Radiative corrections to the Higgs boson coupling constants in multi Higgs models

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Phys.Rev. D87 (2013) 015012 M. Aoki, S. Kanemura, M. K., K. Yagyu
Paper in preparation S. Kanemura, M. K., K. Yagyu

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Introduction

◆ **Higgs boson(*h*) was discovered at LHC last year !**

The data indicate that it is a SM-like Higgs boson.

$m_h=126$ **GeV**

◆ **What is the shape of the Higgs sector?**

No principle for minimal Higgs with one doublet

SM-like ≠ SM

Second Higgs boson

◆ **We have to construct the Higgs sector by the bottom-up approach.**

- **Direct searches**
- **Indirect searches**

We here evaluate *h*-couplings in 2 Higgs doublet models with radiative corrections.

Higgs as a probe of new physics

Physics of *h* Deviations in coupling constants of the *h* due to heavy Higgs bosons (or NP particles)

There are two possibilities to change couplings of *h*

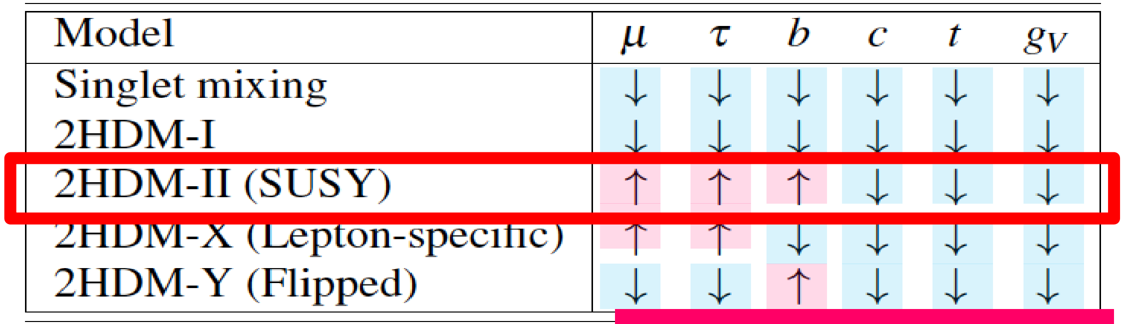
- **Mixing among scalar fields**
- **Radiative corrections**

Kanemura, Tsumura, Yagyu, Yokoya in ILC HIGGS WHITE PAPER

We can discriminate extended Higgs models by precisely measuring the pattern of deviations in *h*-couplings.

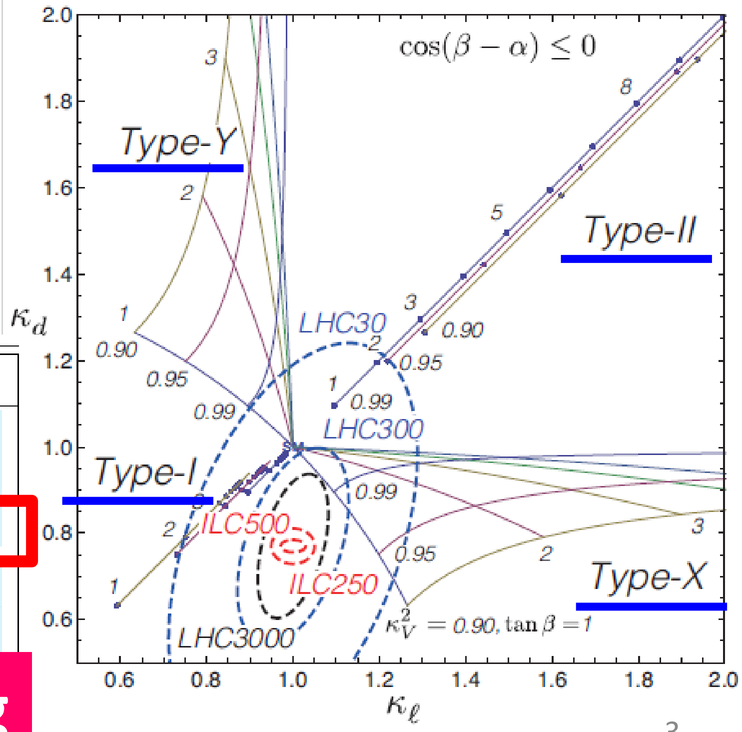
$$g_{hXX} = g_{hXX}{}^{SM} \times \kappa_{hXX}$$

