

Higgs boson decay rates with higher order corrections in extended Higgs sectors

Based on arXiv:1803.04156 [hep-ph]

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Introduction

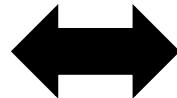
- Current exp. data for the discovered Higgs boson are consistent with the Standard Model (SM).
- On the other hand, structure of the Higgs sector is still unknown.
 - Number of Higgs, its multiplets
 - Symmetry of the Higgs potential
 - Nature of the Higgs boson (elementary or composite)
 - etc.
- Shape of the Higgs sector is closely related to new physics.

New physics models

MSSM, Type-II seesaw,
Composite Higgs, DM,
Electroweak baryogenesis,
Radiative Seesaw, etc.

Extended Higgs sectors

S
 $\Phi + \Phi + \dots$
 Δ



→ It is important to determine the shape of the Higgs sector.

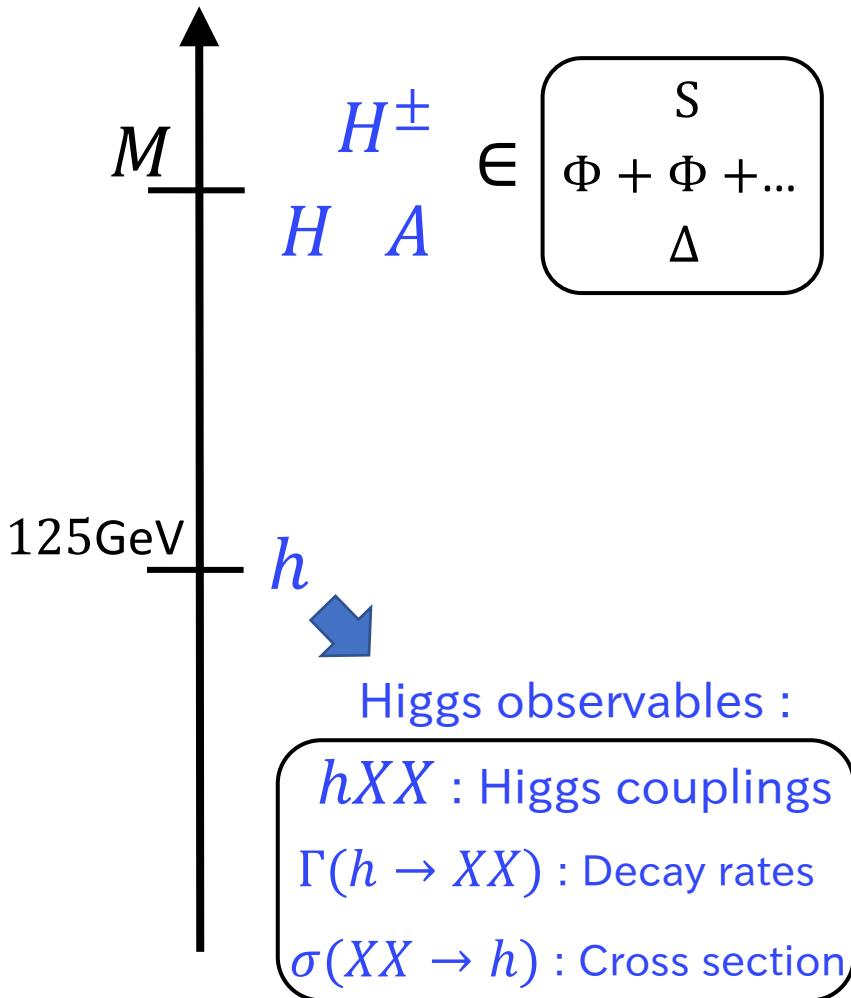
Test of the Higgs sector

- Direct search

Extra Higgs bosons are searched directly by collider exp..

- Indirect search

Effects of extra Higgs are indirectly examined through Higgs observables.



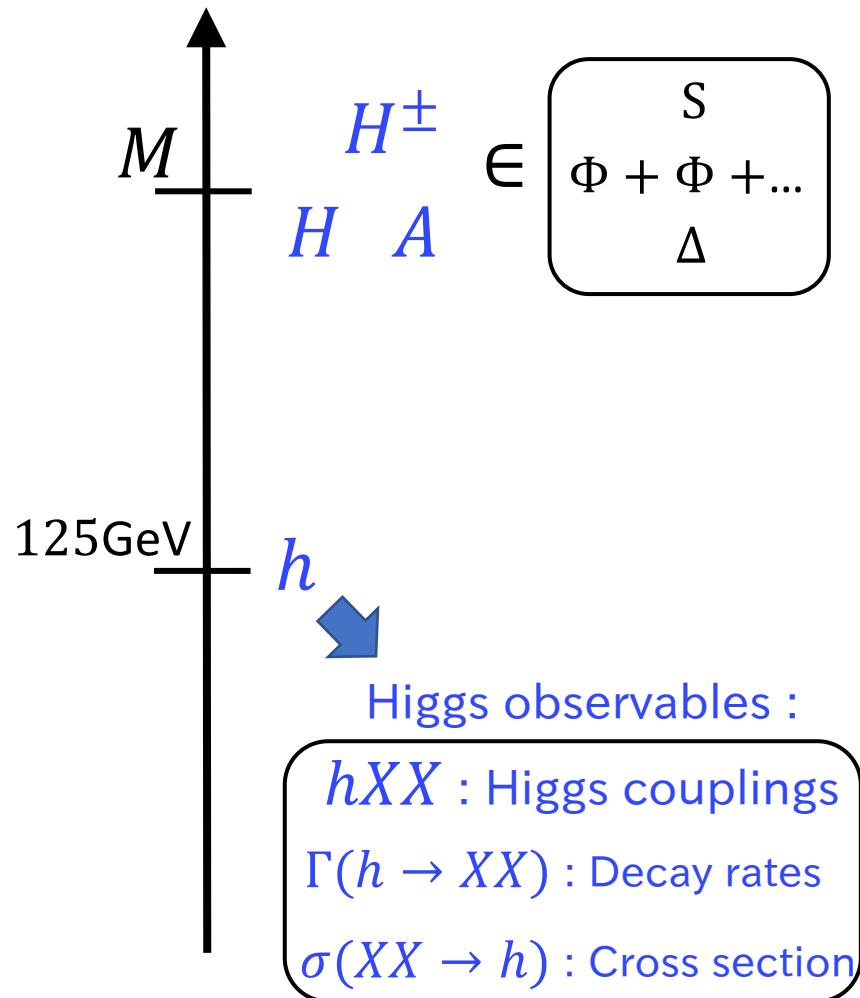
Test of the Higgs sector

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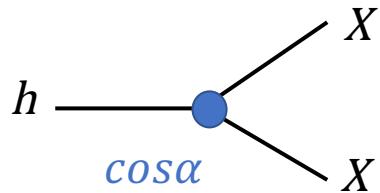


We focus on indirect search with the Higgs observables

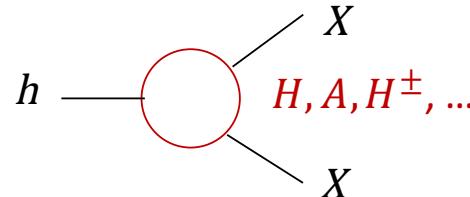
Deviations of Higgs observables

- In extended Higgs models, predictions of Higgs observables deviate from the SM.

Mixing effects :



Loop corrections:



- A pattern of deviations can be different in each model.

[Kanemura, Tsumura, Yagyu, Yokoya, PRD90(2014)075001]

Model	κ_f	κ_V
$\Phi(\text{SM})$	1	1
$\Phi + S$ (Singlet)	$\cos\alpha$	$\cos\alpha$
$\Phi + \Phi$ (Doublet)	$\cos\alpha/\sin\beta$	$\sin\beta\cos\alpha - \cos\alpha\sin\beta$
$\Phi + \Delta$ (Triplet)	$\cos\alpha/\sin\beta$	$\sin\beta\cos\alpha - 1.6\cos\alpha\sin\beta$
$\Phi + \phi_7$ (Septet)	$\cos\alpha/\sin\beta$	$\sin\beta\cos\alpha - 4\cos\alpha\sin\beta$

$$\kappa_X = g_{hXX}^{\text{EX.}} / g_{hXX}^{\text{SM}}$$

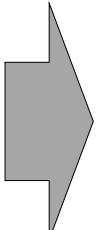
→ Extended Higgs models can be discriminated with patterns of deviations.

Accuracy of the Higgs couplings measurements

Current data (LHC Run I)

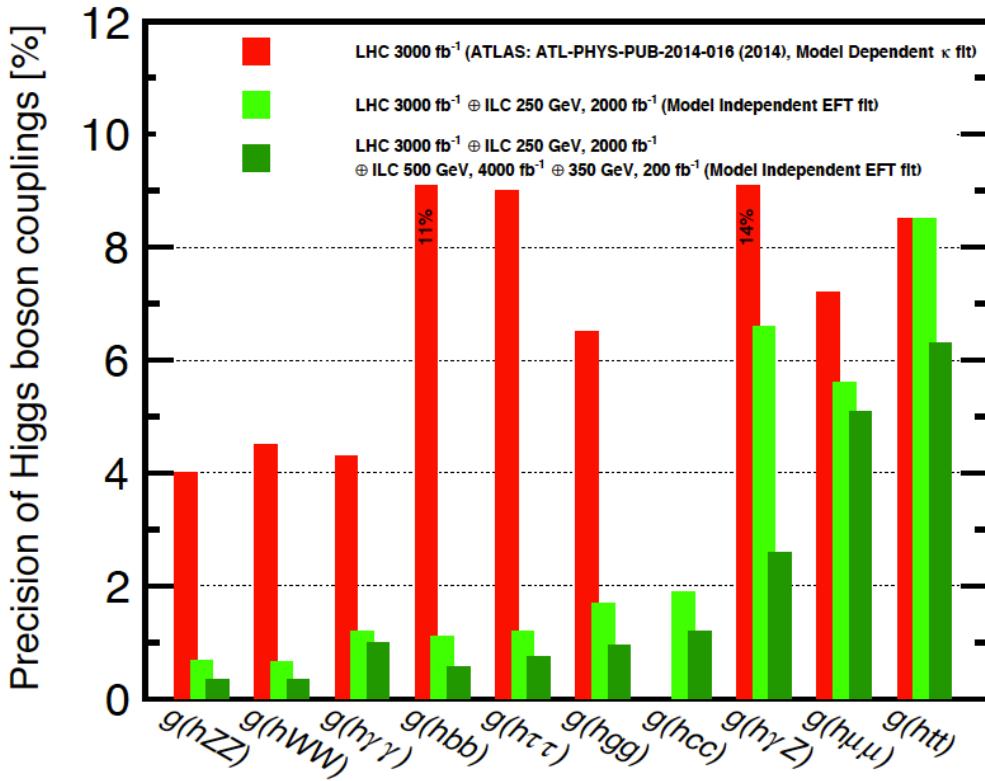
scaling factor: $\kappa_X = g_{hXX}^{exp.}/g_{hXX}^{SM}$

[ATLAS and CMS, JHEP08(2016)045]

κ_Z	-0.98 [-1.08, -0.88] \cup [0.94, 1.13]	
κ_W	0.87 [0.78, 1.00]	
κ_t	$1.40^{+0.24}_{-0.21}$	
$ \kappa_\tau $	$0.84^{+0.15}_{-0.11}$	
$ \kappa_b $	$0.49^{+0.27}_{-0.15}$	
$ \kappa_g $	$0.78^{+0.13}_{-0.10}$	
$ \kappa_\gamma $	$0.87^{+0.14}_{-0.09}$	

Future prospect (HL-LHC, ILC)

[K. Fujii, et al., arXiv:1710.07621]



→ We should evaluate the theoretical predictions including radiative corrections.

