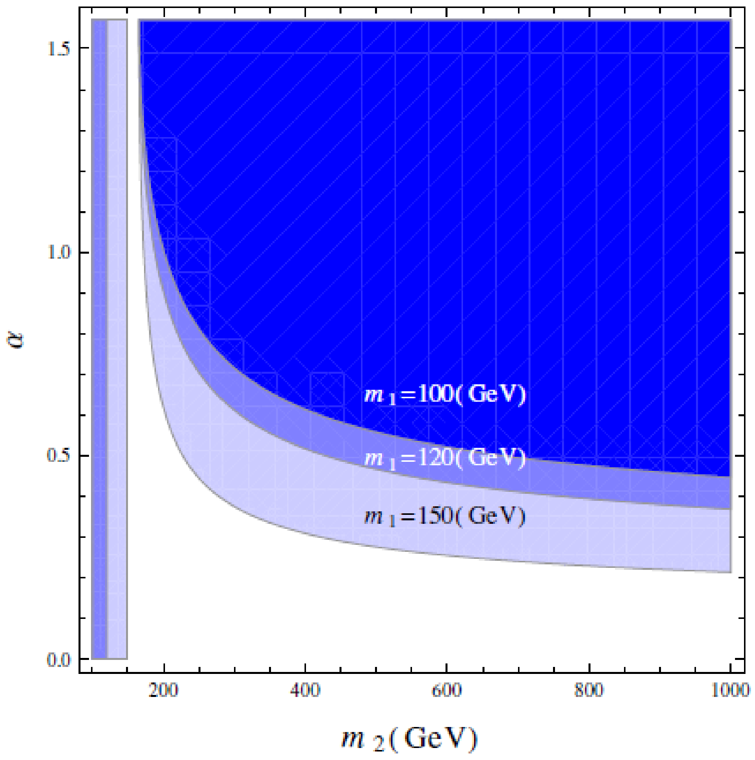
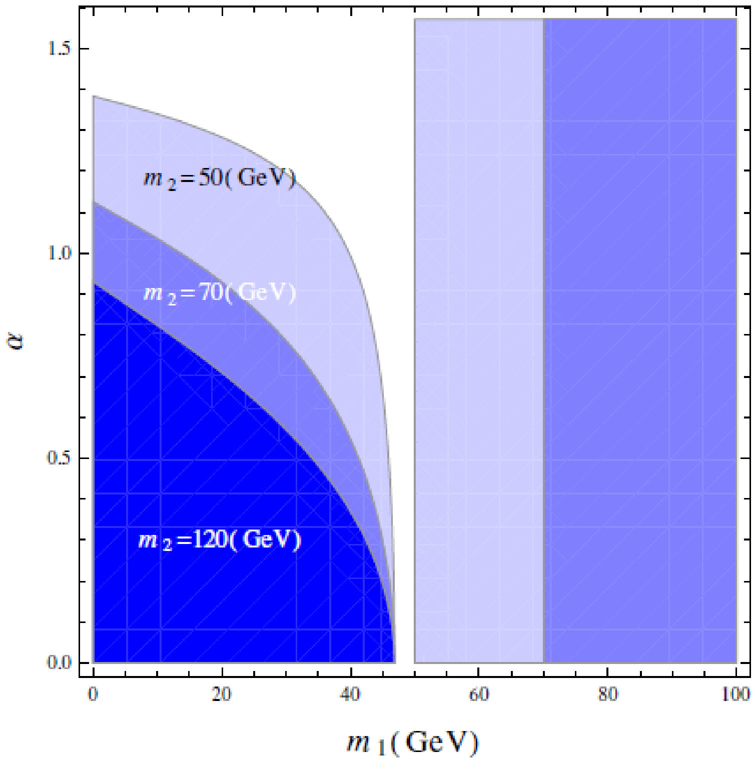


FIG. 2. Feynman diagrams of gauge boson propagators that are affected by Higgs bosons.

