H-COUP: Higher order calculations of Higgs observables in various extended Higgs sectors

In preparation

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Introduction

- The Higgs boson was discovered at the LHC in 2012.

  → The SM has been established as a low energy effective theory.

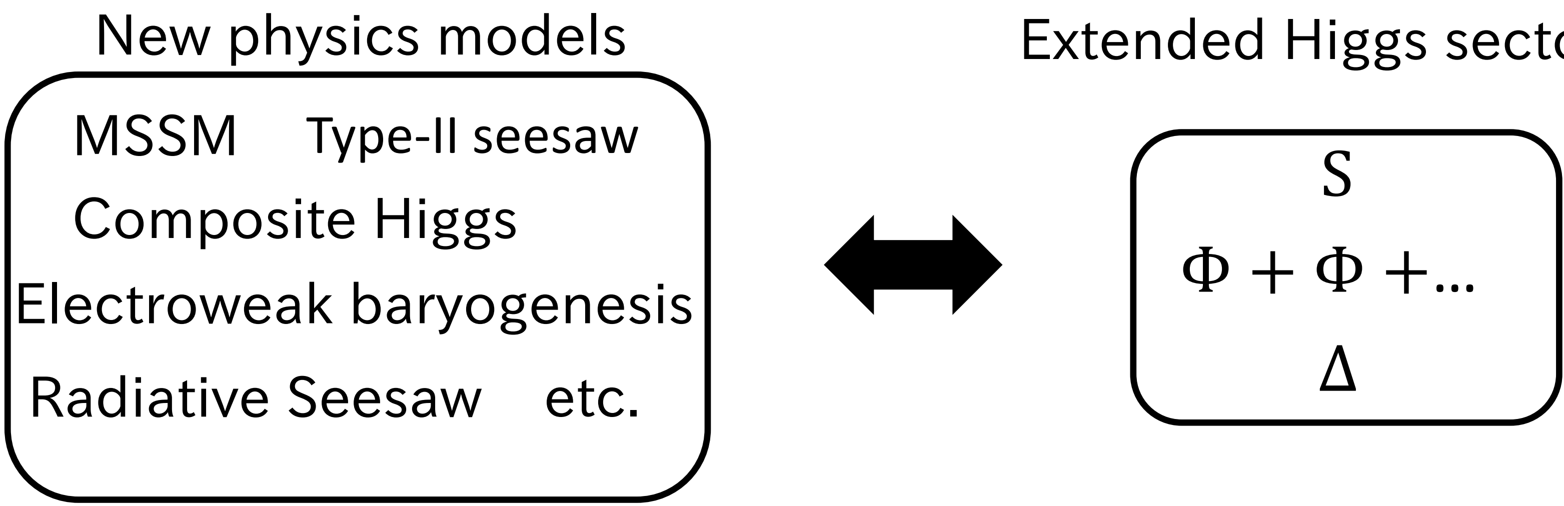
- But, the structure of the Higgs sector is still unknown.

  - Number of Higgs, its multiplets
  - Symmetry of the Higgs potential
  - Nature of the Higgs boson (elementary or composite)
  - etc.

- There are possibilities of Higgs sectors extended from the SM.

  $\Phi + S$ (Singlet), $\Phi + \Phi$ (Doublet), $\Phi + \Delta$ (triplet), …

- New physics models often predict specific Higgs sectors.



→ Shape of Higgs sector closely relates to new physics models.

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

Test of the Higgs sector

- There are two approaches with collider experiments.
  - Direct searches ($H, A, H^{\pm}, \dots$)
  - Indirect searches (Discovered Higgs observables,⋯)

    couplings, decay rates, production cross section, ⋯

→ We focus on indirect searches of the Higgs observables.

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→ We focus on indirect searches of the Higgs observables.

- In the extended Higgs sectors, predictions of Higgs observable deviate from the SM.
  - A pattern of deviations is different in each model.

→ Various extended Higgs sectors can be discriminated with pattern of deviations.

Measurement accuracy of the Higgs couplings

Current data (LHC Run I)

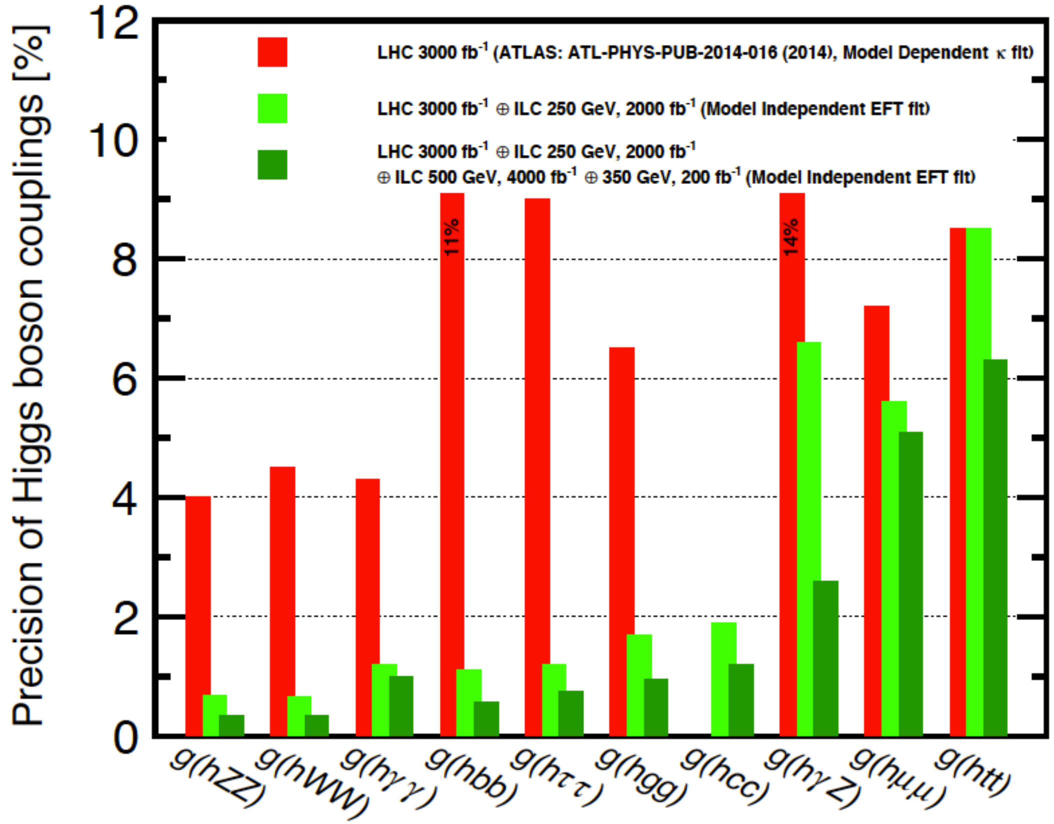
scaling factor: $\kappa_X = g_{hXX}^{exp.} / g_{hXX}^{SM}$

[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	$1.40^{+0.24}_{-0.21}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$

Future prospect (HL-LHC, ILC)

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



- At the HL-LHC and the ILC, the Higgs coup. will be measured with better accuracy .
- We should perform calculations including radiative corrections.

H-COUP project

Precise predictions of Higgs observables

Extended Higgs models

$\Phi + S$, $\Phi + \Phi$, $\Phi + \Delta$, etc.

Comparing

Precision data in future collider exp.

HL-LHC , ILC, CLIC, FCC-ee, etc.

Determination of shape of the Higgs sector

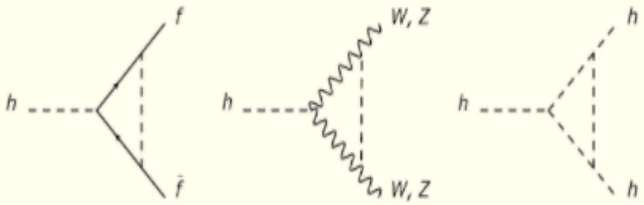
- We have calculated the Higgs couplings included electroweak radiative correction in various extended Higgs models.
- We constructed the computation program called H-COUP.
- H-COUP version 1.0 is released.

H-COUP

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

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 impolved on-shell renormalization scheme is adopted, where the gauge depdence 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].

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

H-COUP

[S. Kanemura, M. Kikuchi, KS, K. Yagyu, arXiv:1710.04603]

H-COUP is a Fortran 90 program to compute the renormalized Higgs couplings at the 1-loop level in various extended Higgs models.