H-COUP project

We have calculated the Higgs couplings at the 1 loop level in various extended Higgs models with on-shell scheme.

	htt	hbb	$h\tau\tau$	hVV	hhh	hgg	$h\gamma\gamma$	$hZ\gamma$
HSM	✓	✓	✓	✓	✓	✓	✓	✓
THDM Type-I	✓	✓	✓	✓	✓	✓	✓	✓
THDM Type-II	✓	✓	✓	✓	✓	✓	✓	✓
THDM Type-X	✓	✓	✓	✓	✓	✓	✓	✓
THDM Type-Y	✓	✓	✓	✓	✓	✓	✓	✓
IDM	✓	✓	✓	✓	✓	✓	✓	✓
HTM				✓	✓	✓	✓	✓

Kanemura, Kikuchi, Yagyu, NPB907 (2016)
 Kanemura, Kikuchi, Yagyu, NPB917 (2017)

Kanemura, Okada, Senaha, Yuan,
 PRD70 (2004)

Kanemura, Kikuchi, Yagyu, PLB731 (2014)

Kanemura, Kikuchi, Yagyu, NPB96 (2015)

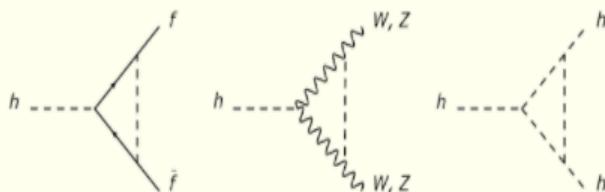
Kanemura, Kikuchi, KS, NPB96 (2015)

Aoki, Kanemura, Kikuchi, Yagyu, PLB714 (2012)
 Aoki, Kanemura, Kikuchi, Yagyu, PRD87 (2013)

- We constructed the computation program called H-COUP.
- H-COUP ver.1.0 was released last Oct.
 [S. Kanemura, M. Kikuchi, KS, K. Yagyu arXiv:1710.04603]

H-COUP

[http://www-het.phys.sci.osaka-u.ac.jp/~kanemu/HCOUP_HP1013/HCOUP_HP.html]



H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The involved on-shell renormalization scheme is adopted, where the gauge dependence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 1.0 can be taken on [arXiv:1710.04603 \[hep-ph\]](https://arxiv.org/abs/1710.04603).

Downloads

- H-COUP version 1.0 : [\[HCOUP-1.0.zip\]](#) [The manual is [here](#)]

In order to run H-COUP version 1.0, you need to install LoopTools (www.feynarts.de/looptools/).

History

Contact

Extended Higgs models

We focus on 4 types of THDMs and the HSM.

	THDMs Type I, II, X, Y (Softly broken Z_2 Sym., CP conserved)	HSM
Higgs sector	$\Phi_1 + \Phi_2$ $\Phi_i = \begin{pmatrix} w_i \\ 1/\sqrt{2}(v + h_i + i z_i) \end{pmatrix} (i=1,2)$	$\Phi + S$ $S = v_s + s$
Physical states (h : 125 GeV Higgs)	h, H, A, H^\pm	h, H
Free parameters	$m_H, m_A, m_{H^\pm}, \alpha, \beta, M^2$	$m_H, \alpha, m_S^2, \lambda_S, \mu_S$
Higgs coup.	$\Gamma_{hVV}^{1,tree} = -\frac{2m_V^2}{v} s_{\beta-\alpha},$ $\Gamma_{hff}^{S,tree} = -\frac{m_f}{v} (s_{\beta-\alpha} + \xi_f c_{\beta-\alpha})$	$\Gamma_{hVV}^{1,tree} = -\frac{2m_V^2}{v} c_\alpha,$ $\Gamma_{hff}^{S,tree} = -\frac{m_f}{v} c_\alpha$

Application of H-COUP ver. 1.0

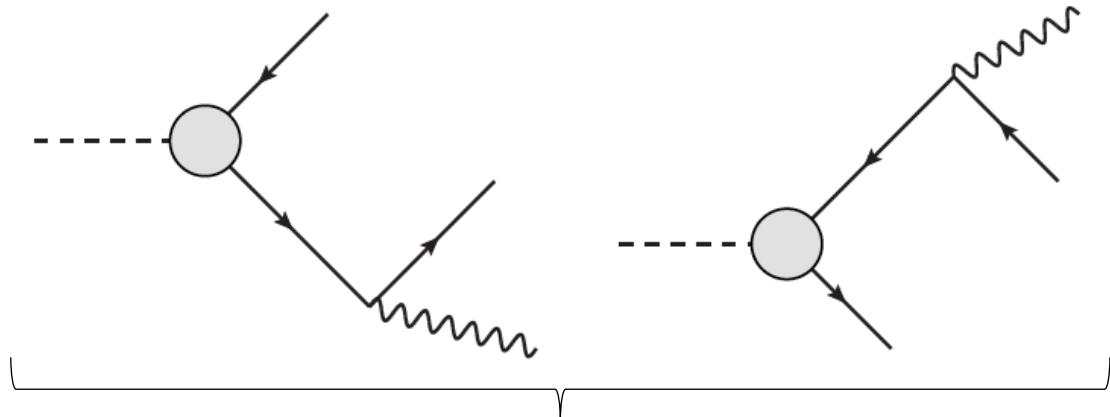
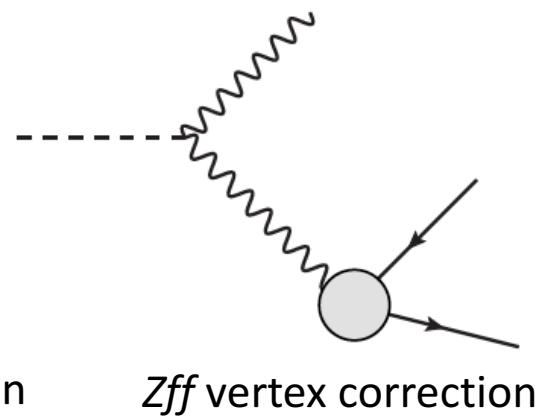
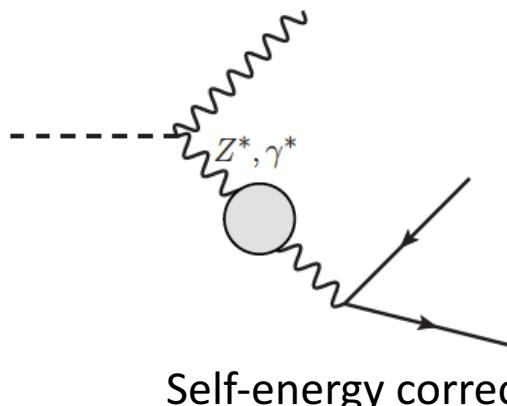
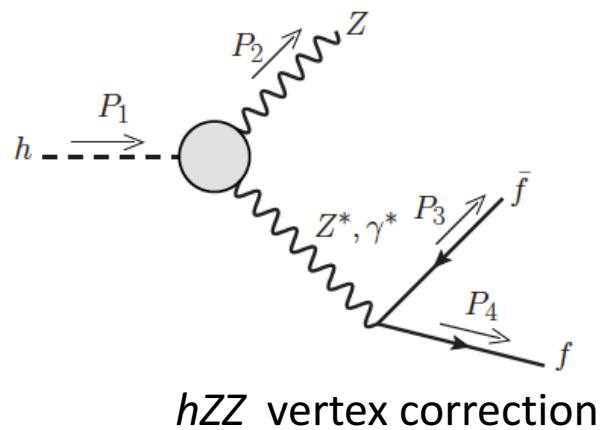
- By H-COUP ver. 1.0 we can numerically calculate each form factor in Higgs boson 3 point vertices functions:

$$\begin{aligned}\hat{\Gamma}_{hVV}^{\mu\nu} &= \underline{\hat{\Gamma}_{hVV}^1} g^{\mu\nu} + \underline{\hat{\Gamma}_{hVV}^2} \frac{p_1^\mu p_2^\nu}{m_V^2} + i \underline{\hat{\Gamma}_{hVV}^3} \epsilon^{\mu\nu\rho\sigma} \frac{p_{1\rho} p_{2\sigma}}{m_V^2} \\ \hat{\Gamma}_{hff} &= \underline{\hat{\Gamma}_{hff}^S} + \gamma_5 \underline{\hat{\Gamma}_{hff}^P} + \not{p}_1 \underline{\hat{\Gamma}_{hff}^{V1}} + \not{p}_2 \underline{\hat{\Gamma}_{hff}^{V2}} \\ &\quad + \not{p}_1 \gamma_5 \underline{\hat{\Gamma}_{hff}^{A1}} + \not{p}_2 \gamma_5 \underline{\hat{\Gamma}_{hff}^{A2}} + \not{p}_1 \not{p}_2 \underline{\hat{\Gamma}_{hff}^T} + \not{p}_1 \not{p}_2 \gamma_5 \underline{\hat{\Gamma}_{hff}^{PT}} \\ \hat{\Gamma}_{hhh} &\end{aligned}$$

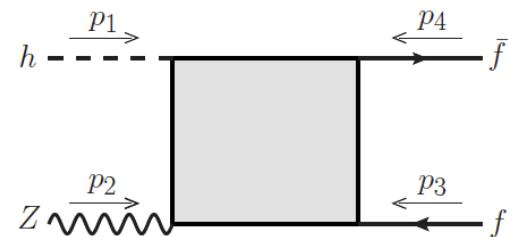
- If we try to compare loop corrected theoretical predictions with exp. data of the Higgs coupling in the future collider exp., it is not clear how we define the scaling factor for the Higgs coupling.
- We should directly evaluate observables for the Higgs boson.
→ With H-COUP, we calculated Higgs decay rates, including NLO EW and QCD corrections.:

$$\Gamma(h \rightarrow f\bar{f}), \Gamma(h \rightarrow ZZ^* \rightarrow Zf\bar{f}), \Gamma(h \rightarrow \gamma\gamma), \Gamma(h \rightarrow Z\gamma), \Gamma(h \rightarrow gg)$$

Calculation of $h \rightarrow ZZ^* \rightarrow Zf\bar{f}$



$hoff$ vertex correction

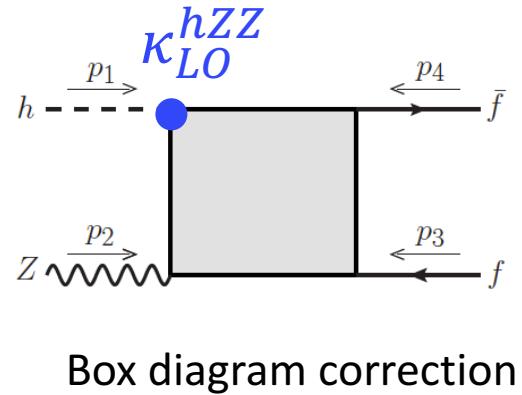
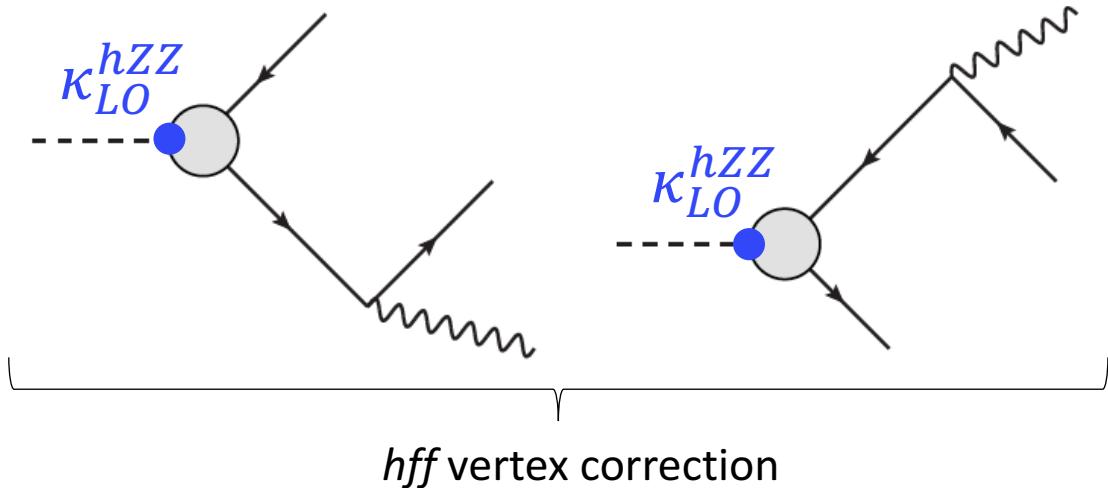
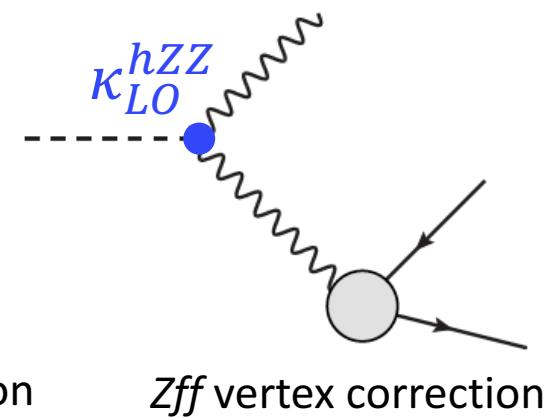
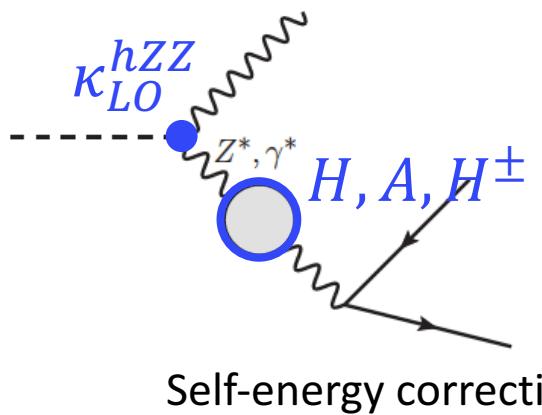
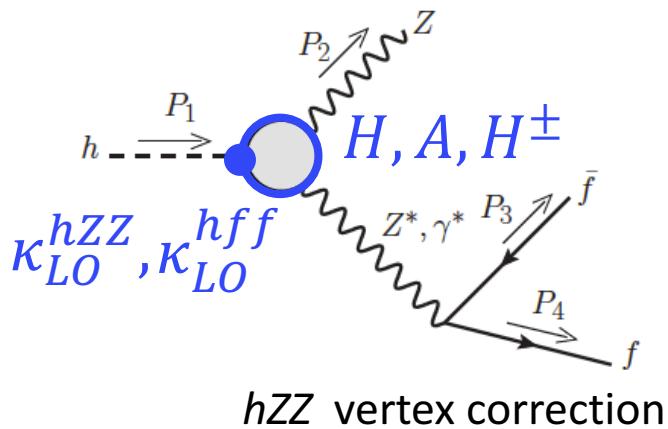