cos(β-α)<0



Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

Finger printing



Future precision measurements

ILC 250-1000GeV

ILC HIGGS WHITE PAPER

D.M. Asner, T. Barklow, C. Calancha, K. Fujii, N. Graf, H. E. Haber, A. Ishikawa, S. Kanemura, S. Kawada, M. Kurata, A. Miyamoto, H. Neal, H. Ono, C. Potter, J. Strube, T. Suehara, T. Tanabe, J. Tian, J. Tsumura, S. Watanuki, G. Weiglein, K. Yagyu, H. Yokoya

(%)

	cc	bb	tt	ττ	μμ	WW	ZZ	γγ	gg	hhh
ILC(250)	6.8	5.3	-	5.7	91	4.8	1.3	17	6.4	-
ILC(250+500)	2.8	1.6	14	2.3	91	1.1	1.0	8.3	2.3	83
ILC (250+500+1000)	1.8	1.3	3.1	1.6	16	1.1	1.0	3.8	1.6	21
ILC(LumUp)	1.0	0.7	1.9	0.9	10	0.6	0.5	2.3	0.9	13

***h*-couplings can be measured typically by O(1) % !!**

Calculating *h*-couplings accurately with radiative corrections is very important !

Precision measurements of Higgs couplings × **Theoretical predictions at loop level**

In this talk

We comprehensively evaluate *h*-coupling constants with radiative corrections assuming extended Higgs models, in order to find the pattern of deviations from the SM.

S: singline field
Φ: doublet field
Δ: triplet feild

◆**Which models do we consider ?**

done

done

①Singlet model (Φ+S), ②2HDM (Type-I, II, X, Y), ③Higgs triplet model (Φ+Δ)

This time

Aoki, Kanemura, Kikuchi, Yagyu,PRD87.015012 (2013)

◆**Which couplings do we consider ?**

hcc, hbb, hττ	*hWW, hZZ*	*hɣɣ, hgg, hɣZ*	*hhh*
Yukawa	Gauge	Loop	Self coupling

◆**We calculate renormalized *h*-couplings**

$$g_{hXX}^{reno} = g_{hXX}^{tree} + \delta g_{hXX} + g_{hXX}^{1PI}$$

$$\Delta g_{hXX} = \frac{g_{hXX} - g_{hXX}^{SM}}{g_{hXX}^{SM}}$$

2 Higgs Doublet Model (Model)

$\Phi_{1,}$ Φ_2 (2-Higgs doublets)

Dangerous!!

In general, in a multi-doublet structure, FCNC appears.

◆ To avoid FCNC, we impose Z_2 symmetry

$$\Phi_1 \rightarrow +\Phi_{1,} \qquad \Phi_2 \rightarrow -\Phi_2$$

4 Types of Yukawa interaction according to charge assignment of Z_2

Barger, Hewett, Phillips(1990),
Aoki, Kanemura, Tsumura, Yagyu(2009),
Logan, Su, Haber, ….

type	Φ_1	Φ_2	u_R	d_R	l_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

Phenomenology is different in each type of Yukawa interaction.