EW precision tests

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





EW precision tests

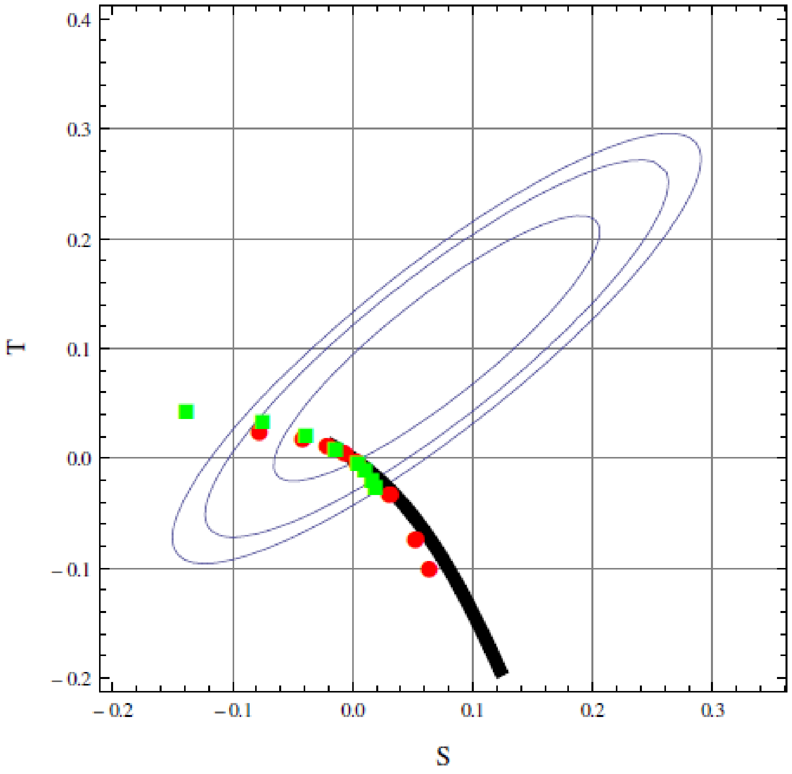


Figure 1. The prediction of (S, T) parameters. We fixed the reference Higgs mass to be 120 GeV. The ellipses are (68, 90, 95) % CL contours from the global fit. The thick black curve shows the SM prediction with the Higgs boson mass in the region $(100, 720)$ GeV. The red, green dots correspond to $\alpha = 45°, 20°$, respectively. The dots are for the choices $(m_1, m_2)(\text{GeV}) = (25, 125), (50, 125), (75, 125), (100, 125), (125, 125), (125, 250), (125, 500), (125, 750)$ from above for each color.

Vacuum stability (EW)

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

$$
\begin{aligned}
\mathrm{EW}: v_H &= 246\ \mathrm{GeV}, \quad v_S = v_S^{\mathrm{in}}, \\
\mathrm{SYM}: v_H &= v_S = 0, \\
\mathrm{I}: v_H &= 0, \quad v_S \neq 0, \\
\mathrm{II}: v_H &\neq 0, \quad v_S = 0, \\
\mathrm{III}: v_H &\neq 246\ \mathrm{GeV}, \quad v_S \neq v_S^{\mathrm{in}},
\end{aligned}
$$