Box diagram correction

Calculation of $h \rightarrow ZZ^* \rightarrow Zff\bar{f}$

$$(\text{THDM}): \quad \kappa_{LO}^{hZZ} = \sin(\beta - \alpha)$$

$$\kappa_{LO}^{hff} = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$$



Numerical evaluation for each contribution

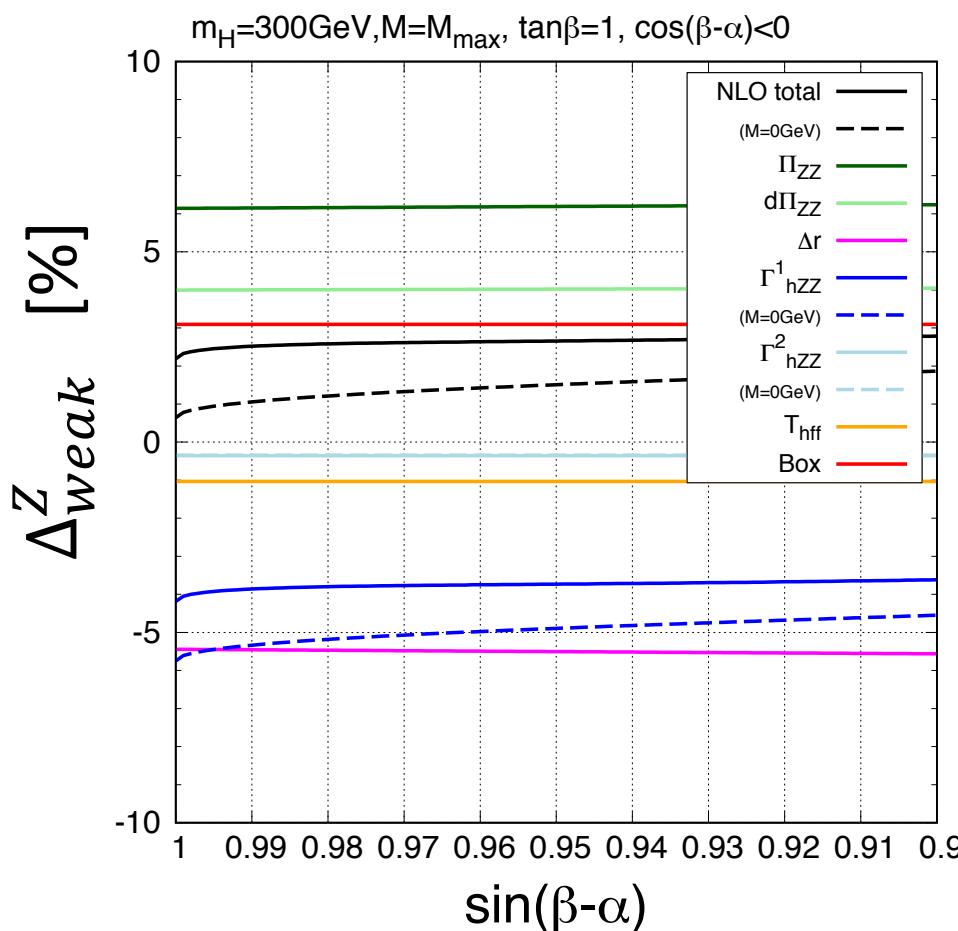
$$\Gamma(h \rightarrow Zff) = \Gamma_0(h \rightarrow Zff)[1 + \Delta_{\text{weak}}^Z + \Delta_{\text{QED}}^Z + \Delta_{\text{QCD}}^Z].$$

$$\Delta_{\text{weak}}^Z = -2\Delta r - \Delta Z_{\text{wf}} + \int d\Phi_3 \frac{1}{|\mathcal{M}_{hZff}^{\text{tree}}|^2} 2\text{Re}(\mathcal{M}_{hZff}^{\text{tree}} \mathcal{M}_{hZff}^{\text{loop}*})$$

$$\Gamma_0(h \rightarrow Zff) = \frac{G_F^2 m_Z^4 m_h}{24\pi^3} (v_f^2 + a_f^2) F\left(\frac{m_Z^2}{m_h^2}\right) \kappa_V^2$$

Δr : weak correction for G_f

ΔZ_{wf} : wave func. reno. for Z boson



Size of total NLO EW correction is $1 \sim 2\%$.

Only Γ^1_{hZZ} is sensitive to extra Higgs loop cont..

Numerical calculations (1-loop)

We discuss whether or not THDMs and the HSM can be distinguished by deviations from the SM in the decay widths.

- Scan region of input parameters in the THDMs :

$$0.95 < \sin(\beta - \alpha) < 1, \quad 1 < \tan\beta < 3,$$

$$m_\Phi = m_H = m_A = m_{H^\pm},$$

$$m_\Phi = 400, 700, 1000, 1500, 2000 \text{ GeV},$$

$$0 < M < m_\Phi$$

- Scan region for the HSM :

$$0.95 < \cos\alpha < 1,$$

$$m_\Phi = 500, 1000, 2000, 3000, 5000 \text{ GeV},$$

$$0 < m_s < m_\Phi, \quad \lambda_s = \mu_s = 0$$

- Constraints :

Perturbative unitarity, Vacuum stability, Wrong vacuum condition (for HSM),
S, T parameters

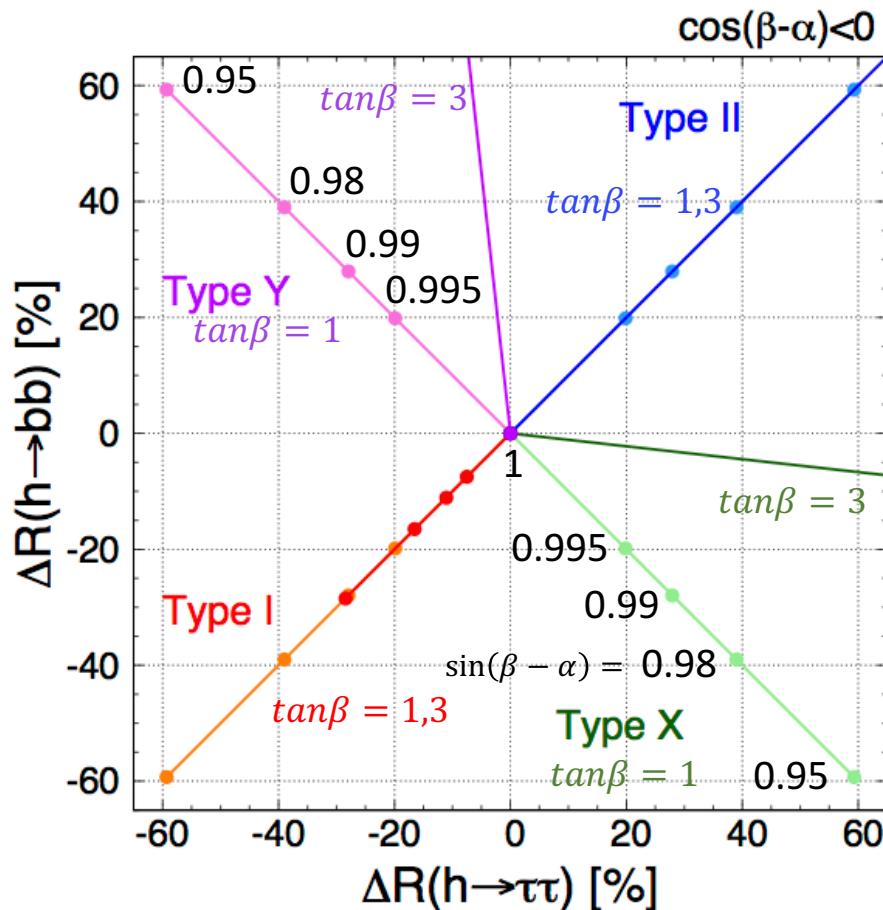
$\Delta R(h \rightarrow b\bar{b})$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$ [Tree]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$

For THDMs :

$$\Delta R(h \rightarrow f\bar{f})^{LO} = (\sin(\beta - \alpha) - \xi_f \cos(\beta - \alpha))^2 - 1$$

	ξ_u	ξ_d	ξ_e
Type-I	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type-II	$\cot \beta$	$-\tan \beta$	$-\tan \beta$
Type-X	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Type-Y	$\cot \beta$	$-\tan \beta$	$\cot \beta$



[S. Kanemura, K. Tsumura, K. Yagyu, H. Yokoya, PRD90 (2014) 075001.]

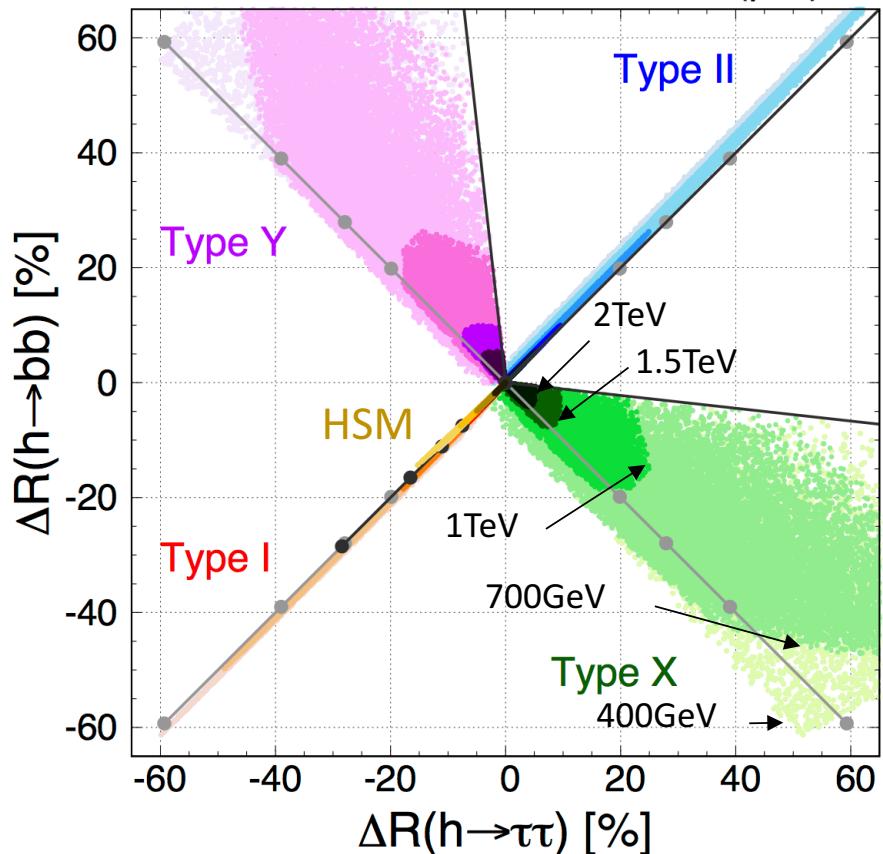
In this plane, 4 types of THDMs can be distinguished.