2 Higgs Doublet Model (2HDM)

$$V_{\text{THDM}} = +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)}$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2$$
$$+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\text{h.c.})\right]$$

$$\Phi_i = \left[\begin{array}{c} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i a_i) \end{array}\right] \quad (i = 1, 2)$$

$$\Phi_1 \text{ and } \Phi_2 \Rightarrow \underline{h,\quad H,}\quad A^0, H^\pm \oplus \text{Goldstone bosons}$$

↑ ↑ ↑charged

CPeven CPodd

Field mixing

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

$$\frac{v_2}{v_1} = \tan\beta$$

$$m_h^2 = v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_H^2 = M_{\text{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda) \sin^2\beta \cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_{H^\pm}^2 = M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2,$$

$$m_A^2 = M_{\text{soft}}^2 - \lambda_5 v^2.$$

M_{soft} $\left(= \frac{m_3}{\sqrt{\cos\beta \sin\beta}}\right)$:

soft-breaking scale

of the discrete symm.

M_{soft}: soft breaking scale

$$\lambda = \lambda_3 + \lambda_4 + \lambda_5$$

SM-like limit

	ξ_h^u	ξ_h^d	ξ_h^e
Type-I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
Type-II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type-X	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type-Y	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

Scale factor κ_{hXX}

$$\boxed{g_{hXX} = {g_{hXX}}^{SM} \times \kappa_{hXX}}$$

SM-like limit

$\kappa_{hVV} = \sin(\beta - \alpha) \rightarrow 1$

$\kappa_{hff} = \xi_h^f \rightarrow 1$

Current LHC data seem to suggest that the Higgs is roughly SM-like within large errors

SM-like ≠ SM

Renormalizations

We calculate all *h*-couplings at one loop-level by on-shell renormalization.

Full EW loop corrections and extra Higgs loop corrections

- ◆ **Gauge couplings** ***hWW, hZZ***
- ◆ **Self coupling** ***hhh***

Kanemura, Okada, Senaha, Yuan (2004)

NEW ◆ **Yukawa coupling** ***hff*** Guasch, Hollik, Peñaranda(2001)

1. Parameter shift

$$\Gamma^{\rm tree}_{hff} = -i\frac{m_f}{v}\xi^f_h,$$

Renormalized coupling

$$\boxed{\hat{\Gamma}_{hff}(p_1^2,p_2^2,q^2) = \Gamma^{\rm tree}_{hff} + \delta\Gamma_{hff} + \Gamma^{\rm 1PI}_{hff}(p_1^2,p_2^2,q^2)}$$

$$\delta\Gamma_{hff} = -i\frac{m_f}{v}\xi^f_h\left[\frac{\delta m_f}{m_f} - \frac{\delta v}{v} + \delta Z^f_V + \frac{1}{2}\delta Z_h + \frac{\delta\xi^f_h}{\xi^f_h} + \frac{\xi^f_H}{\xi^f_h}(\delta C_h + \delta\alpha)\right].$$

2. Calculation of 1PI diagrams (2 point functions , 3 point functions)

3. On-shell conditions

Renormalization conditions ➡ $\delta m_b = \Pi^{1PI}_{bb}[m_b],$

4. Evaluations of the deviations from SM predictions

$$\Delta\Gamma_{hff} \equiv \frac{\Gamma^{\rm THDM}_{hff} - \Gamma^{\rm SM}_{hff}}{\Gamma^{\rm SM}_{hff}}$$

Renormalized coupling (*hbb* in TypeII)

$$\boxed{\Gamma_{hbb} = \Gamma_{hbb}^{tree} + \delta\Gamma_{hbb} + \Gamma_{hbb}^{1PI}}$$

◆**Counter-term**

$$\delta\Gamma_{hbb} = -\frac{m_b}{v}\frac{c_\alpha}{c_\beta}\delta C_{Hh} + \frac{m_b}{v}\frac{s_\alpha}{c_\beta}\left(\frac{\delta m_b}{m_b} - \frac{\delta v}{v} + \frac{s_\beta}{c_\beta}\delta\beta + \delta Z_b + \frac{1}{2}\delta Z_h\right)$$