Model:

- Higgs Singlet Model (HSM)
  - $\Phi + S$ (singlet)
- Two Higgs Doublet Models (THDMs)
  - $\Phi_1 + \Phi_2$(doublet)
  - Softly broken Z_2 sym. ⇨ 4 types of Yukawa int. : Type –I, II, X, Y

	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R
Type-I	+	−	+	+	−	−	−
Type-II	+	−	+	+	−	+	+
Type-X	+	−	+	+	−	−	+
Type-Y	+	−	+	+	−	+	−

[V. D. Barger, J. L. Hewett, R. J. N. Phillips, Phys. Rev. D41 (1990) 3421]

- Inert Doublet Model (IDM)
  - $\Phi + \eta$ (doublet)
  - Exact Z_2 sym.

Output:

- Renormalized Higgs boson vertices *hff, hVV* and *hhh* at the 1-loop level

  EX.) *hff*

$$\hat{\Gamma}_{hf\bar{f}}(p_1^2, p_2^2, q^2) = \hat{\Gamma}^S_{hf\bar{f}} + \gamma_5 \hat{\Gamma}^P_{hf\bar{f}} + \not{p}_1 \hat{\Gamma}^{V_1}_{hf\bar{f}} + \not{p}_2 \hat{\Gamma}^{V_2}_{hf\bar{f}} + \not{p}_1 \gamma_5 \hat{\Gamma}^{A_1}_{hf\bar{f}} + \not{p}_2 \gamma_5 \hat{\Gamma}^{A_2}_{hf\bar{f}} + \not{p}_1 \not{p}_2 \hat{\Gamma}^{T}_{hf\bar{f}} + \not{p}_1 \not{p}_2 \gamma_5 \hat{\Gamma}^{PT}_{hf\bar{f}}$$

  - Renormalized 8 form factors are computed by on shell scheme
  - *hVV* → 3 form factors
  - *hhh* → 1 form factor

- Also, loop induced decay rate $h \to \gamma\gamma$, $h \to \gamma Z$ and $h \to gg$ at the 1-loop level

Input:

EX.) THDM : 7 free parameters

α: Mixing angle of CP-even Higgs

β: Mixing angle of CP-odd Higgs

$v(= 246\text{GeV})$, $m_h(= 125\text{GeV})$, $m_H, m_A, m_{H^\pm}$, M, $\sin(\beta-\alpha)$, $\tan\beta$, Sign $(\cos(\beta-\alpha))$

Application of H-COUP ver. 1.0

- Higgs boson vertices are not physical quantities.
- It is not directly compared with the exp. data.

→ We calculated the Higgs decay rates at the 1loop level by H-COUP :

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

EX.) $h \to f\bar{f}$

Δr : Weak correction to G_f

$$\Gamma(h \to f\bar{f}) = \frac{N_c m_h}{8\pi}\left(1 - 4\frac{m_f^2}{m_h^2}\right)^{\frac{3}{2}} G_{\rm tree}^2\left[1 + 2\frac{{\rm Re}G_{\rm 1loop}}{G_{\rm tree}} - \Delta r\right],$$

$$G_{\rm tree} = \underline{\Gamma_{hff}^{S,{\rm tree}}},$$

These are calculated by H-COUP ver.1.0

$$G_{\rm 1loop} = \underline{\Gamma_{hff}^{S,{\rm 1loop}}} + 2m_f \underline{\Gamma_{hff}^{V1,{\rm 1loop}}} + m_h^2\left(1 - \frac{m_f^2}{m_h^2}\right)\underline{\Gamma_{hff}^{T,{\rm 1loop}}}$$

Numerical calculations

We discuss a possibility of discrimination among various extended Higgs models with the deviations from the SM in the decay widths.