$\Delta R(h \rightarrow b\bar{b})$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu,] $\cos(\beta-\alpha)<0$

- Color plots : predictions at the 1-loop level for each model
- Contrast of color : values of mass of extra Higgs bosons
- Black line : predictions at the tree level ($\tan\beta = 1, 3$).

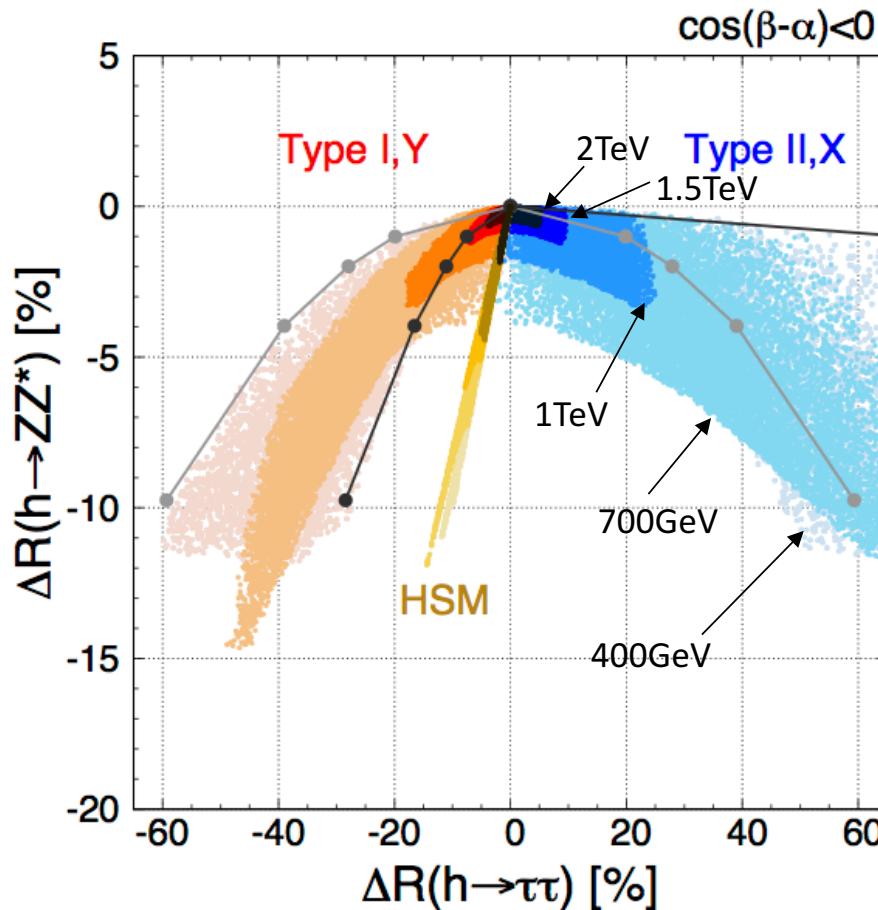


- Even if we include loop corrections in the calculation, pattern of deviations are almost unchanged from the result at the tree level .
- The upper bounds of mass of extra Higgs can be obtained from magnitude of deviations.

$\Delta R(h \rightarrow ZZ^*)$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$

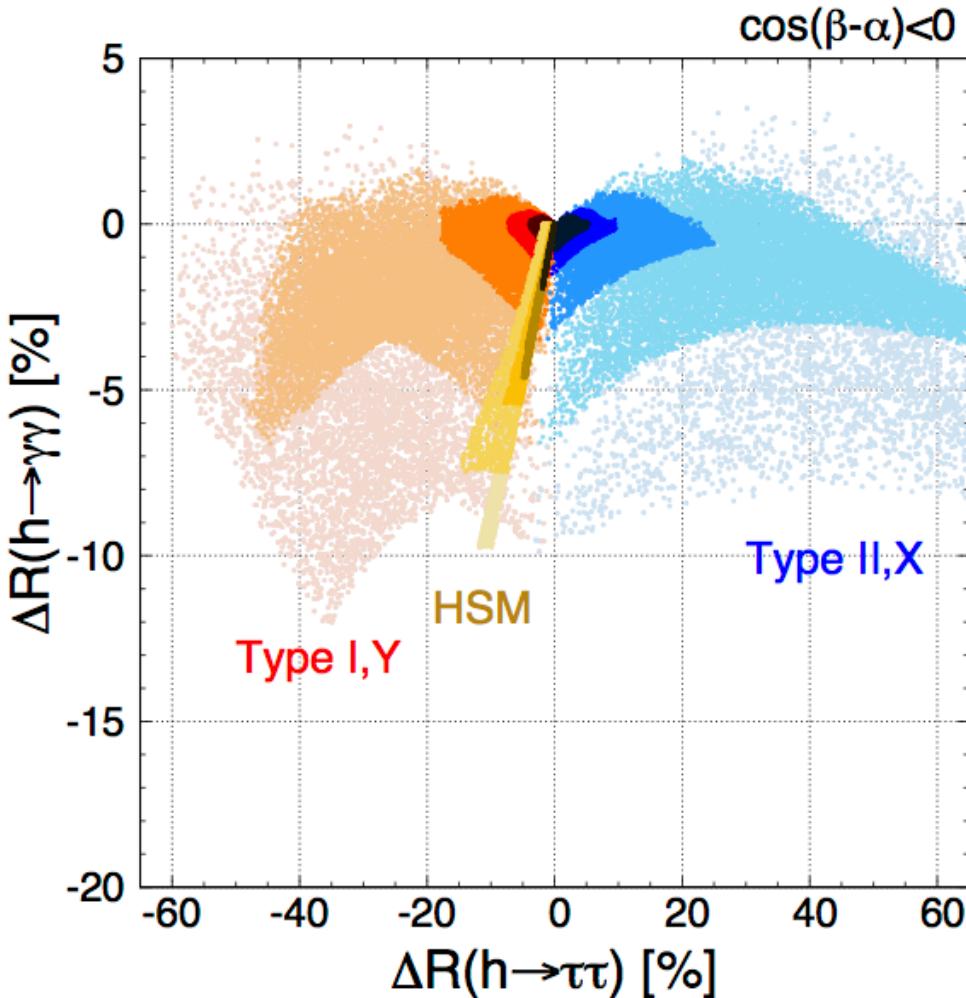


- HSM can be separated from the THDMs.
- Type I and Type II can be discriminated in this plane.

$\Delta R(h \rightarrow \gamma\gamma)$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$



- The behavior is similar to the correlation between $\Delta R(h \rightarrow ZZ^*)$ vs $\Delta R(h \rightarrow \tau\tau)$
- By investigating various correlations of deviations, we can discriminate all the models

Summary

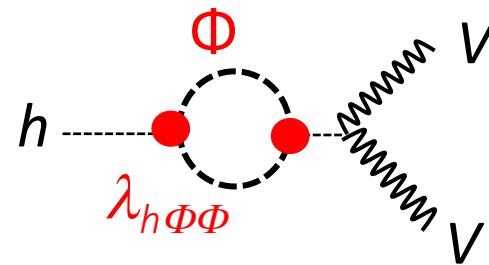
- Higgs sector can be thoroughly tested by precision measurement of the Higgs observables.
- We calculated the Higgs decay widths at the 1-loop level by using H-COUP ver. 1.0.
- We discussed a possibility of discrimination among HSM and 4 types of the THDMs with the deviations from the SM.
 - Pattern of deviations : HSM and 4 types of THDMs can be discriminated.
 - Magnitude of deviation : Information of the mass of extra Higgs boson can be obtained.

Back up slides

Impact of Loop correction of extra Higgs in hZZ vertex

Approximate formula ($m_A, m_H, m_{H^\pm} \gg m_h$)
 $\sin(\beta - \alpha) = 1, \tan\beta = 1$

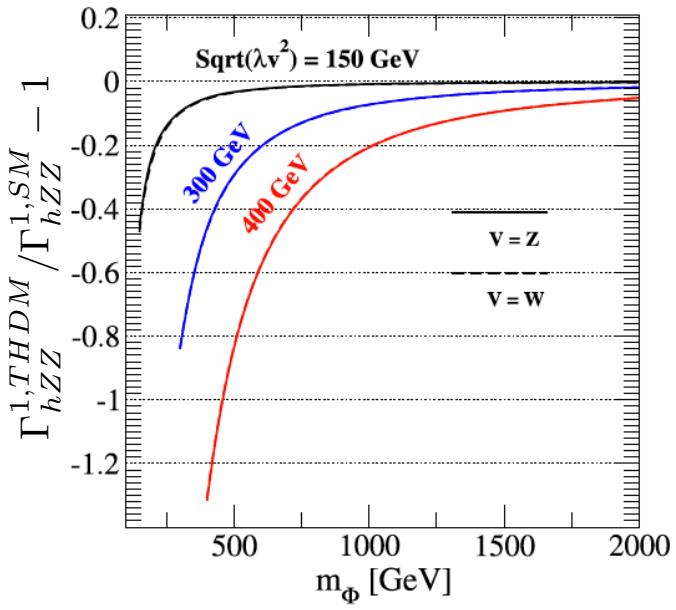
$$\Gamma_{hZZ}^1 = \frac{2m_Z^2}{v} \left\{ 1 - \sum_{\Phi=A,H,H^\pm} c_\Phi \frac{1}{6} \frac{m_\Phi^2}{v^2} \left(1 - \frac{M^2}{m_{\Phi^2}} \right)^2 \right\}$$



1) $M^2 \gg v^2$ Decoupling case

$$m_\Phi^2 \simeq M^2 + \lambda_i v^2 \sim M^2$$

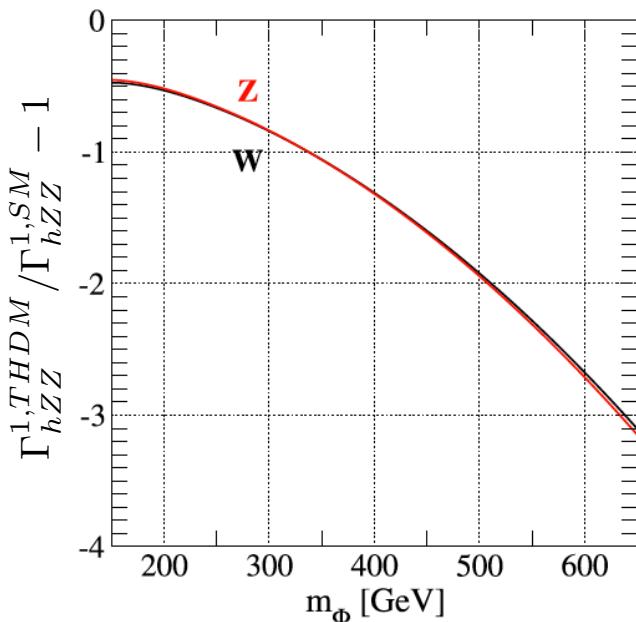
[S. Kanemura, M. Kikuchi, K. Yagyu Nucl.Phys. B896,80.]