◆**Each counter-term**

$$\delta m_b = \Pi_{bb}^{\text{1PI}}[m_b],$$

$$\frac{\delta v}{v} = \frac{1}{2}\left(\frac{s_W^2 - c_W^2}{s_W^2}\frac{\Pi_{WW}^{1PI}[m_W^2]}{m_W^2} + \frac{c_W^2}{s_W^2}\frac{\Pi_{ZZ}^{1PI}[m_Z^2]}{m_Z^2} - \frac{d}{dp^2}\Pi_{\gamma\gamma}^{1PI}[p^2]|_{p^2=0} + \frac{2s_W}{c_W}\frac{\Pi_{\gamma Z}^{1PI}[0]}{m_Z^2}\right),$$

$$\delta C_{Hh} = \frac{1}{2(m_H^2 - m_h^2)}\left(\Pi_{Hh}^{\text{1PI}}[m_h^2] - \Pi_{Hh}^{\text{1PI}}[m_H^2]\right),$$

$$\delta\alpha = \frac{1}{2(m_H^2 - m_h^2)}\left\{2c_\alpha s_\alpha\left(-\frac{1}{c_\beta}\frac{\delta T_1}{v} + \frac{1}{s_\beta}\frac{\delta T_2}{v}\right) + \Pi_{Hh}^{\text{1PI}}[m_H^2] + \Pi_{Hh}^{\text{1PI}}[m_h^2]\right\},$$

$$\delta\beta = -\frac{1}{2m_A^2}\left(\Pi_{zA}^{\text{1PI}}[0] + \Pi_{zA}^{\text{1PI}}[m_A^2] - 2s_\beta\frac{\delta T_1}{v} + 2c_\beta\frac{\delta T_2}{v}\right),$$

$$\delta Z_h = -\frac{d}{dp^2}\Pi_{hh}^{\text{1PI}}[p^2]|_{p^2=m_h^2},$$

$$\delta Z_b = -\frac{d}{d\not{p}}\Pi_{bb}^{\text{1PI}}[\not{p}]|_{\not{p}=m_b}.$$

Deviations in *hZZ, hhh*

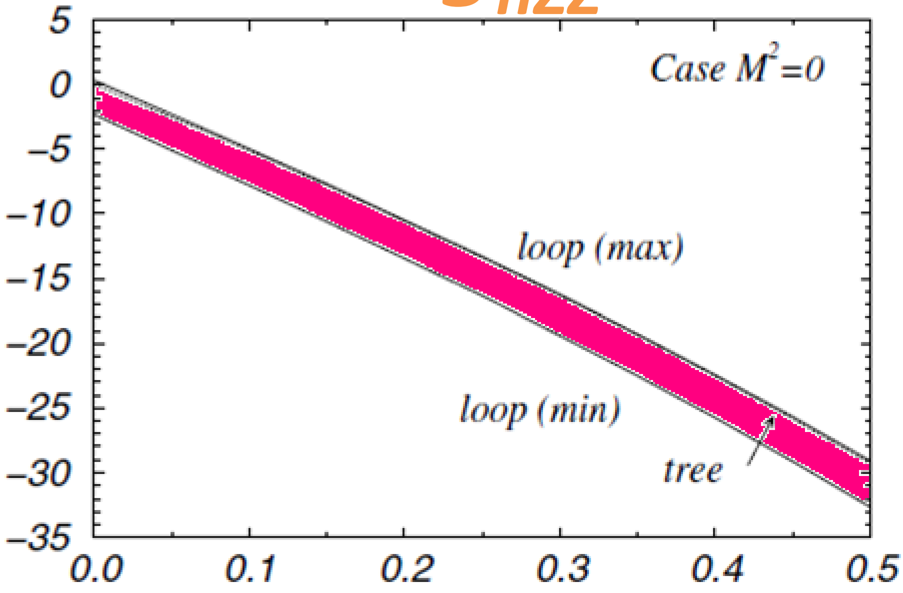
Kanemura, Okada, Senaha, Yuan (2004)

Mixing angle dependence

Allowed region of the deviation in the *hZZ, hhh* coupling under the unitarity and the vacuum stability bounds.