- Model

  HSM, THDM Type-I, THDM Type-II, THDM Type-X, THDM Type-Y

- Scan region of input parameters in the THDMs

  $0.9 < \sin(\beta - \alpha) < 1, \quad 1 < tan\beta < 3,$

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

  $m_\Phi = 300, 500, 700, 1000$ GeV, $\quad 0 < M^2 < m_\Phi$

- Constraint

  Perturbative unitarity, Vacuum stability,

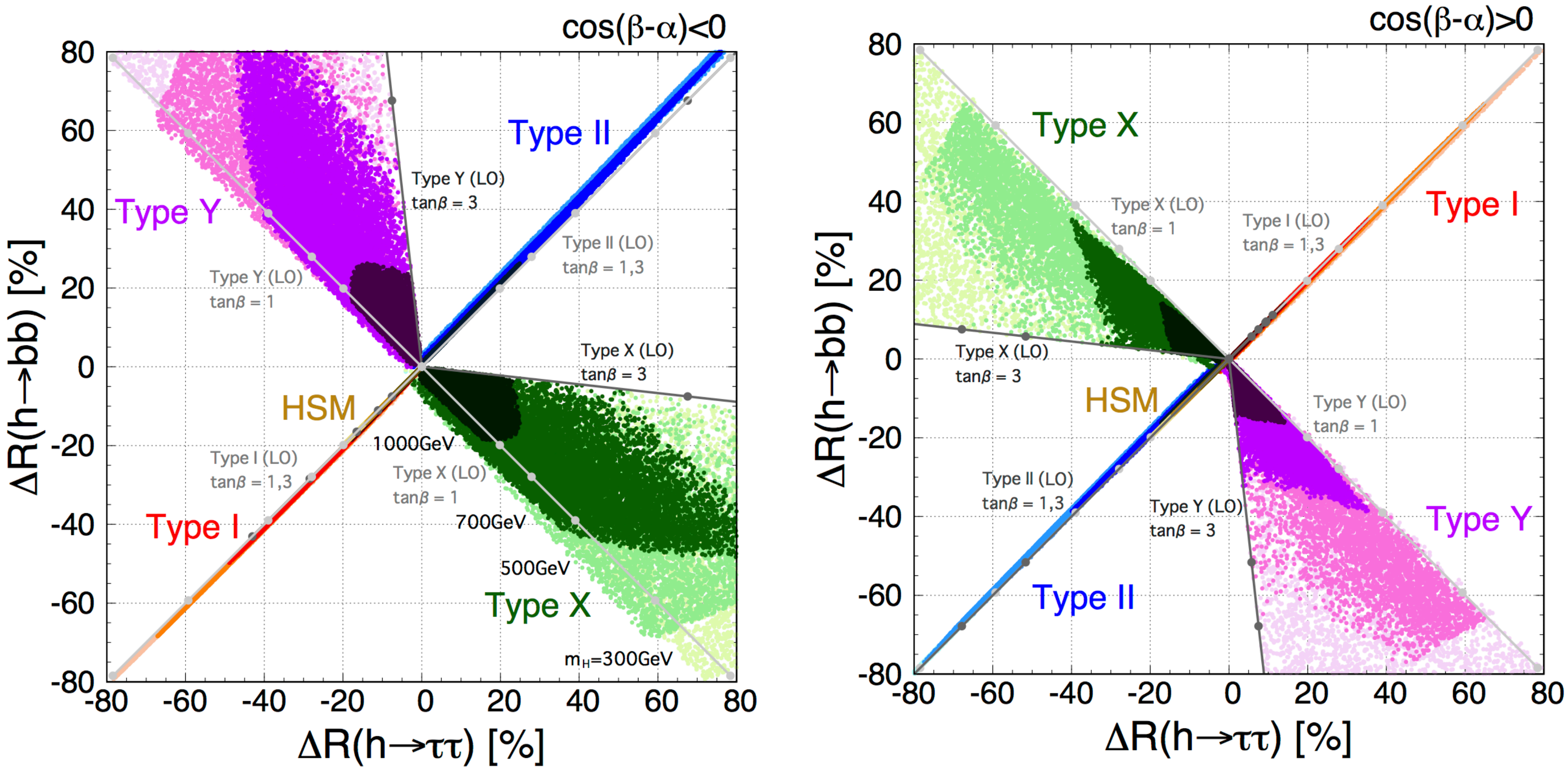
  Wrong vacuum condition (for HSM),

  S, T parameters

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

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

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



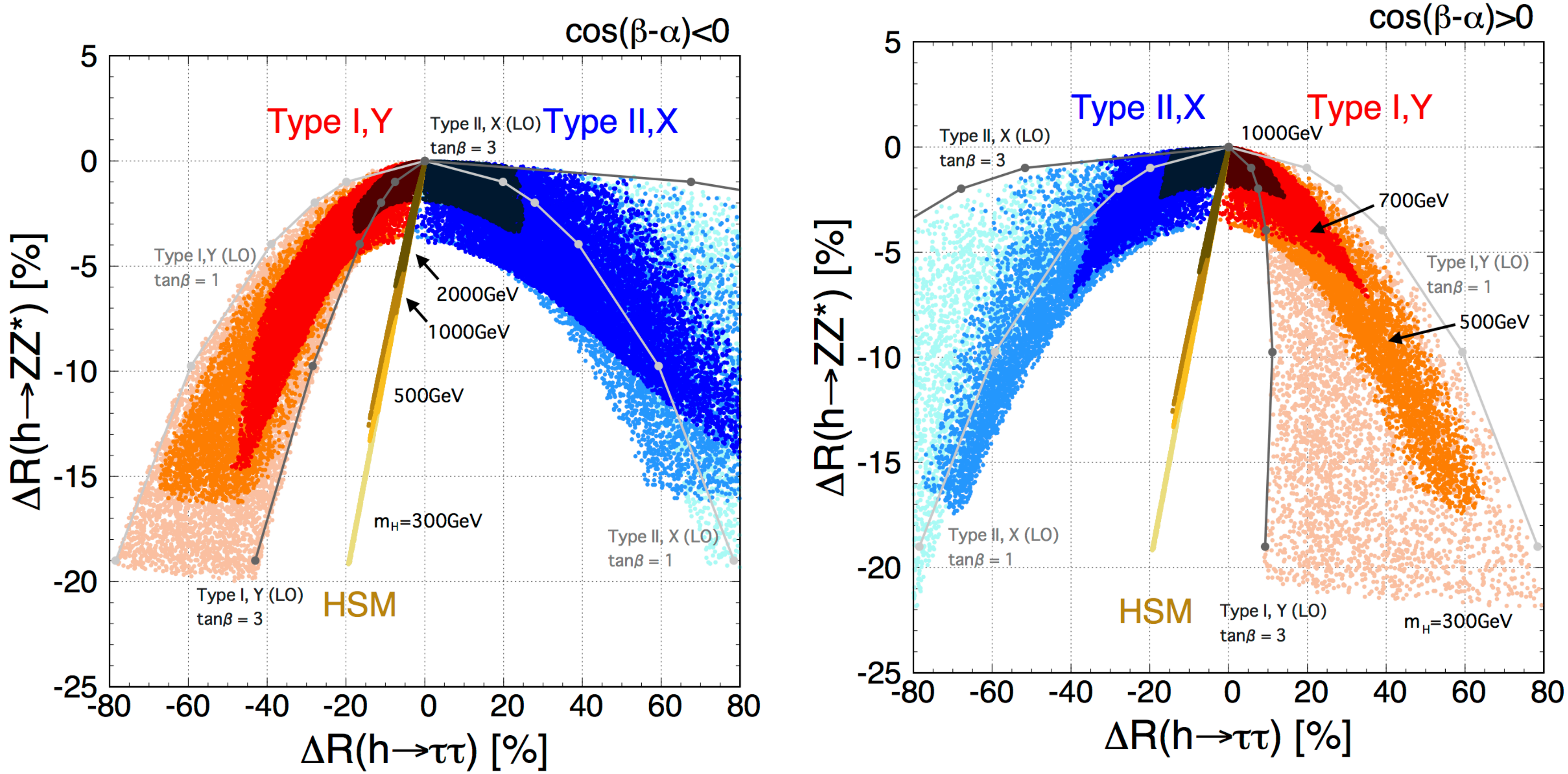
→ Type X and Y can be discriminated from other models.

→ the upper bounds of mass of extra Higgs can be obtained from magnitude of deviations.

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

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

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

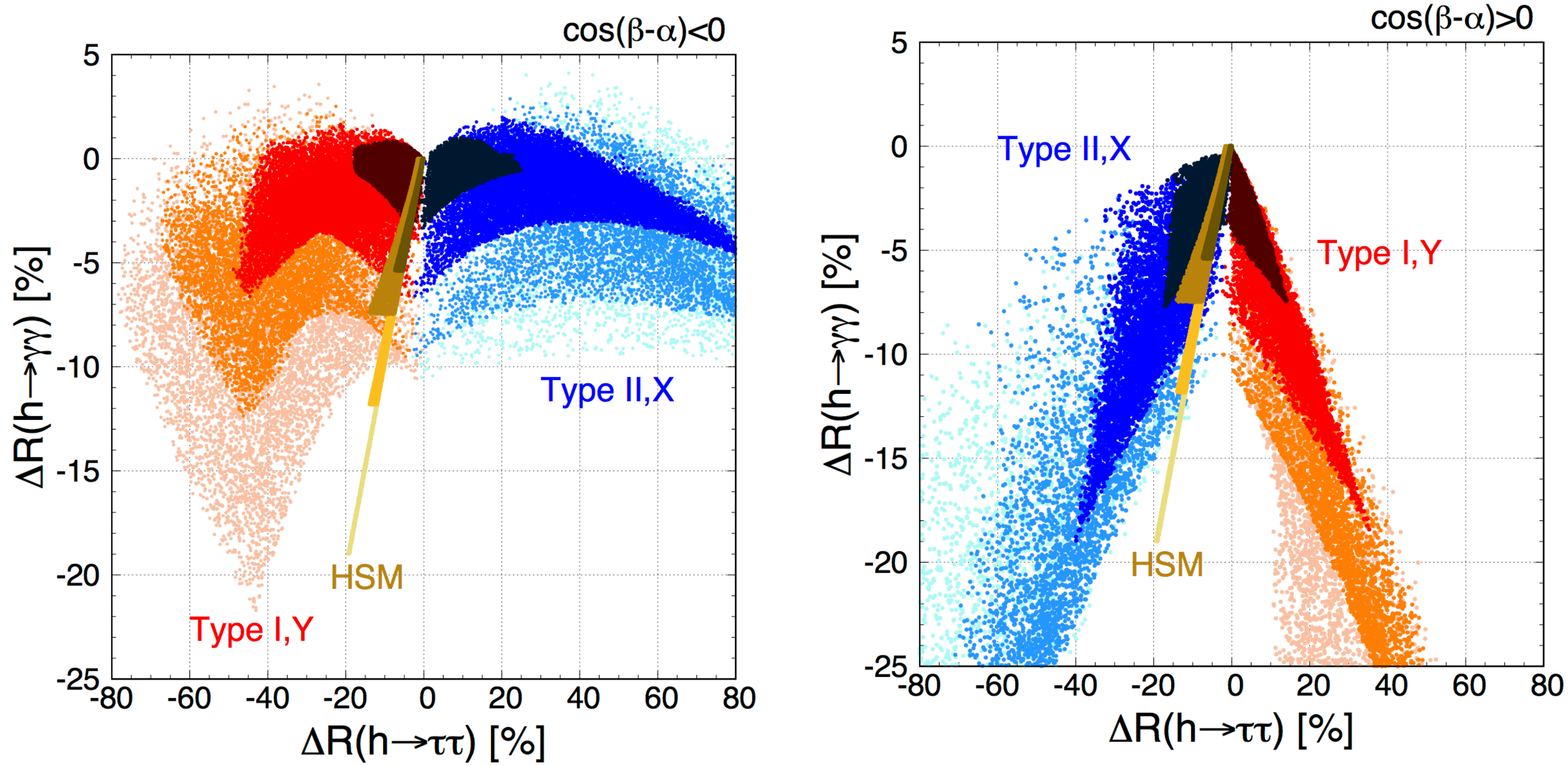


→ Type I and Type II can be discriminate in this plane.

→ Also, HSM can be separated from the THDMs .

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

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



- The behavior is similar to the correlation between $\Delta R(h \to ZZ*)$ vs $\Delta R(h \to \tau\tau)$
- Even if sign of cos(β - α) is scaned, some regions of predictions in each model are not overaped

By investigating various correlations of deviations, we could discriminate all the models

Summary

- Higgs sector could be 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 THDM with the deviations from the SM.