2) $M^2 \lesssim v^2$ Non-decoupling case

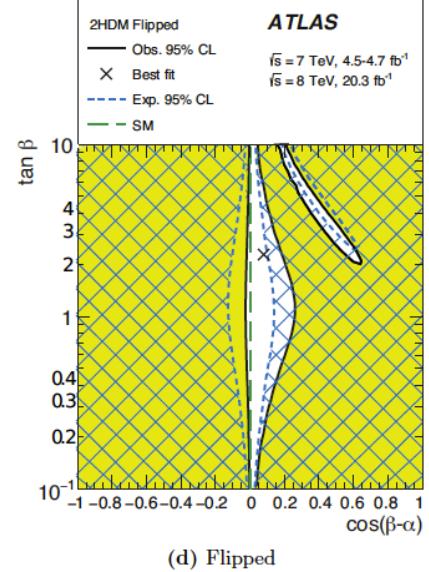
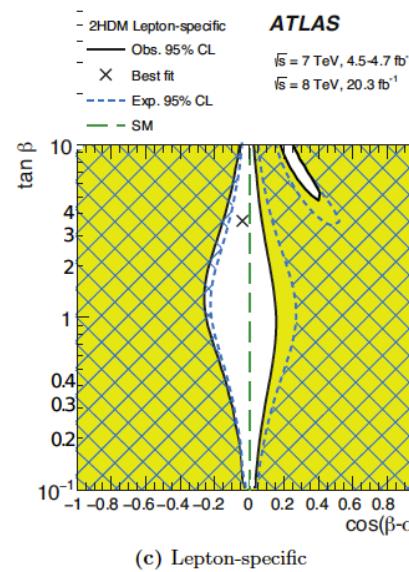
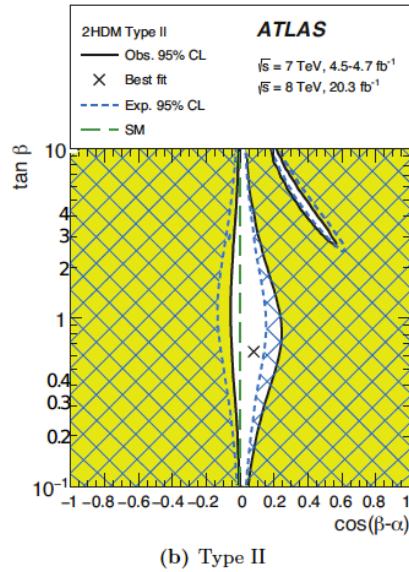
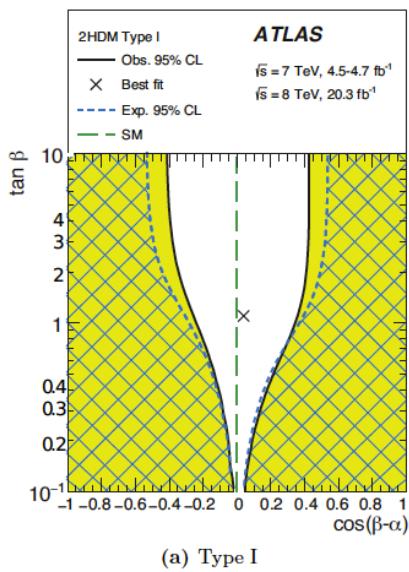
$$m_\Phi^2 \simeq M^2 + \lambda_i v^2 \sim \lambda_i v^2$$

[S. Kanemura, M. Kikuchi, K. Yagyu Nucl.Phys. B896,80.]



constraint for THDMs (Higgs signal strength)

[ATLAS, JHEP1511(2015)206]



$$c_{\beta-\alpha} = 0.1 \rightarrow s_{\beta-\alpha} = 0.99$$

$$c_{\beta-\alpha} = 0.2 \rightarrow s_{\beta-\alpha} = 0.98$$

$$c_{\beta-\alpha} = 0.3 \rightarrow s_{\beta-\alpha} = 0.95$$

Constraint of direct search (HSM)

[T. Robens, T. Stefaniak, Eur. Phys. J. C (2016) 76,268]

LHC Run II

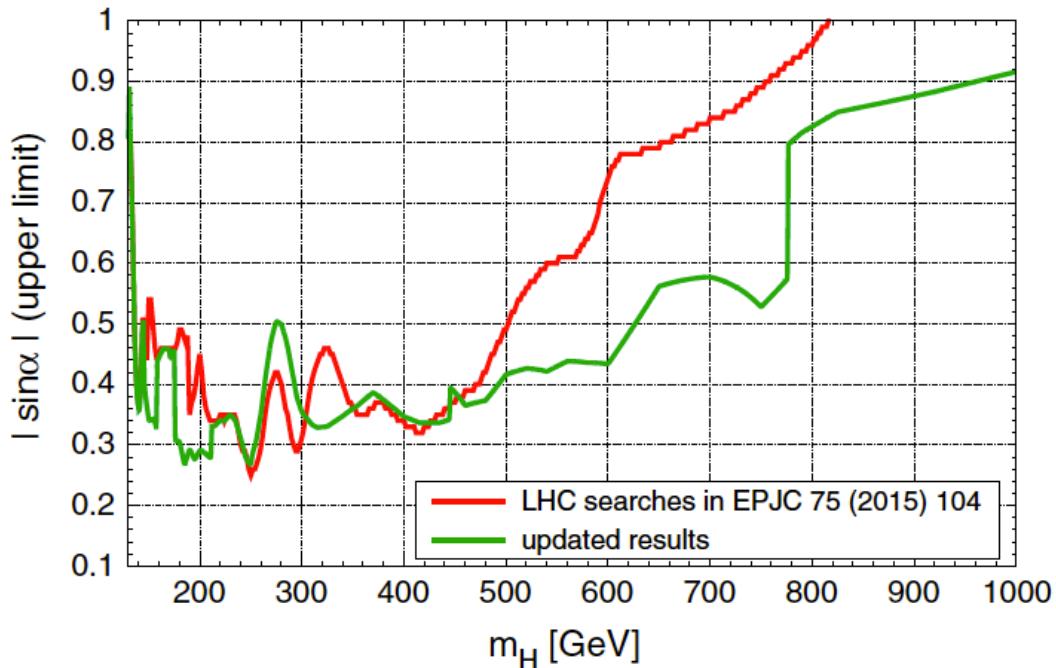


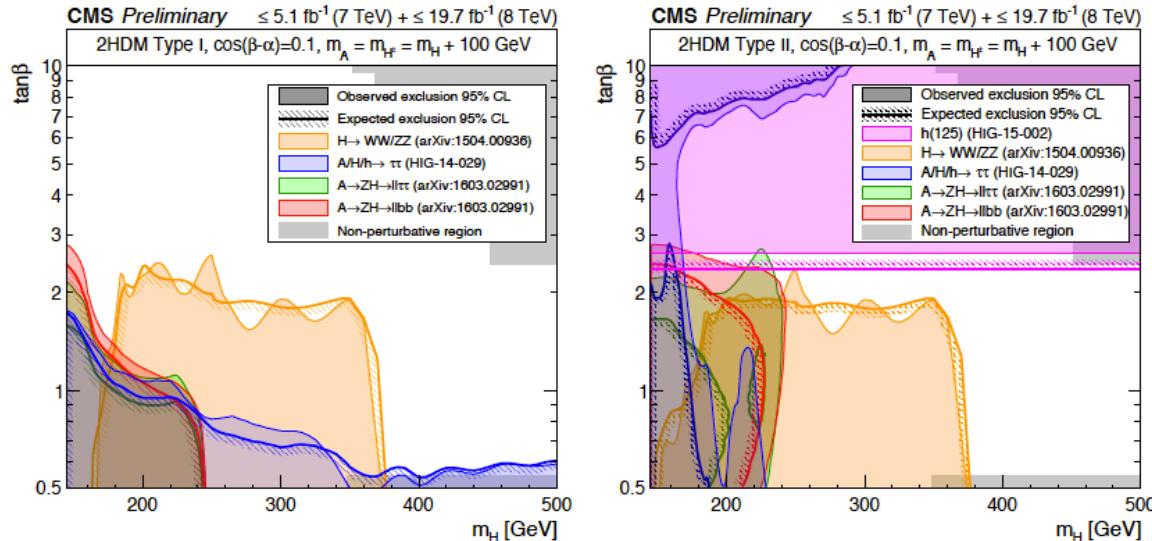
Table 1 List of LHC Higgs search channels that are applied by HiggsBounds in the high-mass region, yielding the upper limit on $|\sin \alpha|$ shown in Figs. 1 and 2

Range of m_H [GeV]	Search channel	Reference
130–145	$H \rightarrow ZZ \rightarrow 4l$	[94] (CMS)
145–158	$H \rightarrow VV$ ($V=W,Z$)	[66] (CMS)
158–163	SM comb.	[95] (CMS)
163–170	$H \rightarrow WW$	[96] (CMS)
170–176	SM comb.	[95] (CMS)
176–211	$H \rightarrow VV$ ($V=W,Z$)	[66] (CMS)
211–225	$H \rightarrow ZZ \rightarrow 4l$	[94] (CMS)
225–445	$H \rightarrow VV$ ($V=W,Z$)	[66] (CMS)
445–776	$H \rightarrow ZZ$	[70] (ATLAS)
776–1000	$H \rightarrow VV$ ($V=W,Z$)	[66] (CMS)

Status of direct search of extra Higgs

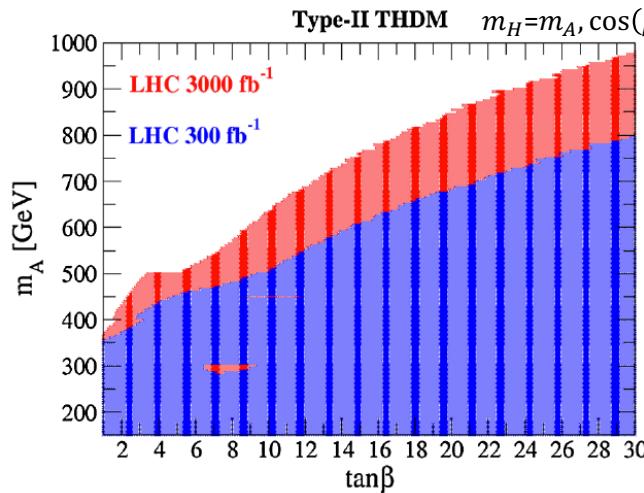
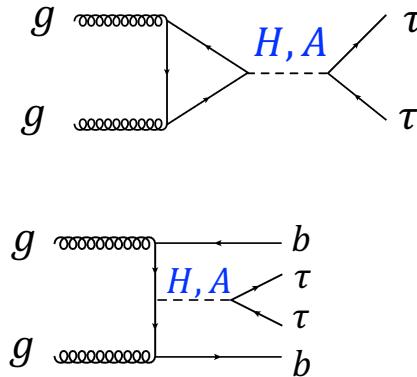
- constraint for THDMs (LHC Run I, Summary plots by CMS)

[CMS PAS HIG-16-007]



→ Basically, $\tan\beta < 2$,
 $m_H < 380$ GeV are excluded.

- Future prospect of excluded regions [Kanemura, Tsumura, Yagyu, Yokoya, PRD90(2014)075001]

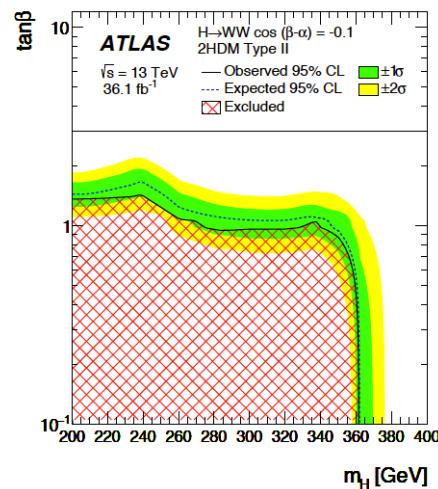
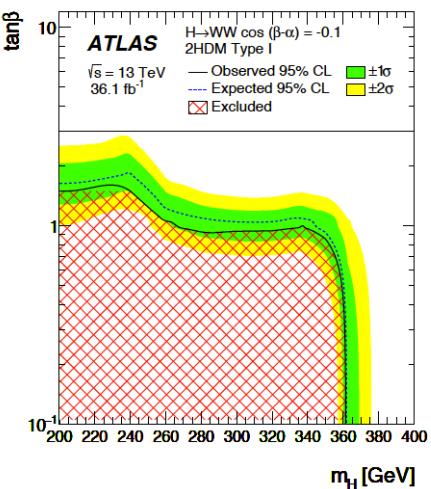


→ In the future exp.
excluded regions are spread.