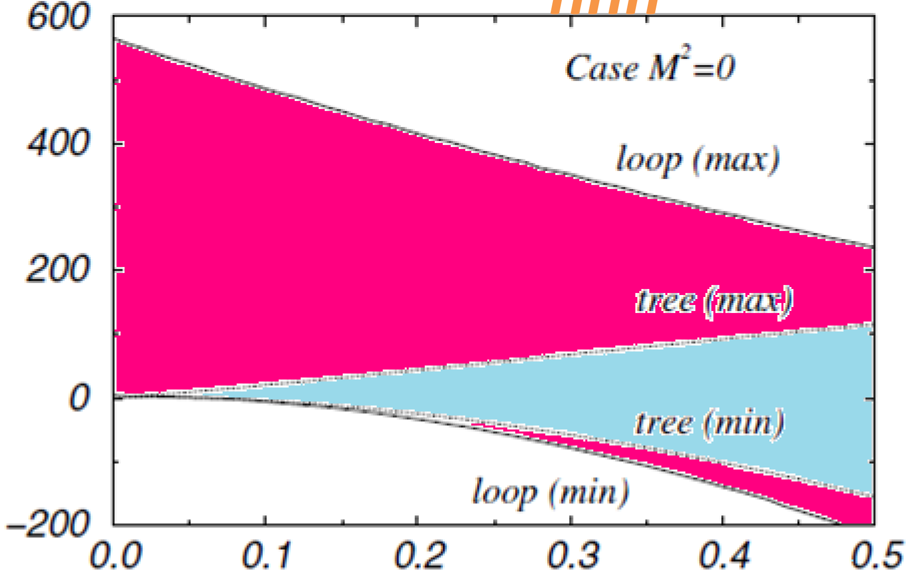
$m_H = m_{H\pm} = m_A$
$m_h = 120\ GeV$

Δg_{hZZ}



sin²(β−α)

$\Delta\lambda_{hhh}$



sin²(β−α)

- $\Delta g_{hZZ} \leq 0$
- ***hZZ*** **can deviate several % by radiative correction.**