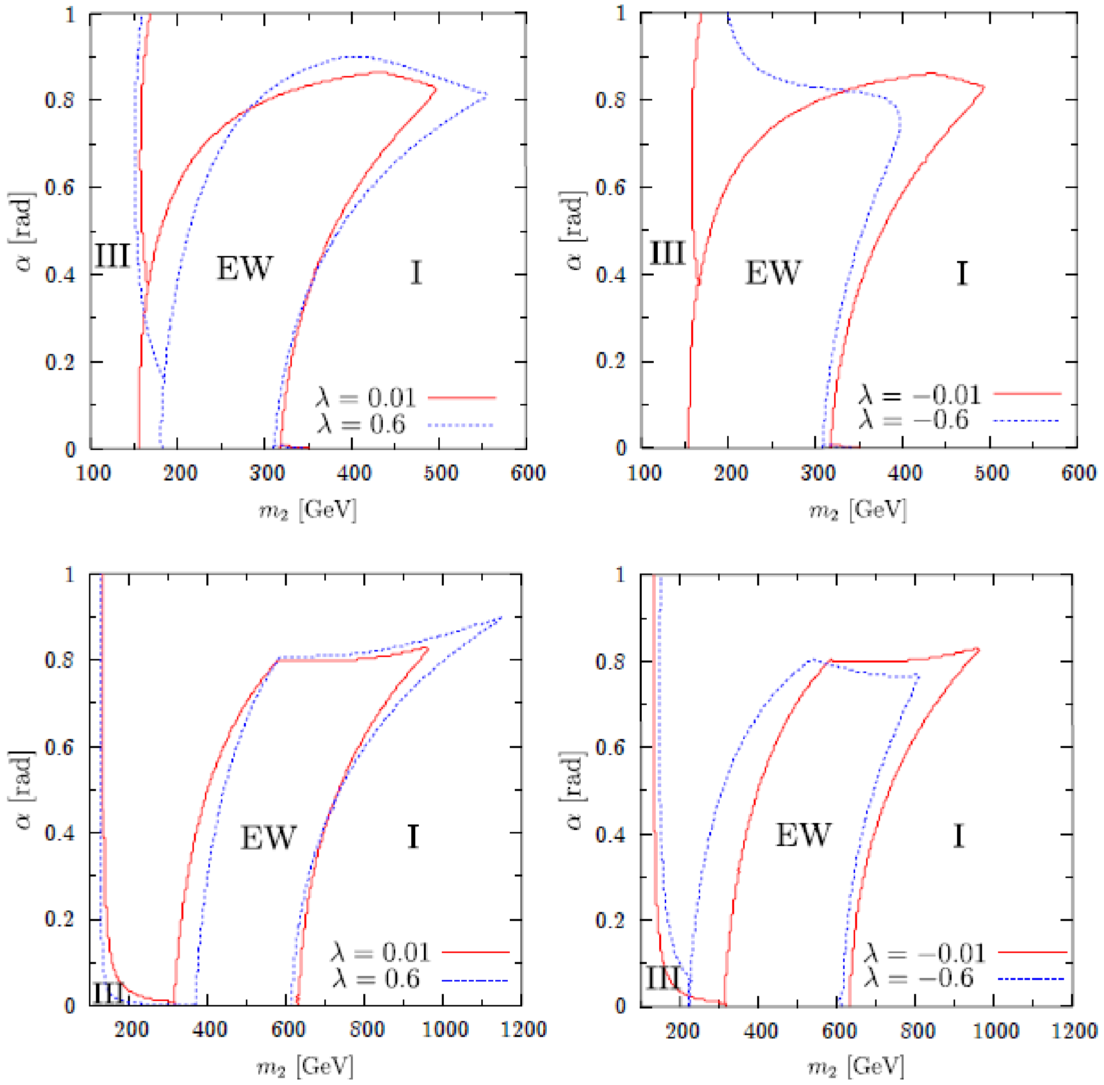
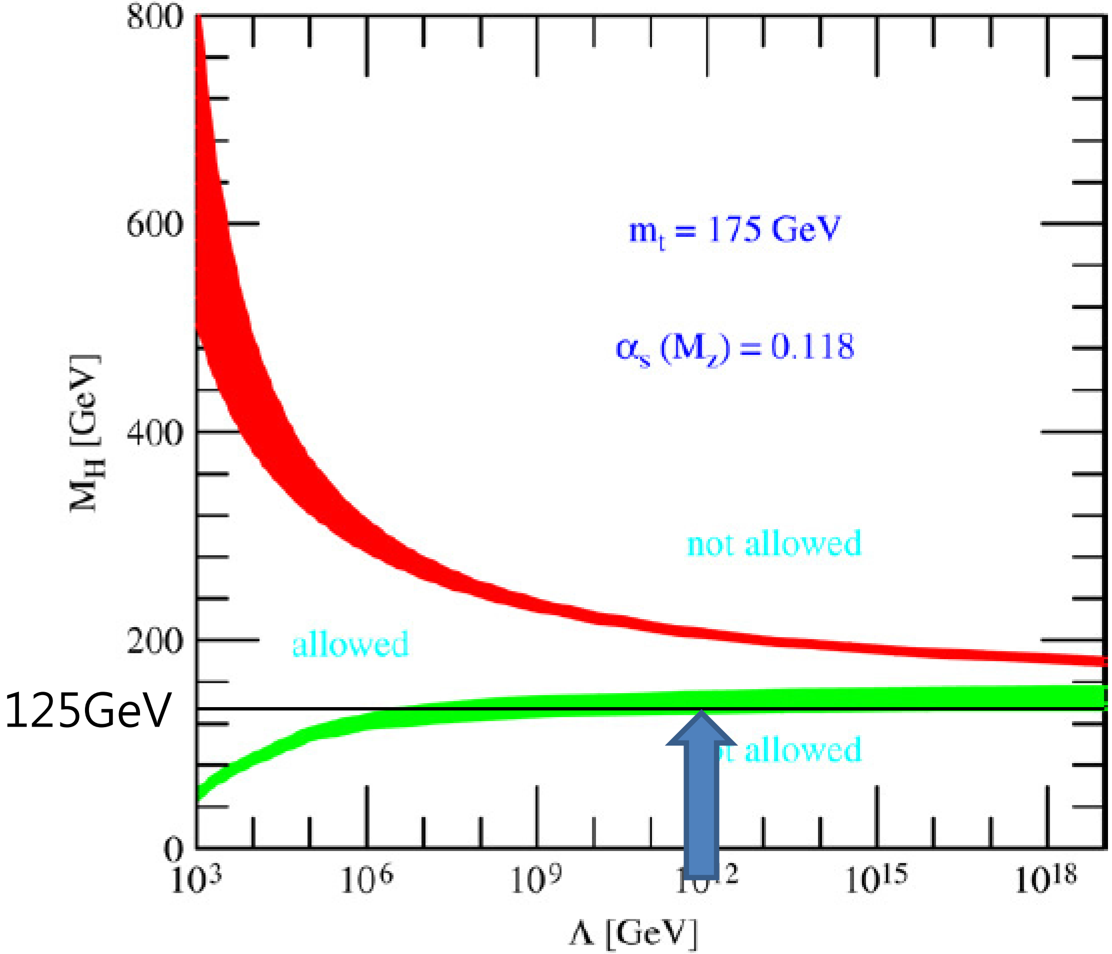