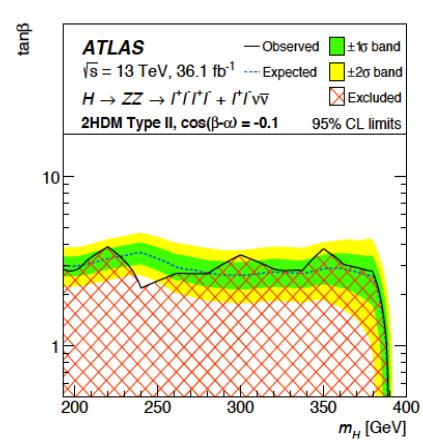
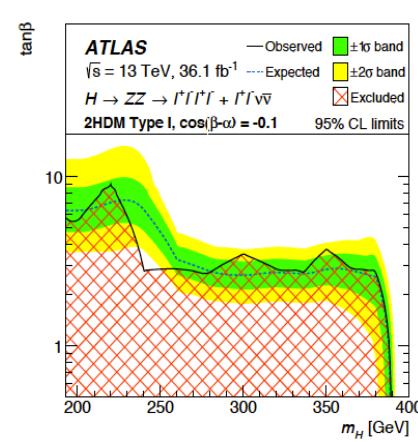
Constraint of direct search (THDM)

At LHC Run II

[ATLAS ,Eur.Phys.J. C78 (2018) 24]



[ATLAS, arXiv:1712.06386]



final state: $e\nu\mu\nu$

$\ell: e, \mu$

Signal strength(current data)

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.14^{+0.19}_{-0.18}$ $(^{+0.18}_{-0.17})$	$1.14^{+0.27}_{-0.25}$ $(^{+0.26}_{-0.24})$	$1.11^{+0.25}_{-0.23}$ $(^{+0.23}_{-0.21})$
μ^{ZZ}	$1.29^{+0.26}_{-0.23}$ $(^{+0.23}_{-0.20})$	$1.52^{+0.40}_{-0.34}$ $(^{+0.32}_{-0.27})$	$1.04^{+0.32}_{-0.26}$ $(^{+0.30}_{-0.25})$
μ^{WW}	$1.09^{+0.18}_{-0.16}$ $(^{+0.16}_{-0.15})$	$1.22^{+0.23}_{-0.21}$ $(^{+0.21}_{-0.20})$	$0.90^{+0.23}_{-0.21}$ $(^{+0.23}_{-0.20})$
$\mu^{\tau\tau}$	$1.11^{+0.24}_{-0.22}$ $(^{+0.24}_{-0.22})$	$1.41^{+0.40}_{-0.36}$ $(^{+0.37}_{-0.33})$	$0.88^{+0.30}_{-0.28}$ $(^{+0.31}_{-0.29})$
μ^{bb}	$0.70^{+0.29}_{-0.27}$ $(^{+0.29}_{-0.28})$	$0.62^{+0.37}_{-0.37}$ $(^{+0.39}_{-0.37})$	$0.81^{+0.45}_{-0.43}$ $(^{+0.45}_{-0.43})$
$\mu^{\mu\mu}$	$0.1^{+2.5}_{-2.5}$ $(^{+2.4}_{-2.3})$	$-0.6^{+3.6}_{-3.6}$ $(^{+3.6}_{-3.6})$	$0.9^{+3.6}_{-3.5}$ $(^{+3.3}_{-3.2})$

JHEP08,045

Definition of μ^f

$$\mu^f = \frac{\text{BR}_{EX}}{\text{BR}_{SM}}$$

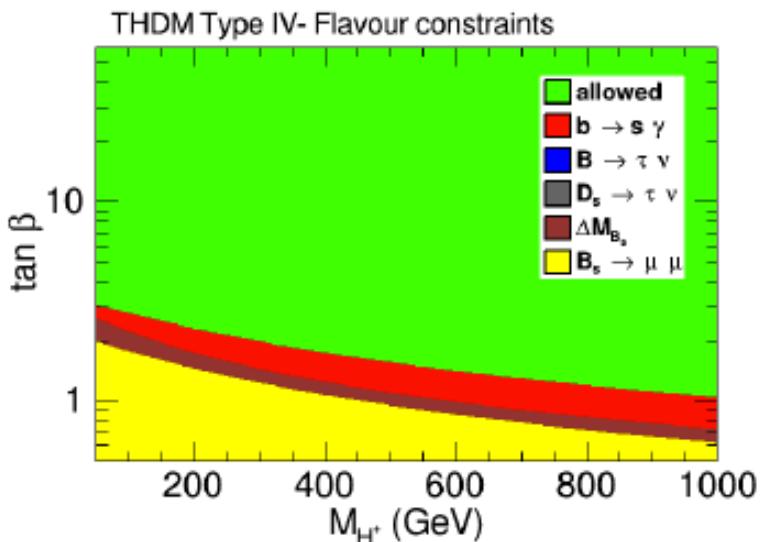
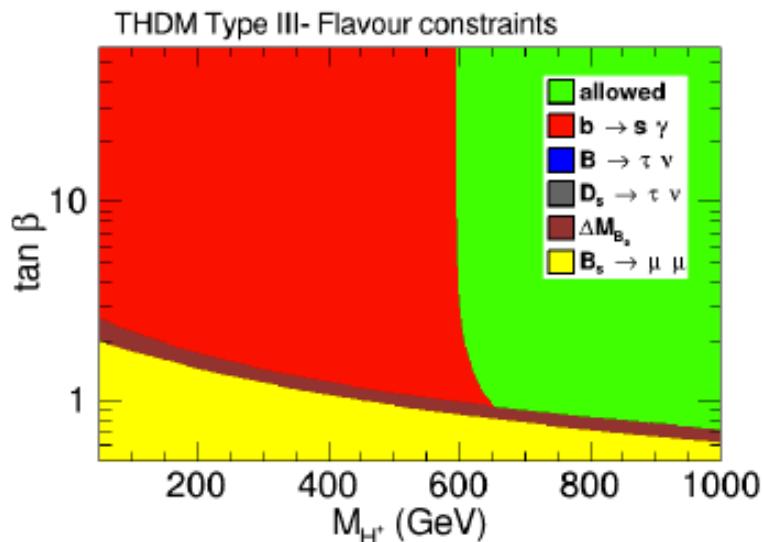
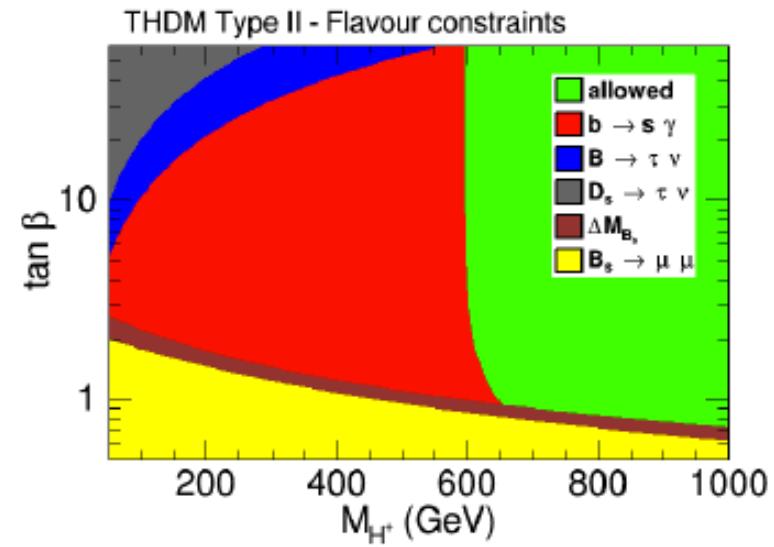
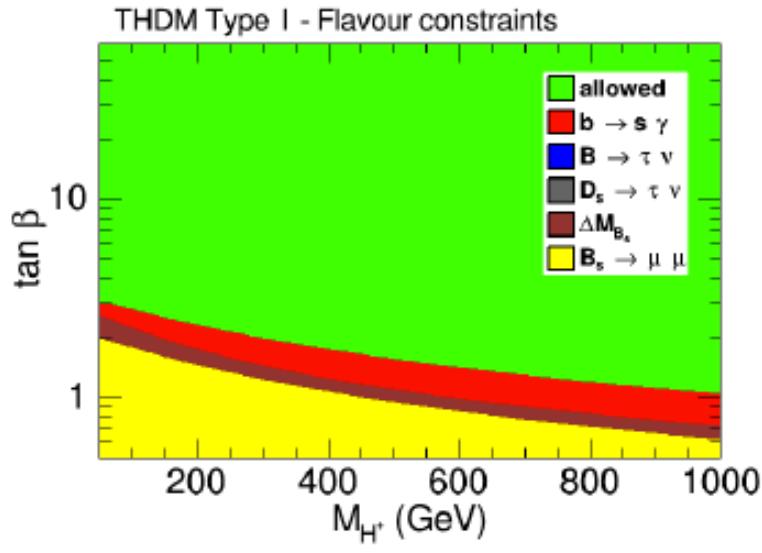
Signal strength by ILC (prospect)

ArXiv: 1310.8361

	ILC 250/500/1000 GeV		ILC LumiUp [‡] 250/500/1000 GeV	
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$
Inclusive	$2.6/3.0/-\%$	—	$1.2/1.7/-\%$	—
$H \rightarrow \gamma\gamma$	29-38%	$-/20-26/7-10\%$	16/19/-%	$-/13/5.4\%$
$H \rightarrow gg$	$7/11/-\%$	$-/4.1/2.3\%$	$3.3/6.0/-\%$	$-/2.3/1.4\%$
$H \rightarrow ZZ^*$	$19/25/-\%$	$-/8.2/4.1\%$	$8.8/14/-\%$	$-/4.6/2.6\%$
$H \rightarrow WW^*$	$6.4/9.2/-\%$	$-/2.4/1.6\%$	$3.0/5.1/-\%$	$-/1.3/1.0\%$
$H \rightarrow \tau\tau$	$4.2/5.4/-\%$	$-/9.0/3.1\%$	$2.0/3.0/-\%$	$-/5.0/2.0\%$
$H \rightarrow b\bar{b}$	$1.2/1.8/-\%$	$11/0.66/0.30\%$	$0.56/1.0/-\%$	$4.9/0.37/0.30\%$
$H \rightarrow c\bar{c}$	$8.3/13/-\%$	$-/6.2/3.1\%$	$3.9/7.2/-\%$	$-/3.5/2.0\%$
$H \rightarrow \mu\mu$	—	$-/-/31\%$	—	$-/-/20\%$
	$t\bar{t}H$		$t\bar{t}H$	
$H \rightarrow b\bar{b}$	$-/28/6.0\%$		$-/16/3.8\%$	

Constraint from flavor experiments

A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak arXiv:1706.07414v1



Higgs singlet model(HSM)

- Higgs potential
- $$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi + iG^0) \end{pmatrix}, \quad S = v_S + s,$$
- $$V(\Phi, S) = m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \lambda_{\Phi S} |\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4$$

- Mass eigenstates

$$\begin{pmatrix} s \\ \phi \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix} \quad \text{with} \quad R(\alpha) = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

Physical state : h, H

- Physical parameters

$$v, m_h, m_H, \alpha, m_S^2, \lambda_S, \mu_{\Phi S}$$

Two Higgs doublet model(THDM)

- Higgs potential

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad \text{with } i = 1, 2$$

$$V = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.})$$

$$+ \frac{1}{2} \lambda_1 |\Phi_1|^4 + \frac{1}{2} \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

- Mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta) \begin{pmatrix} z \\ A \end{pmatrix}, \quad \begin{pmatrix} w_1^+ \\ w_2^+ \end{pmatrix} = R(\beta) \begin{pmatrix} w^+ \\ H^+ \end{pmatrix}$$

Physical state : h, H, A, H^\pm

- Physical parameters

$$v, m_h, m_H, m_A, m_{H^\pm}, \alpha, \beta, M^2$$

Scaling factor

$$\kappa_X = \Gamma_{hXX}^{EX}/\Gamma_{hXX}^{SM}$$

THDM :

$$\Gamma(h \rightarrow \gamma\gamma) \simeq \frac{G_F \alpha_{\text{em}}^2 m_h^3}{128\sqrt{2}\pi^3} \left| -\frac{1}{3} \left(1 - \frac{M^2}{m_{H^\pm}^2} \right) + \sum_f Q_f N_c^f \left(1 + \xi_f x - \frac{x^2}{2} \right) I_F + \left(1 - \frac{x^2}{2} \right) I_W \right|^2$$