- ***hhh*** **can deviate O(100)% by radiative correction.**

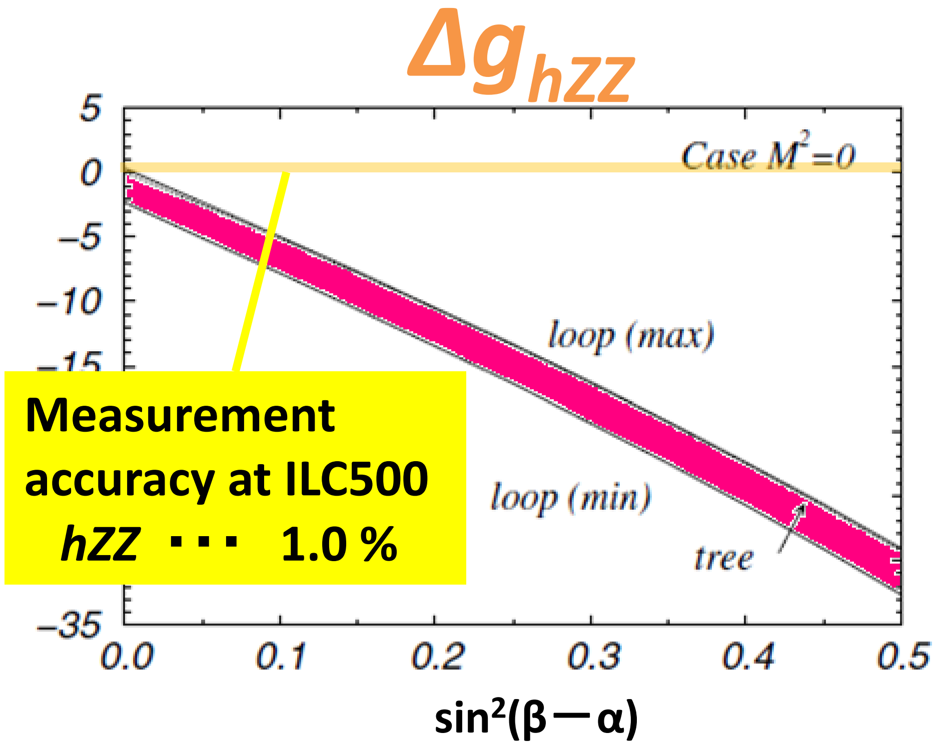
Non-decoupling loop effect

Deviations in *hZZ, hhh*

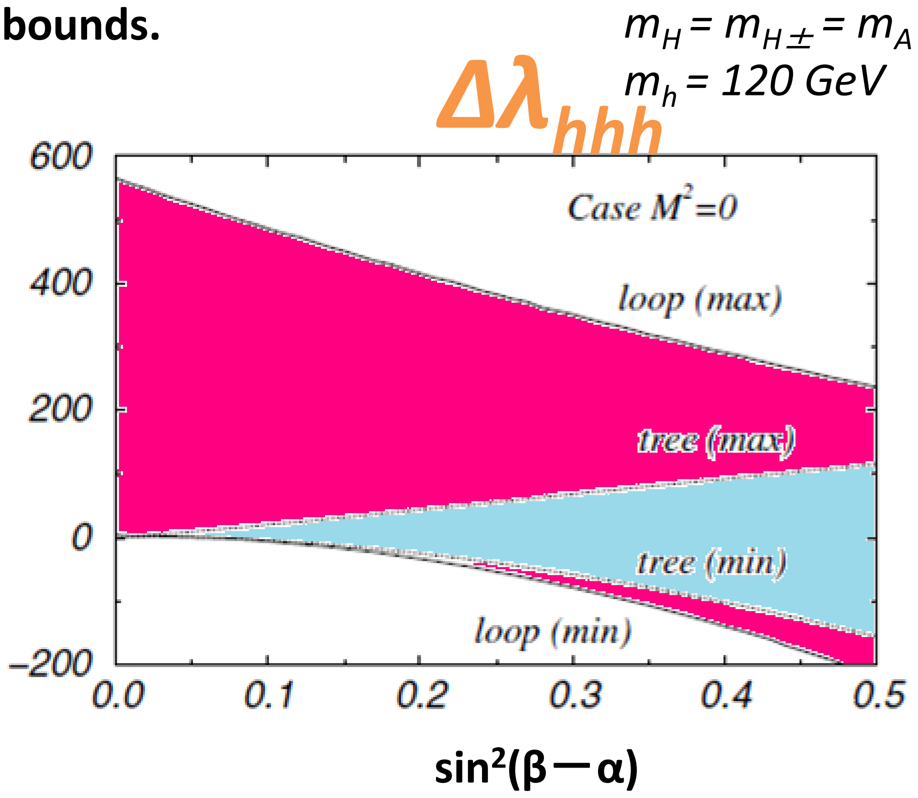
Kanemura, Okada, Senaha, Yuan (2004)

Mixing angle dependence

Allowed region of the deviation in the *hZZ, hhh* coupling under the unitarity and the vacuum stability bounds.