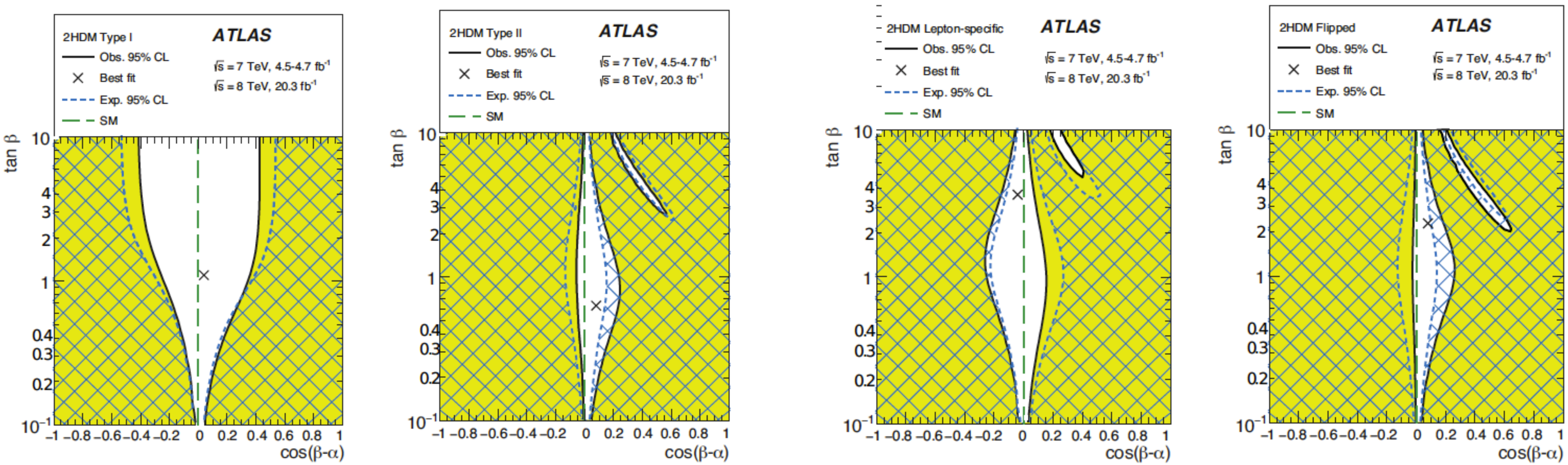
→ Pattern of deviations : HSM and 4 types of 2HDMs can be discriminated.

→ Magnitude of deviation: Information of the mass of extra Higgs boson can be obtained.

back up

constraint for THDMs (Higgs signal strength)

[ATLAS, JHEP1511(2015)206]



(a) Type I (b) Type II (c) Lepton-specific (d) Flipped

Constraint of direct search (HSM)

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

LHC Run II

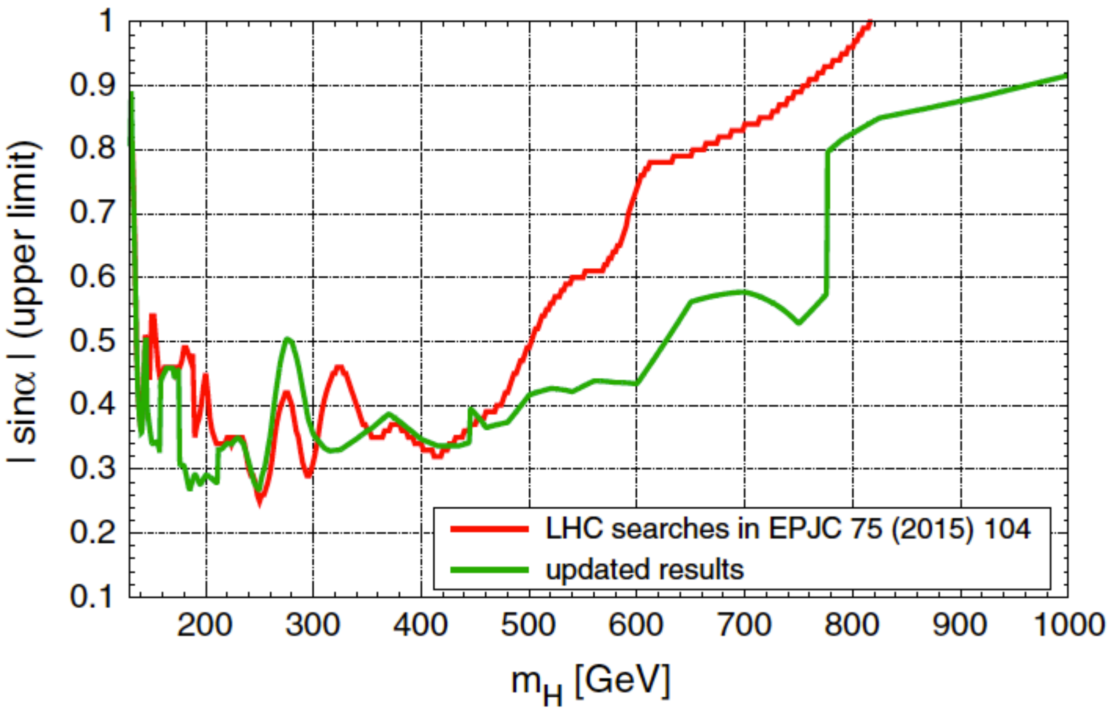


Table 1 List of LHC Higgs search channels that are applied by HiggsBounds in the high-mass region, yielding the upper limit on $|\sin\alpha|$ shown in Figs. 1 and 2

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

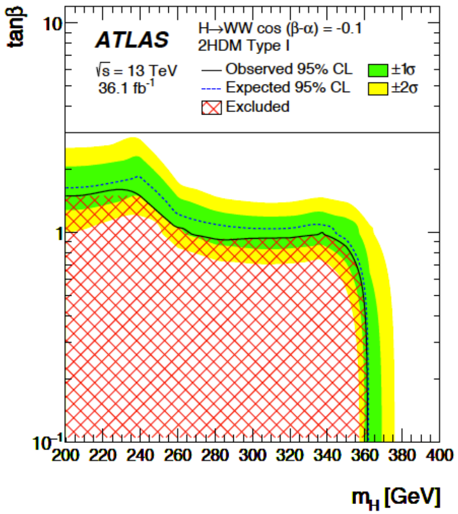
Constraint of direct search (THDM)

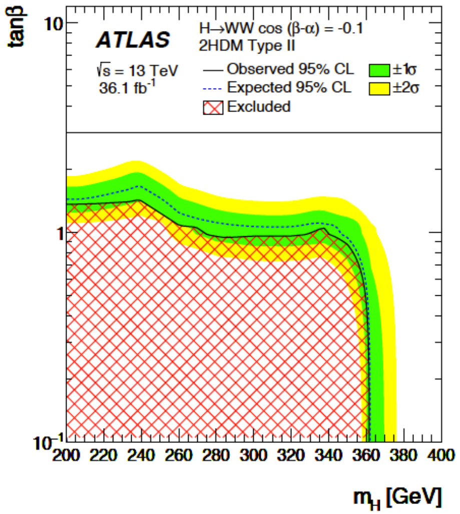
At LHC Run II

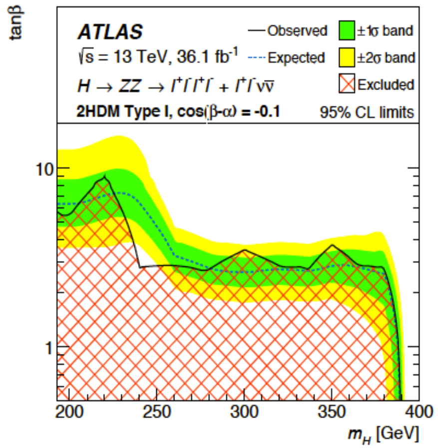
[ATLAS ,Eur.Phys.J. C78 (2018) 24]

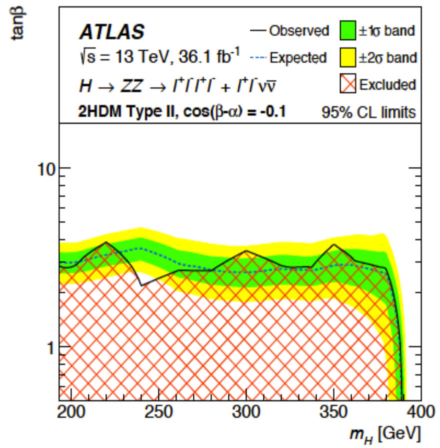
[ATLAS, arXiv:1712.06386]