HSM :

$$\kappa_\gamma = \cos \alpha^2$$

Some tools

Prophecy4f :

arXiv:1710.07598

- Model: THDMs, HSM
- $h \rightarrow WW/ZZ \rightarrow 4 \text{ fermions}$

RECOLA2 :

arXiv:1711.07388

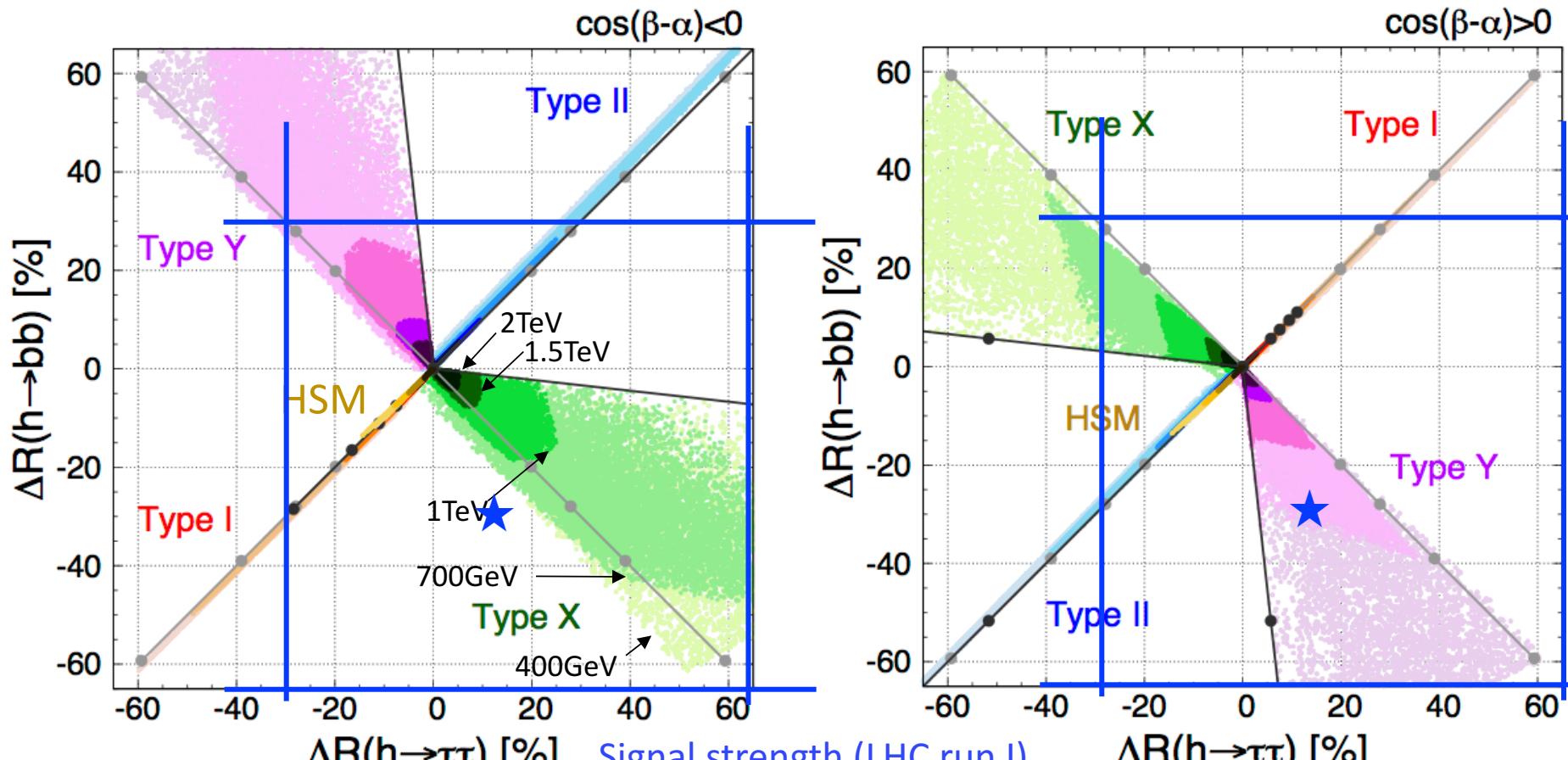
- Model: THDMs, HSM
- Calculation to NLO amplitude

Other plot

$\Delta R(h \rightarrow b\bar{b})$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$



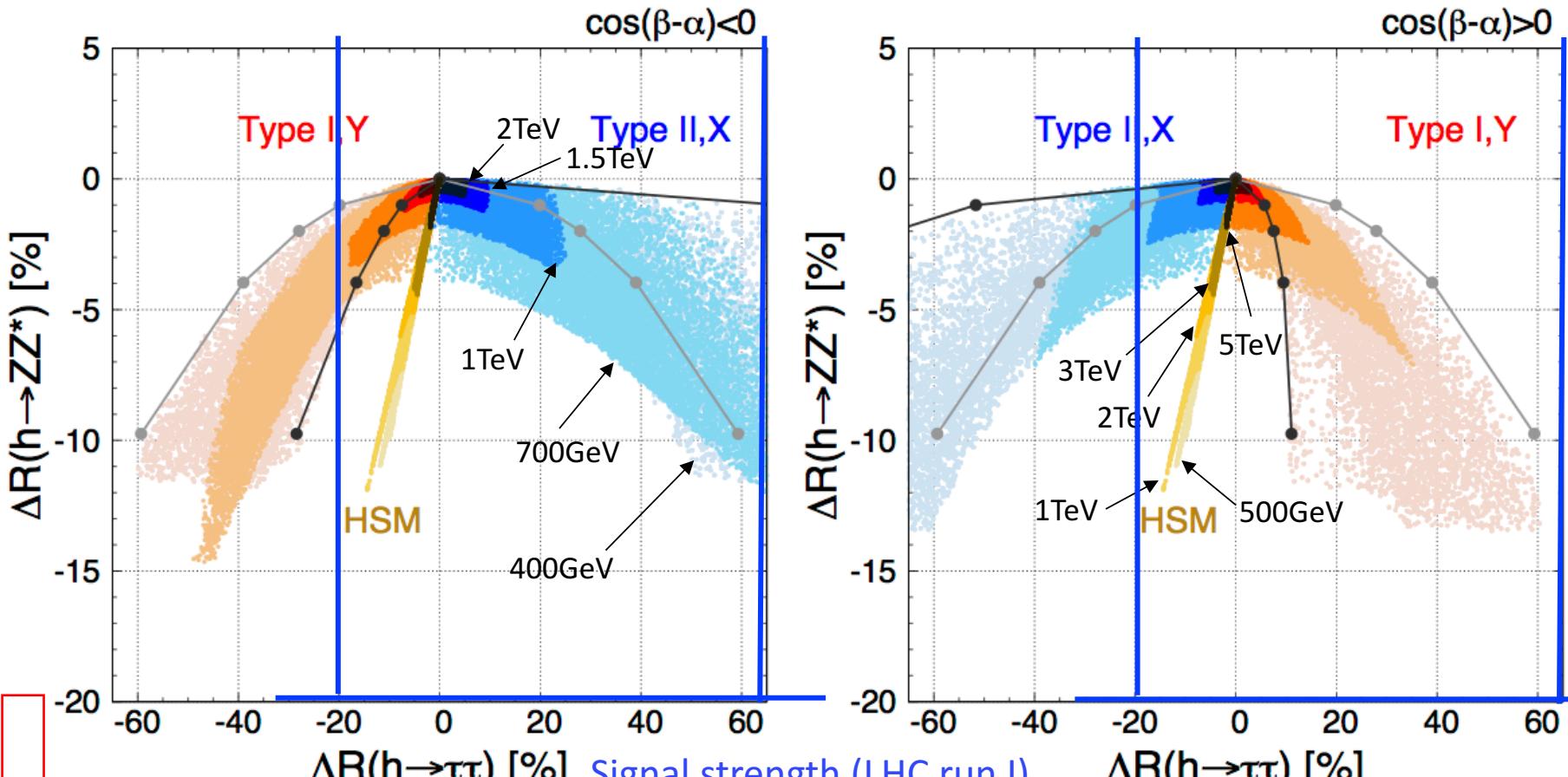
ILC250 (2 σ) [K. Fujii, et al., arXiv:1710.07621]

→ Type X and Y can be discriminated from other models.

$\Delta R(h \rightarrow ZZ^*)$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$



ILC250 (2 σ) [K. Fujii, et al., arXiv:1710.07621]

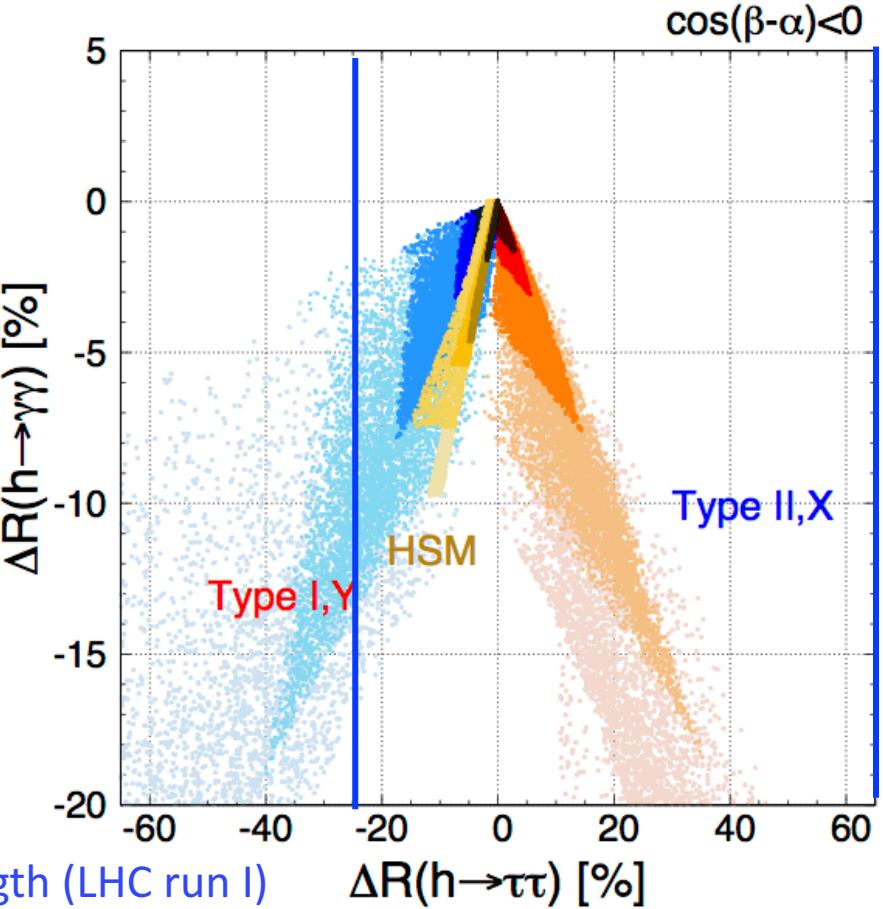
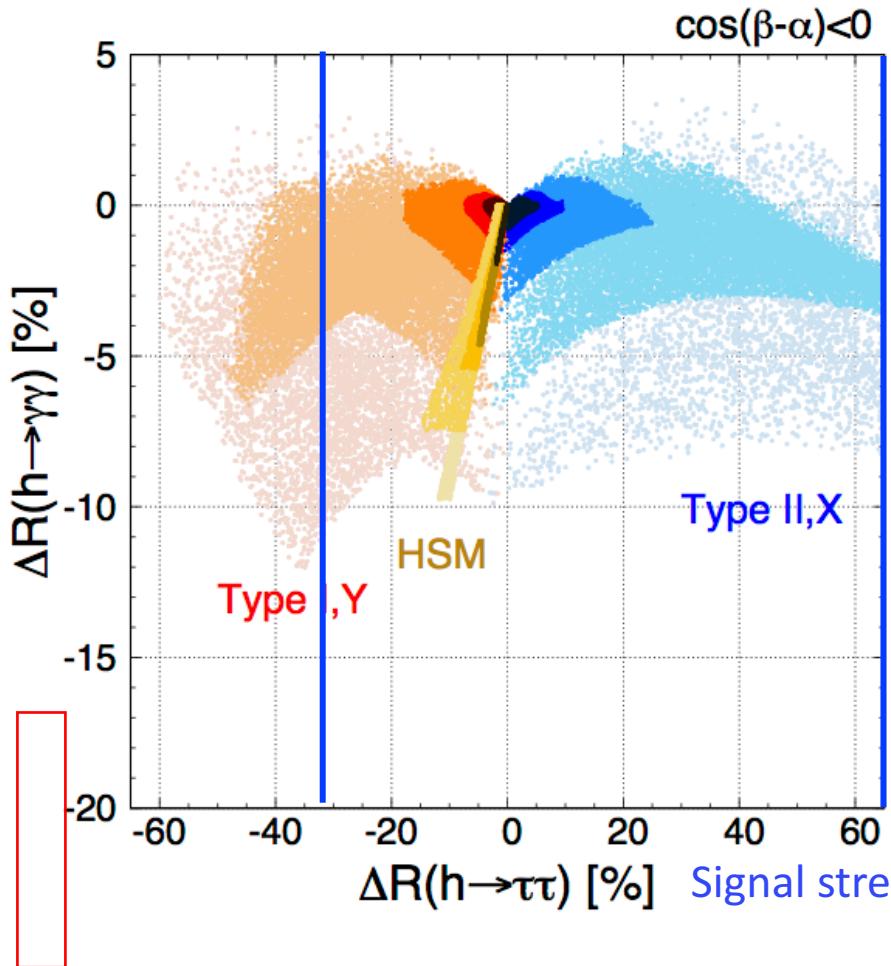
→ HSM can be separated from the THDMs.

→ Type I and Type II can be discriminated in this plane.