Figure 6. The effects of λ on the vacuum structures. The red straight curves corresponds to the case of $|\lambda| = 0.01$ and the blue dotted curves denotes to the case of $|\lambda| = 0.6$. (Upper) $v_S = -500$ GeV; $\lambda = 0.01, 0.6$ (left) and $\lambda = -0.01, -0.6$ (right). (Lower) $v_S = -1000$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

Triviality and vacuum stability bound on m_H



The Higgs potential may become unstable before Mpl.

- Higgs portal model can provide negative contribution to the SM-like Higgs.
- Lebedev 2012, J. Elias-Miro, et.al 2012

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

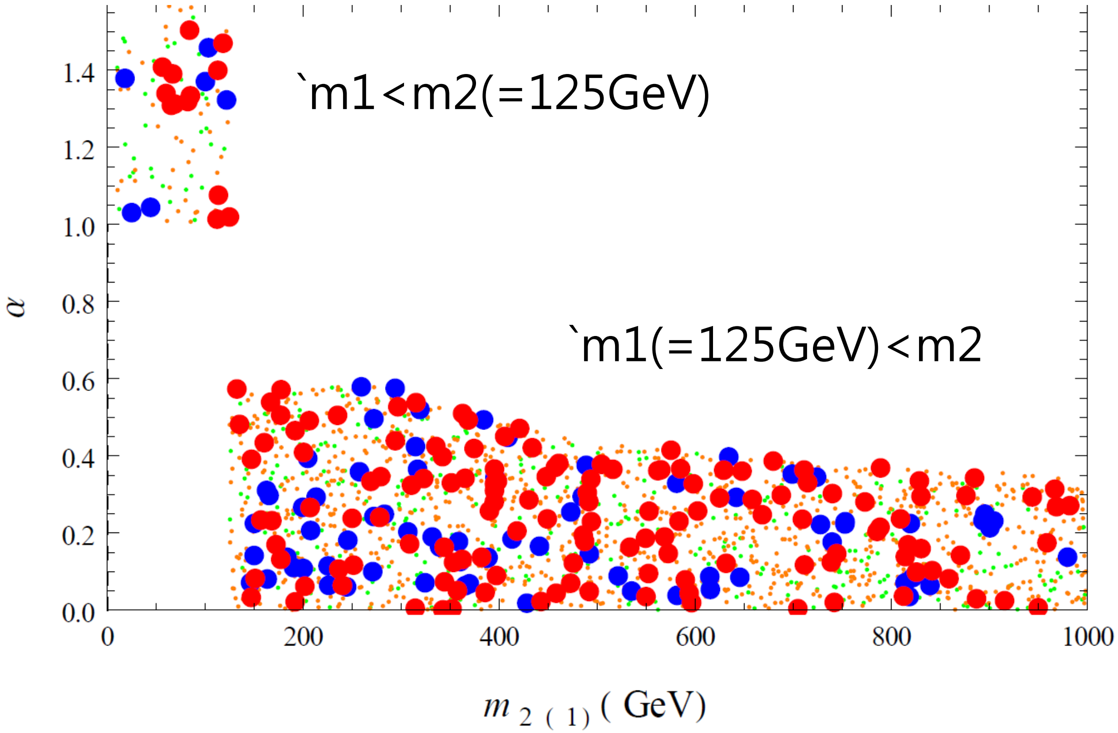
$$m_2^2 \simeq 2\lambda_s u^2 + \frac{\lambda_{hs}^2}{2\lambda_s}\ v^2\ ,$$