ℓ: e, μ









final state: eνμν

Signal strength(current data)

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

JHEP08,045

Definition of μ^f

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

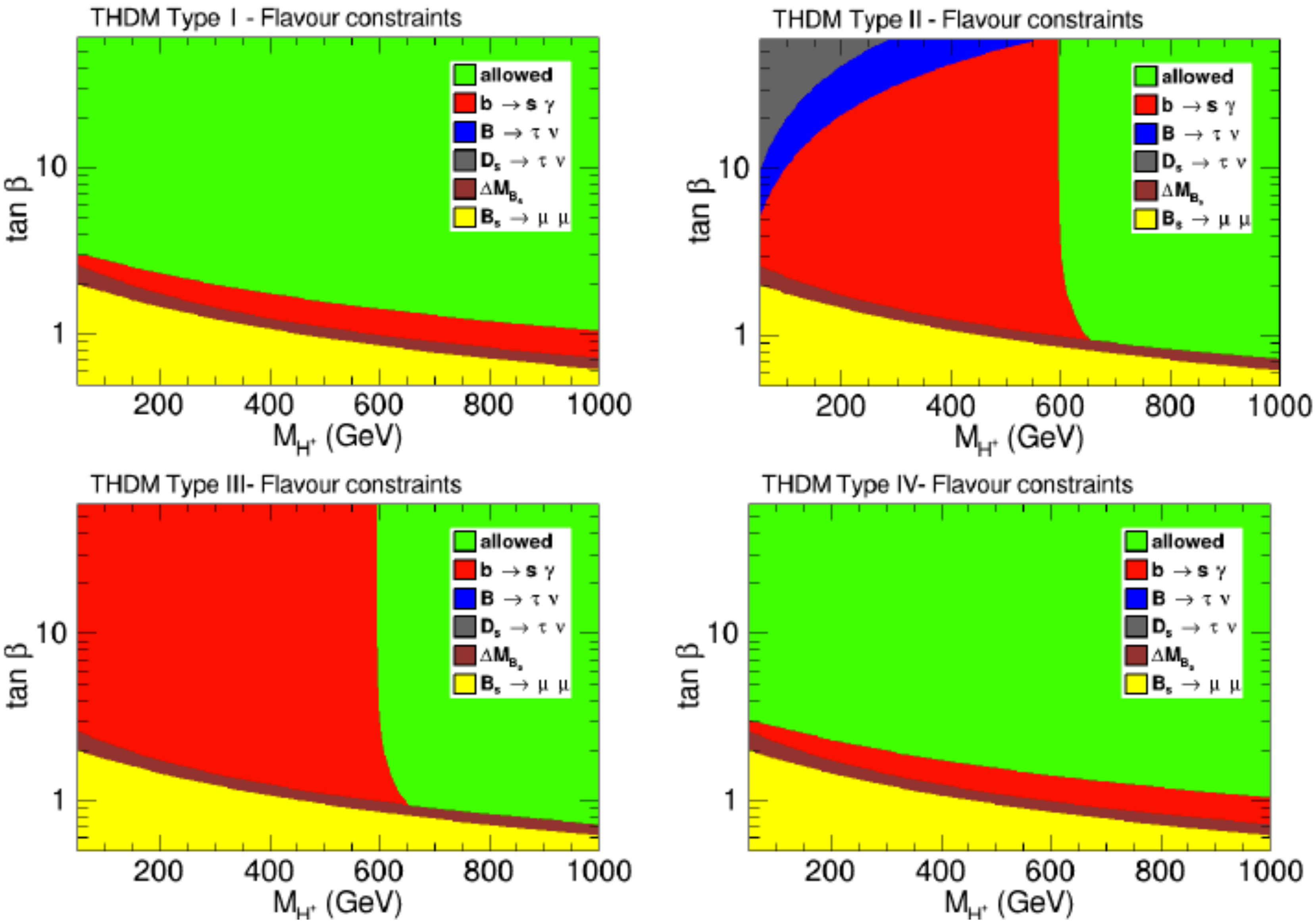
Signal strength by ILC (prospect)

ArXiv: 1310.8361

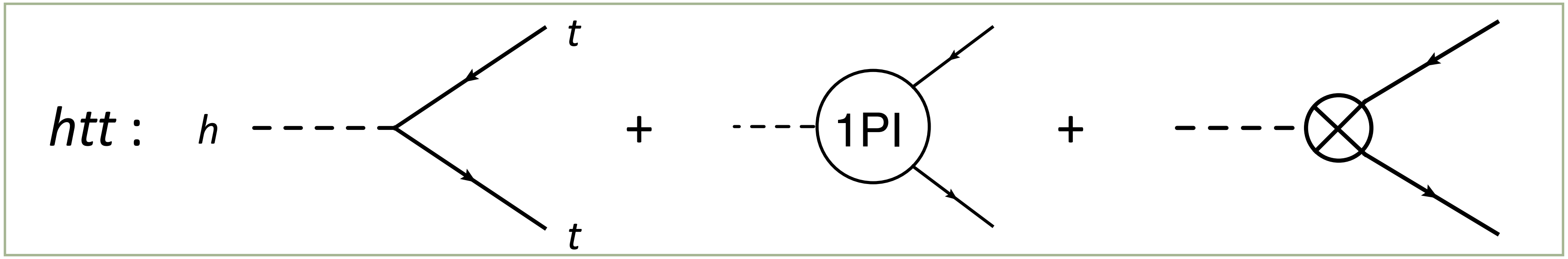
	ILC 250/500/1000 GeV		ILC LumiUp[‡] 250/500/1000 GeV	
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$
Inclusive	2.6/3.0/–%	–	1.2/1.7/–%	–
$H \to \gamma\gamma$	29-38%	–/20-26/7-10%	16/19/–%	–/13/5.4%
$H \to gg$	7/11/–%	–/4.1/2.3%	3.3/6.0/–%	–/2.3/1.4%
$H \to ZZ^*$	19/25/–%	–/8.2/4.1%	8.8/14/–%	–/4.6/2.6%
$H \to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

Constraint from flavor experiments

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

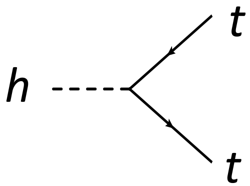


For example: renormailzed *htt* coupling



tree level　　　1-loop level　　　counter term

tree level



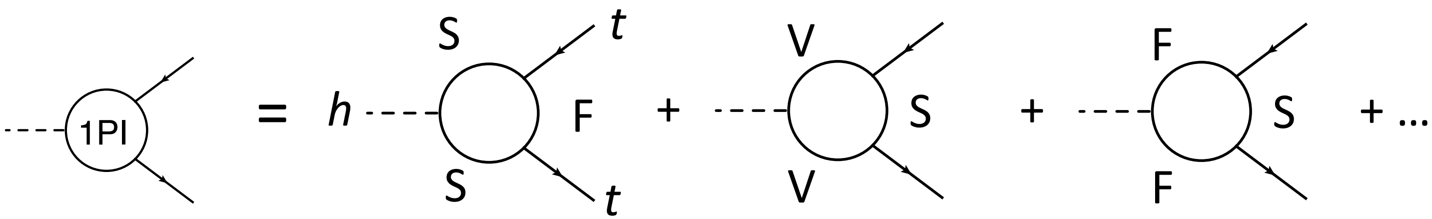
$= -\frac{m_t}{v}\xi_h^u$

$\xi_h^u = \sin(\beta-\alpha) + cot\beta\cos(\beta-\alpha)$

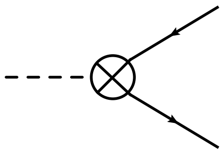
α : mixing angle for CP-even Higgs *H,h*

β : mixing angle for CP-odd Higgs *A,G⁰*

1-loop level



counter term



$= -\frac{m_t}{v}\xi_h^u\left[\frac{\delta m_t}{m_t} - \frac{\delta v}{v} + \frac{1}{2}\delta Z_h + \delta Z_t + \frac{\delta\xi_h^u}{\xi_h^u} + \frac{\xi_H^u}{\xi_h^u}(\delta C_h + \delta\alpha)\right]$

counter term parameters : $\delta m_t, \delta v, \delta\alpha, \delta\xi_h^u, \delta Z_h, \delta Z_t, \delta C_h$

these are determined by relevant renormalization conditions.