$\Delta R(h \rightarrow \gamma\gamma)$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$



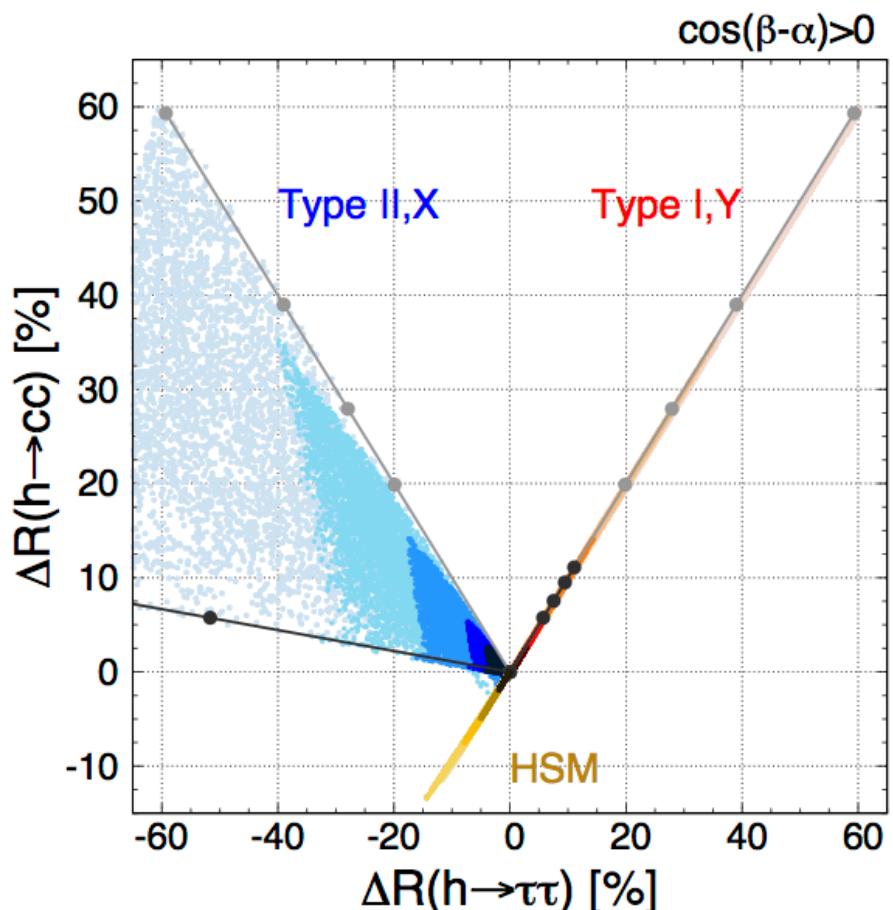
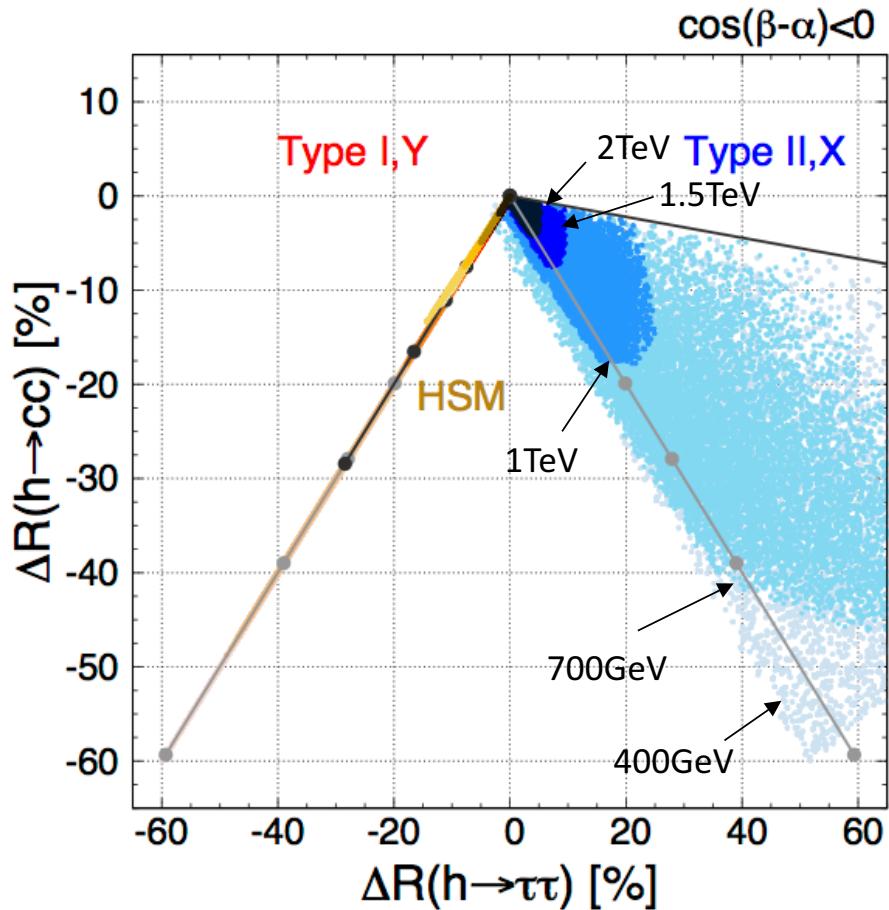
ILC250 (2 σ) [K. Fujii, et al., arXiv:1710.07621]

→ Type X and Y can be discriminated from other models.

$\Delta R(h \rightarrow c\bar{c})$ vs $\Delta R(h \rightarrow \tau\bar{\tau})$

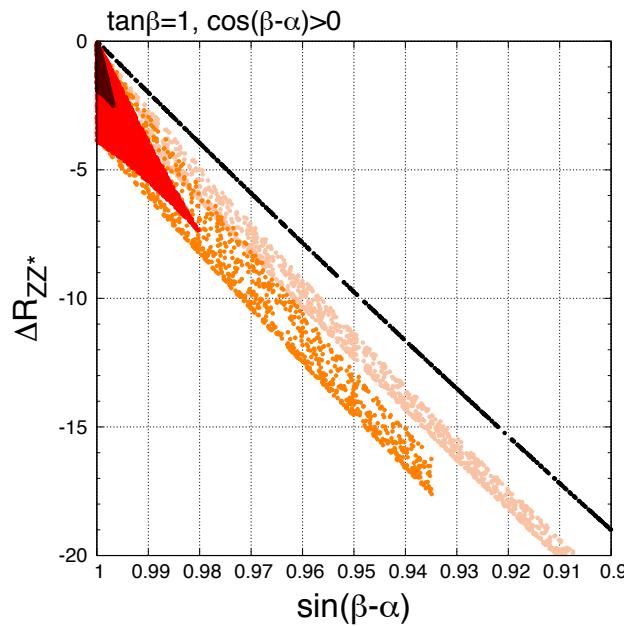
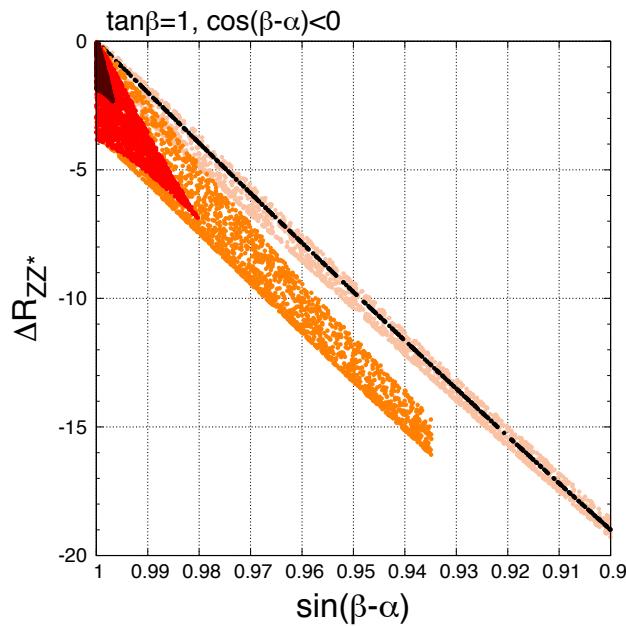
[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)_{EX}}{\Gamma(h \rightarrow XX)_{SM}} - 1$$

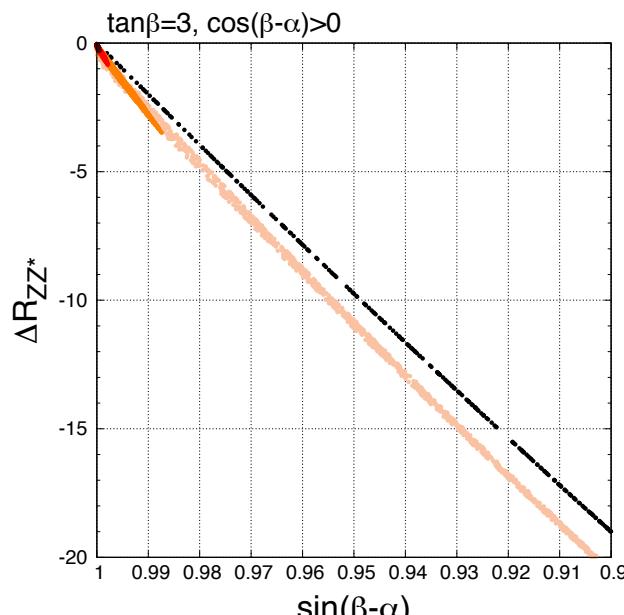
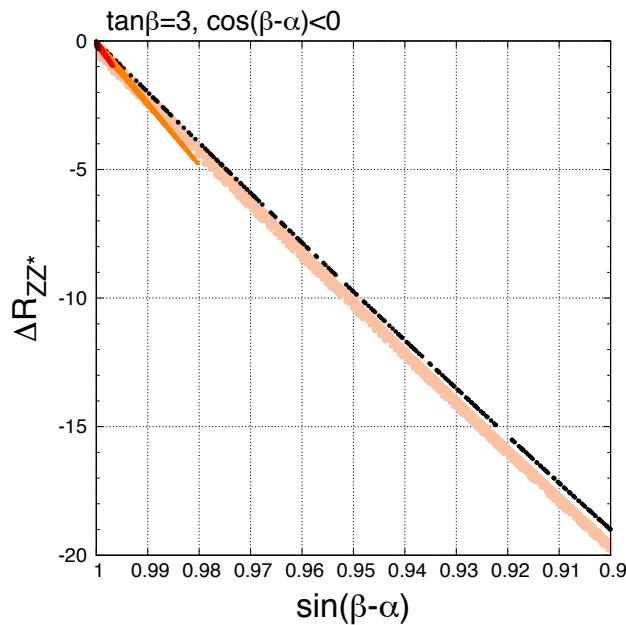


→ Type I and Type II can be discriminated in this plane.

$\Delta R(h \rightarrow ZZ^*)$ vs $\sin(\beta - \alpha)$



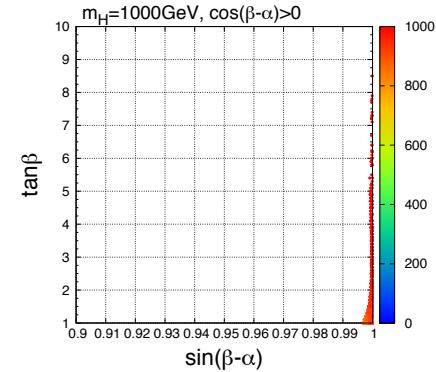
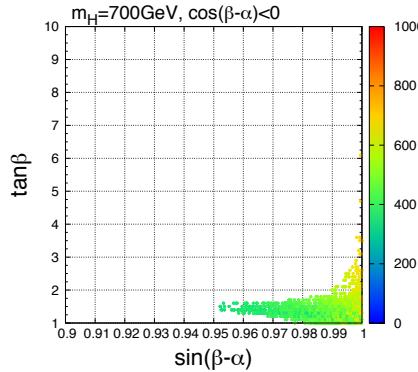
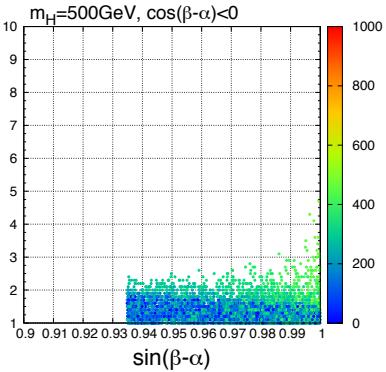
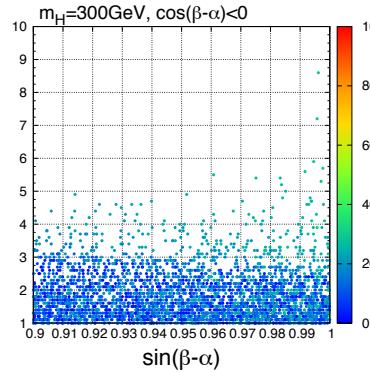
300GeV,
500GeV,
700GeV,
1TeV



$\tan\beta$ vs $\sin(\beta - \alpha)$

constraint:
 Perturbative unitarity
 vacuum stability
 S, T parameters

M



M