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

LHC tests

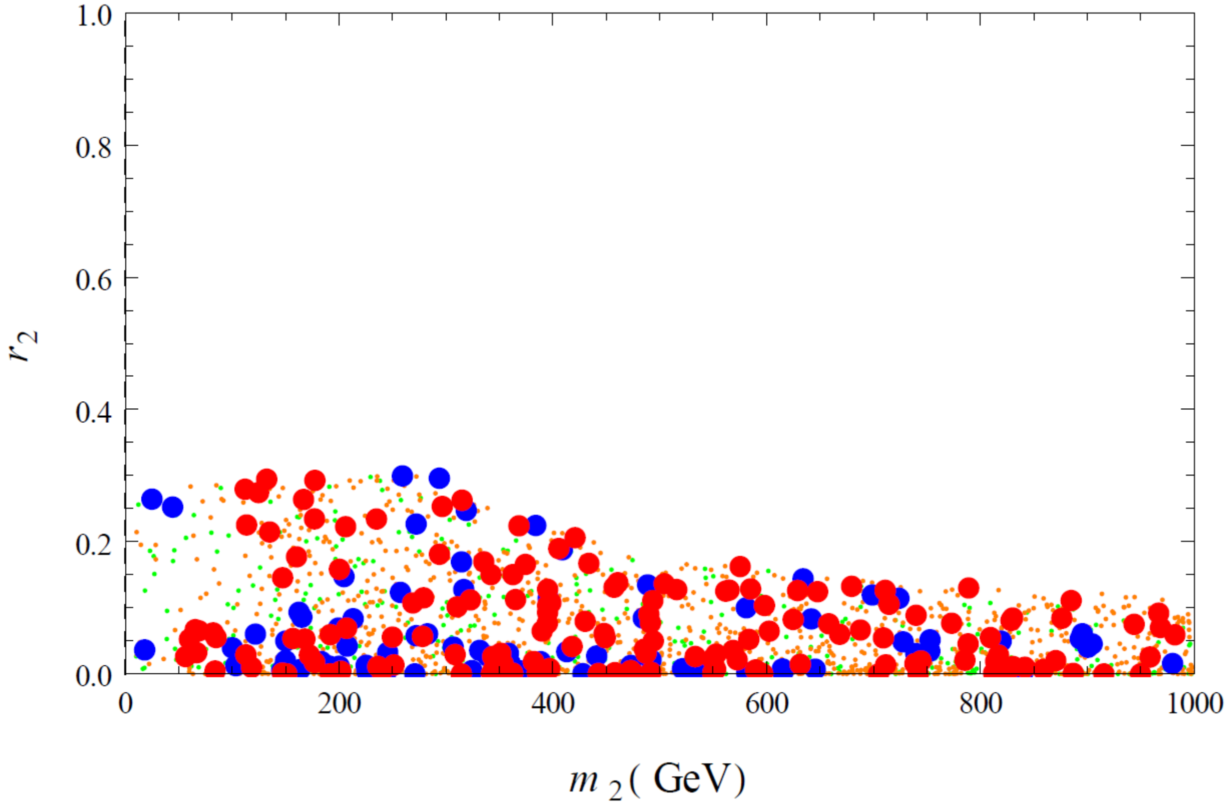
	$\sigma_p^>$	$\sigma_p^<$
$(\Omega_{\rm CDM}h^2)^{3\sigma}$	big red	small orange
$(\Omega_{\rm CDM}h^2)^<$	big blue	small green

r1>0.7



LHC tests

- r1>0.7



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

Conclusions

- DM with Higgs portal
  - provides cancellation to reduce 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.