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

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

Two Higgs doublet model(THDM)

- Higgs potential

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

$$\begin{aligned} V =& m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ &+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}] \end{aligned}$$

- 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

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

Scaling factor(1)

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

	Mixing factor		
	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	$\cot\beta$	$-\tan\beta$	$\cot\beta$

THDM :

$$\kappa_V = \sin(\beta - \alpha)$$

$$\kappa_f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$$

HSM :

$$\kappa_V = \cos\alpha$$

$$\kappa_f = \cos\alpha$$

$$\frac{\Gamma(h \to VV^*)_{EX.}}{\Gamma(h \to VV^*)_{SM}} \sim \kappa_V^2$$

$$\frac{\Gamma(h \to ff)_{EX.}}{\Gamma(h \to ff)_{SM}} \sim \kappa_f^2$$

Scaling factor

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

THDM :

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

HSM :

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

Procedure of prescription of renormalization

1 . Count number of parameters and fields in Lagrangian.

$$\mathcal{L} = \mathcal{L}(\mu_1^B, \mu_2^B, ...\lambda_1^B, \lambda_2^B, ...; \phi_1, \phi_2, ...)$$

2. Shift parameters and fields to introduce counter terms
   as same number these.

$$\mu_i^B \to \mu_i^R + \delta\mu_i \ , \ \phi_i \to Z_{\phi_i}\phi_i^R$$

$$\lambda_i^B \to \lambda_i^R + \delta\lambda_i \qquad (\ i = 1,2,3,\ \dots\ )$$

3. Impose only as many renormalization conditions as
   number of counter terms to determine these counter terms.

→ Any observables can be renormalized.

$$\mathcal{O} = \mathcal{O}(\mu_1^R, \mu_2^R, \dots\ \lambda_1^R, \lambda_2^R, \dots) + \mathcal{O}^{1PI} + \delta\mathcal{O}(\delta\mu_1^R, \mu_2^R, \dots\ \delta\lambda_1^R, \delta\lambda_2, \dots)$$

Introduction of counter terms(IDM)

● Parameters of Higgs potential ： 7

$$T_h \ m_h \ m_H \ m_A \ m_{H^\pm} \ \mu_2 \ \lambda_2$$

● Fields of Higgs sector ： 4

$$h \ H^\pm \ H \ A$$

● Shift of parameters : （$\Phi = h, H^\pm, H, A$）

$$m_\Phi \to m_\Phi + \delta m_\Phi \qquad \mu_2 \to \mu_2 + \delta\mu_2 \qquad T_h \to 0 + \delta T_h$$

$$\Phi \to \Phi + Z_\Phi \Phi/2 \qquad \lambda_2 \to \lambda_2 + \delta\lambda_2$$

● Counter terms : 11

$$\delta T_h \ \delta m_h \ \delta m_H \ \delta m_A \ \delta m_{H^\pm} \ \delta\mu_2 \ \delta\lambda_2 \ \delta Z_h \ \delta Z_H \ \delta Z_A \ \delta Z_{H^+}$$

(On-shell renormalization)

Renormalization conditions(IDM)

δT_h : $\Gamma_h^R \equiv T_h^{1PI} + \delta T_h = 0$ $\Rightarrow$ $\delta T_h = -T_h^{1PI}$

δm_h : $Re\Gamma_{hh}^R[m_h^2] = 0$ $\Rightarrow$ $\delta m_h^2 = Re\Pi_{hh}^{1PI}(m_h^2) - \frac{1}{v} ReT_h^{1PI}$

δZ_h : $\frac{\partial}{\partial p^2} Re\Gamma_{hh}^R(p^2)\Big|_{p^2=m_h^2} = 0$ $\Rightarrow$ $\delta Z_h = -\frac{\partial}{\partial p^2} Re\Pi_{hh}^{1PI}(p^2)\Big|_{p^2=m_h^2}$

(at Φ =H , A , $H^{\pm}$)

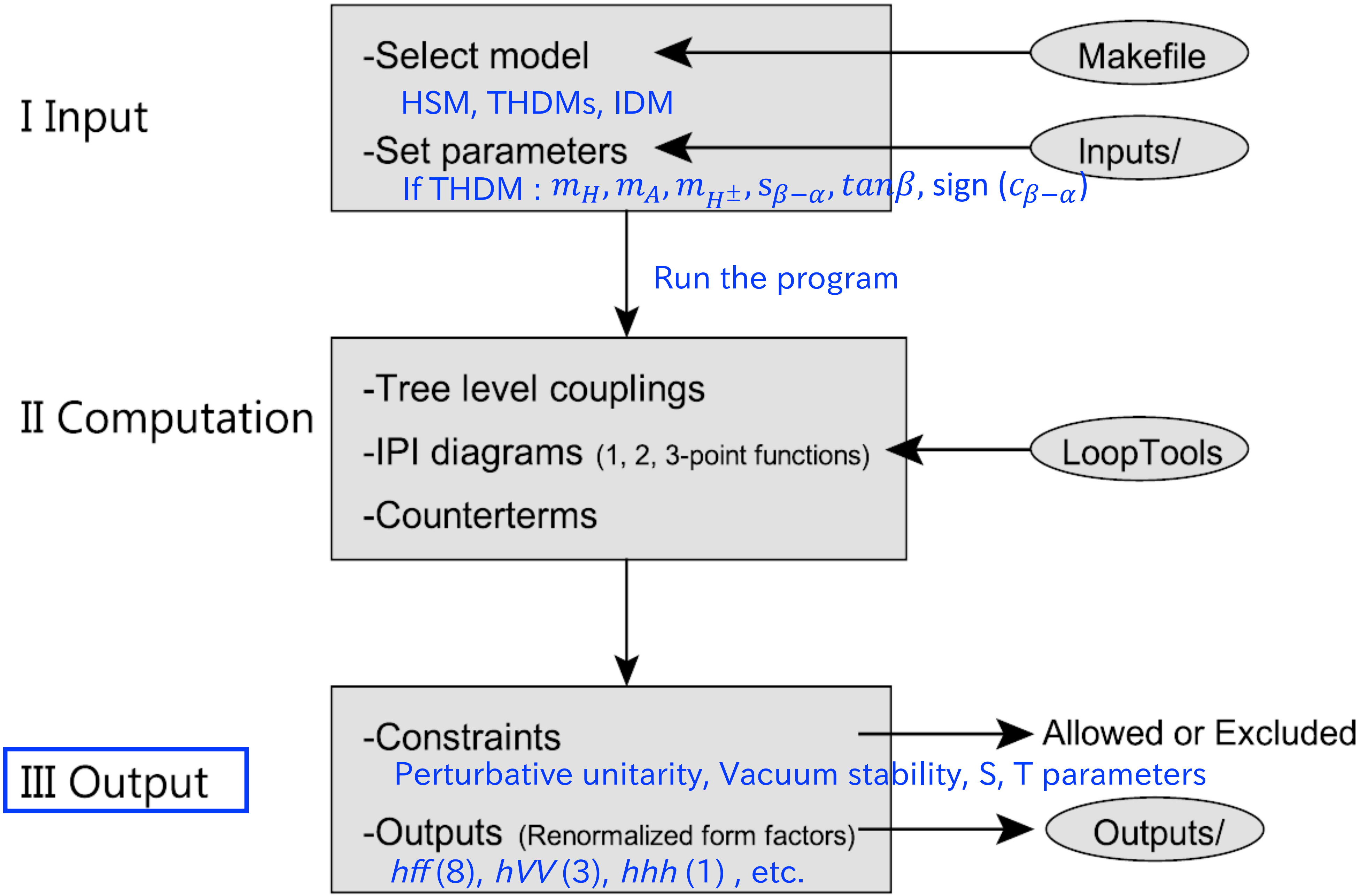
δm_Φ : $Re\Gamma_{\Phi\Phi}^R[m_h^2] = 0$ $\Rightarrow$ $\delta m_\Phi^2 = Re\Pi_{\Phi\Phi}^{1PI}(m_h^2)$

δZ_Φ : $\frac{\partial}{\partial p^2} Re\Gamma_{\Phi\Phi}^R(p^2)\Big|_{p^2=m_\Phi^2} = 0$ $\Rightarrow$ $\delta Z_\Phi = -\frac{\partial}{\partial p^2} Re\Pi_\Phi^{1PI}(p^2)\Big|_{p^2=m_\Phi^2}$

$\delta\mu_2$: It is determined to cancel a divergence at a scalar triinear coupling such as *hHH.*

$\delta\lambda_2$: It is determined to cancel a divergence at a scalar quartic coupling such as *HHHH.*

Structure of H-COUP



Structure of H-COUP

outputs — emacs out_thdm.txt — 83×20

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   Re[rGam_hZZ(1)]:    6.66615250E+01     Im[rGam_hZZ(1)]:   -1.54198133E+00
   Re[rGam_hZZ(2)]:   -1.08763248E-01     Im[rGam_hZZ(2)]:   -9.30143658E-01
   Re[rGam_hZZ(3)]:    4.45532608E-03     Im[rGam_hZZ(3)]:   -2.50250045E-06
   Re[rGam_hWW(1)]:    5.33946191E+01     Im[rGam_hWW(1)]:   -1.40793590E+00
   Re[rGam_hWW(2)]:   -9.26602552E-02     Im[rGam_hWW(2)]:   -9.14195453E-01
   Re[rGam_hWW(3)]:    1.46086850E-03     Im[rGam_hWW(3)]:   -4.40555863E-02
   Re[rGam_htt(S)]:   -7.30899549E-01     Im[rGam_htt(S)]:   -4.18826166E-03
   Re[rGam_hbb(S)]:   -1.88720530E-02     Im[rGam_hbb(S)]:   -4.03031469E-06
   Re[rGam_hcc(S)]:   -5.16584879E-03     Im[rGam_hcc(S)]:   -5.95102942E-05
   Re[rGam_hll(S)]:   -7.02321748E-03     Im[rGam_hll(S)]:   -2.22377046E-04
      Re[rGam_hhh]:   -1.91267505E+02        Im[rGam_hhh]:    1.49468778E+00
    Gam(h->gamgam):    8.95726899E-06
      Gam(h->Zgam):    6.31549430E-06
        Gam(h->gg):    1.92656103E-04

-uu-:---F1  out_thdm.txt   All L1     (Text)-----------------------------------
Loading image...done
```

III Output

-Constraints → Allowed or Excluded

Perturbative unitarity, Vacuum stability, S, T parameters

-Outputs (Renormalized form factors) → Outputs/

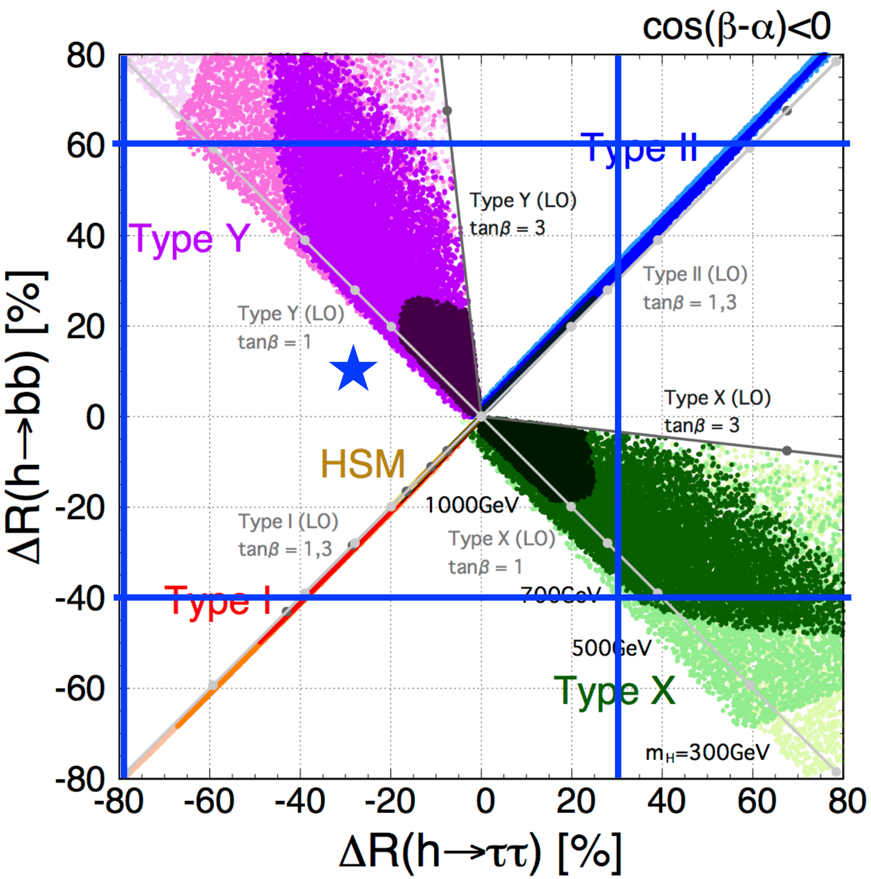
hff (8), *hVV* (3), *hhh* (1) , etc.

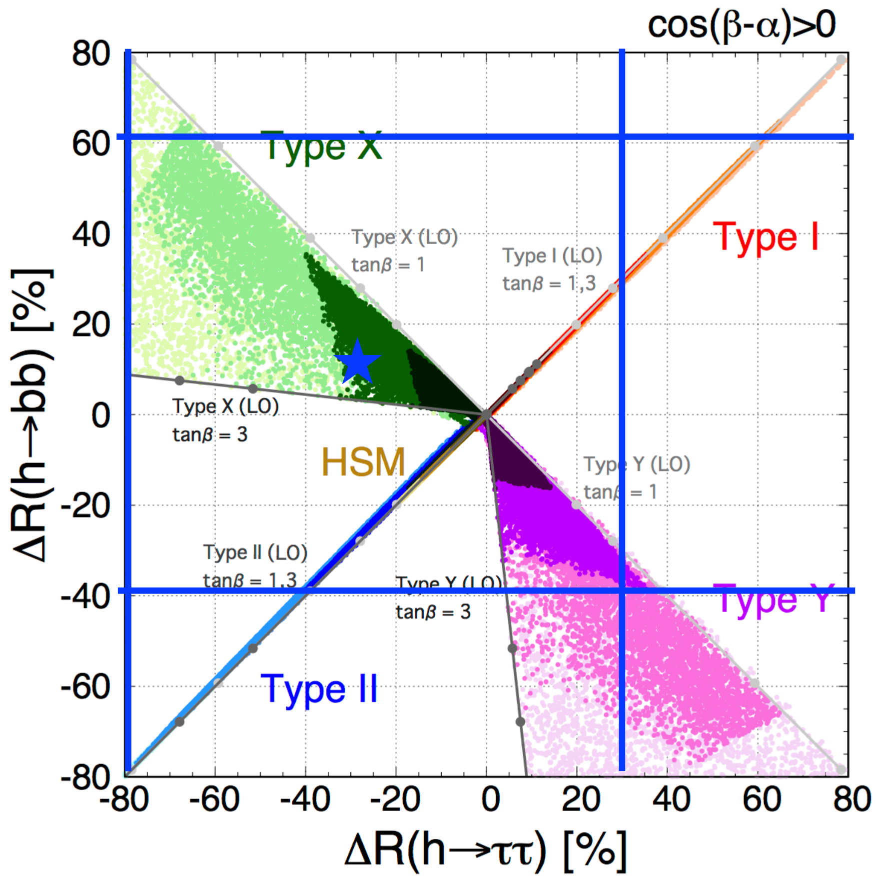
Other plot

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

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

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



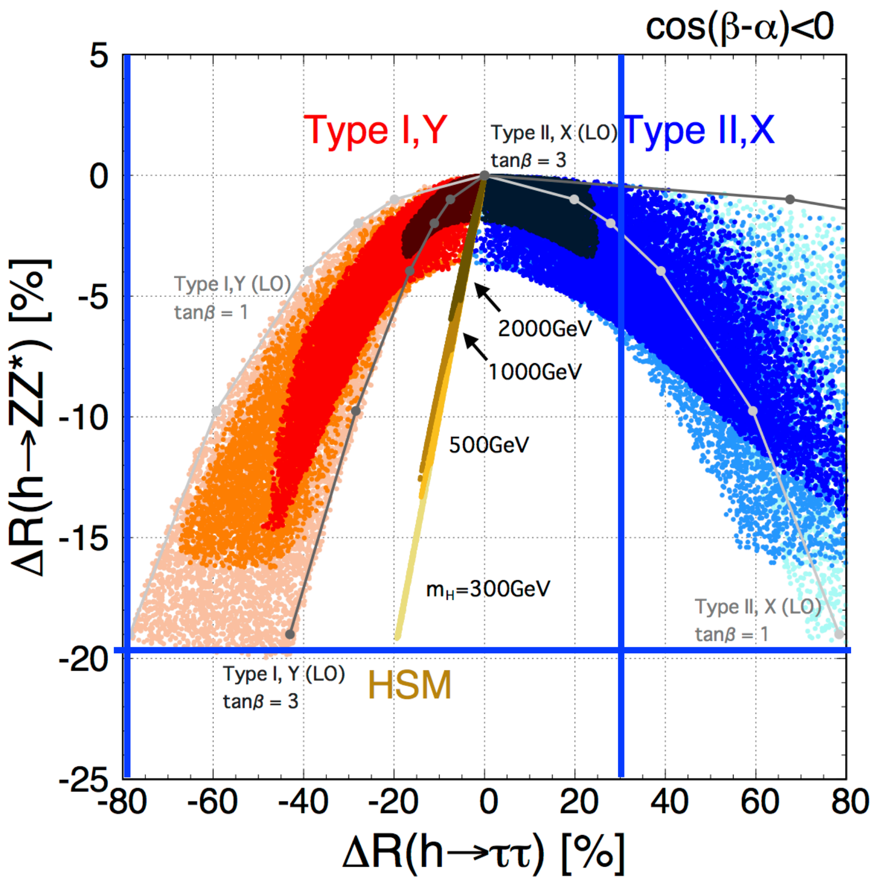


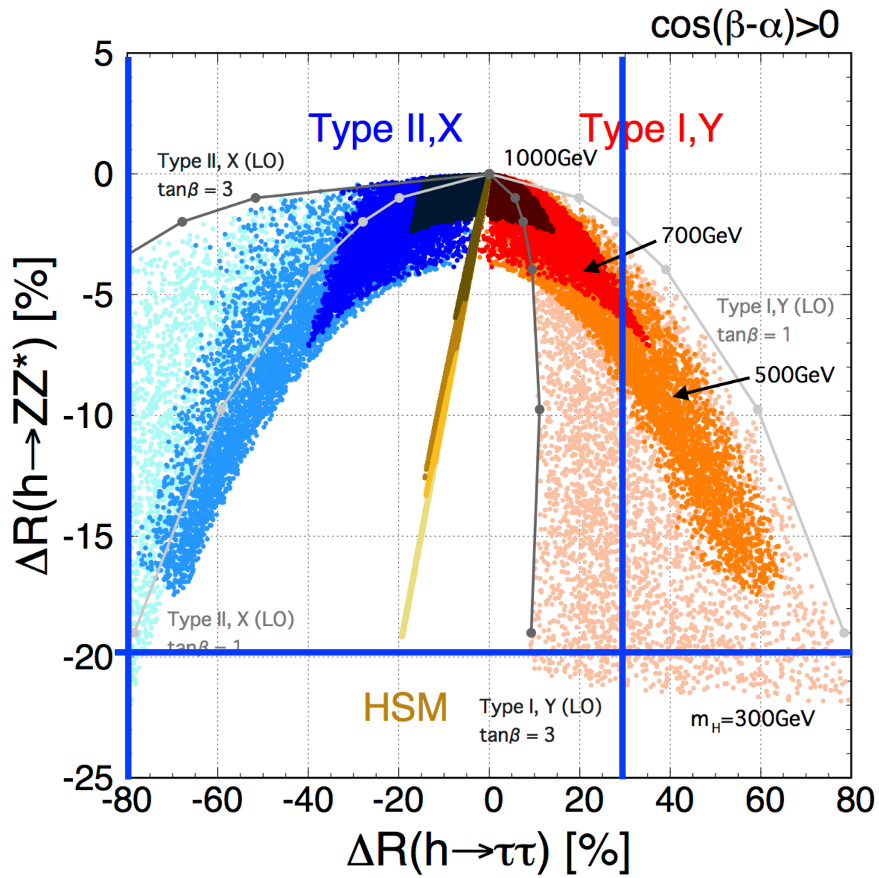
LHC Run I current data (2σ)

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

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

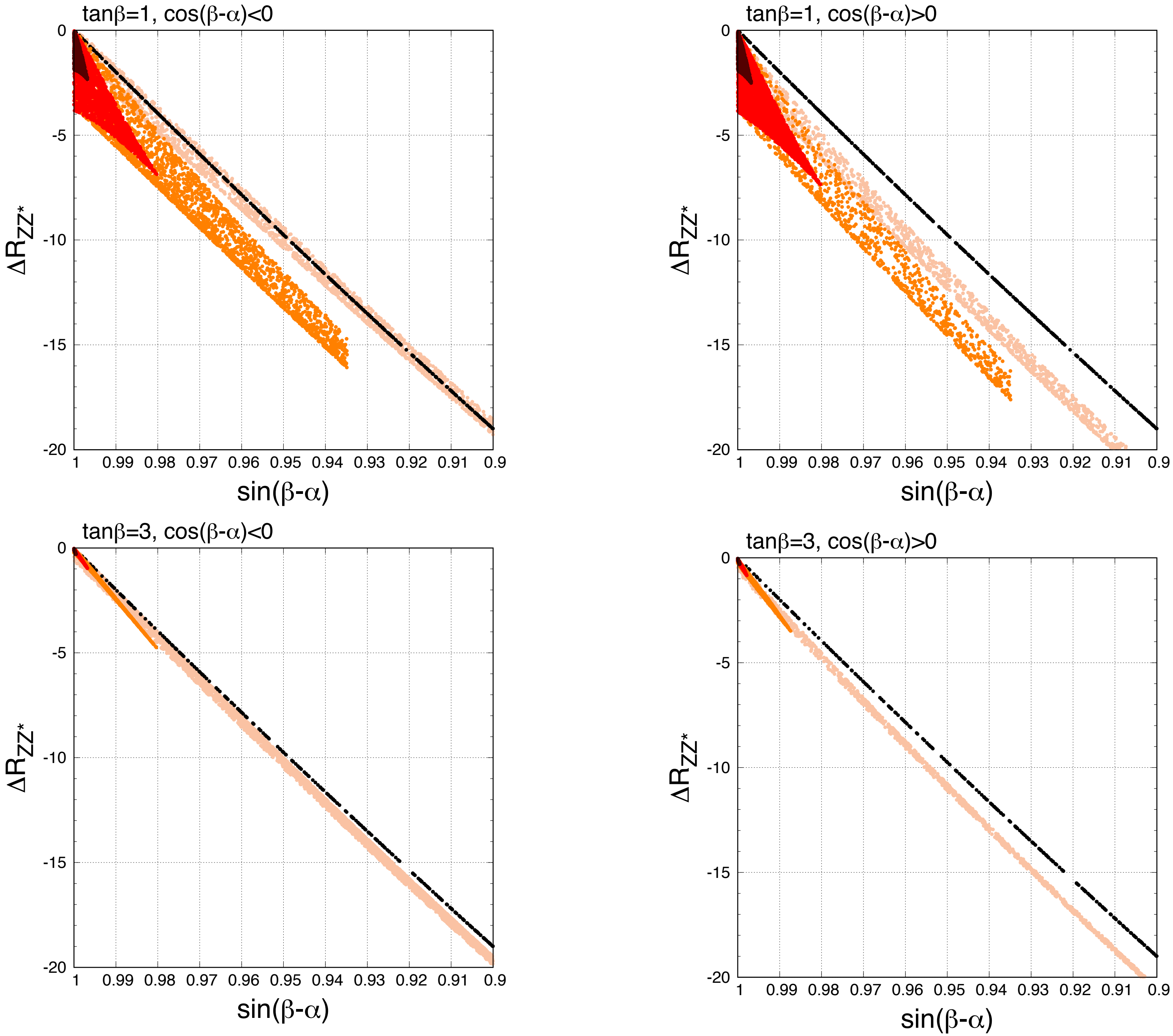
$$\Delta R(\mathrm{h} \to XX) = \frac{\Gamma(\mathrm{h} \to XX)_{EX}}{\Gamma(\mathrm{h} \to XX)_{SM}} - 1$$





LHC Run I current data (2σ)

$\Delta R(h \to ZZ^*)$ vs $Sin(\beta - \alpha)$



$\tan\beta$ **vs** $Sin(\beta - \alpha)$