Measurement accuracy at ILC500
hZZ **・・・ 1.0 %**

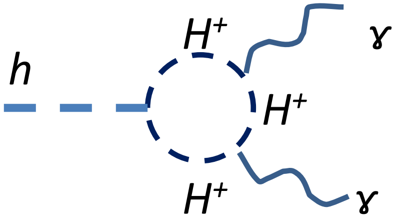


→ **We can determine $\sin^2(\beta-\alpha)$ with high precision.**

- ***hhh*** **can deviate O(100)% by radiative correction.**

Non-decoupling loop effect

$h \to \gamma\gamma$



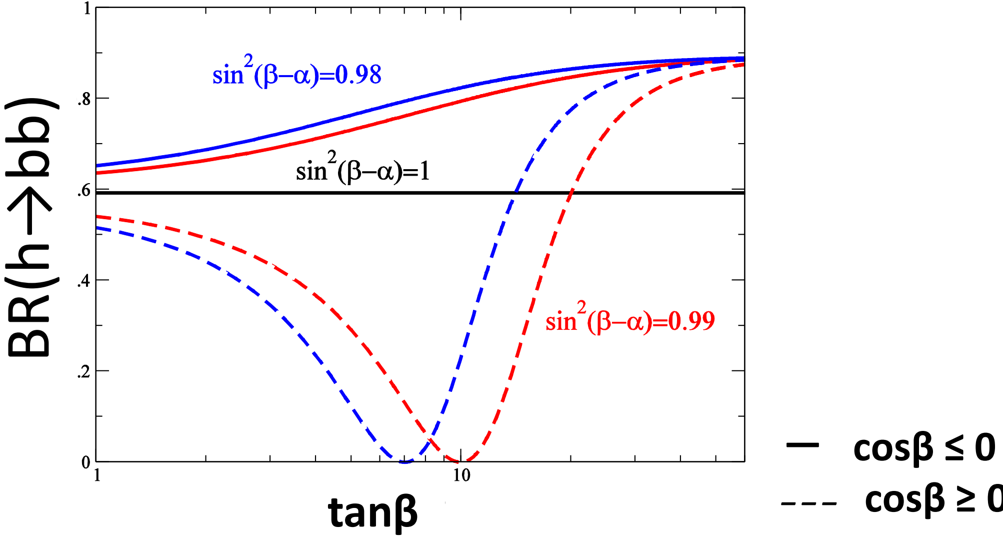
Zeppenfeld, Kinnunen, Nikitenko, Richter-Was(2000), Ginzburg, Krawczyk, Osland(2001), Spira, Djouadi, Graudenz, Zerwas(1995), Arhrib, Hollik, Penaranda, Capdequi Peyranere(2004), Pocsh(2011)

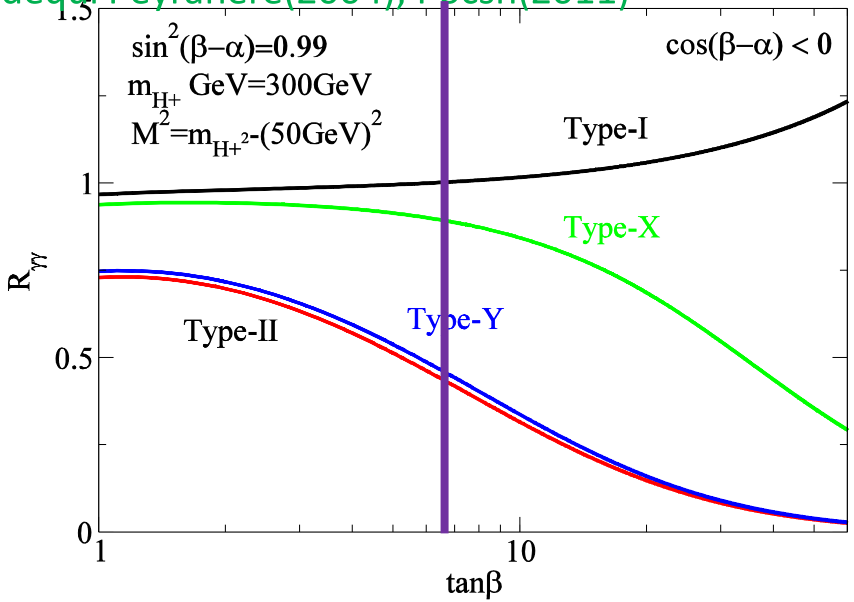
$$R_{\gamma\gamma} \equiv \frac{\sigma(gg \to h)_{2HDM} \times BR(h \to \gamma\gamma)_{2HDM}}{\sigma(gg \to h)_{SM} \times BR(h \to \gamma\gamma)_{SM}}$$

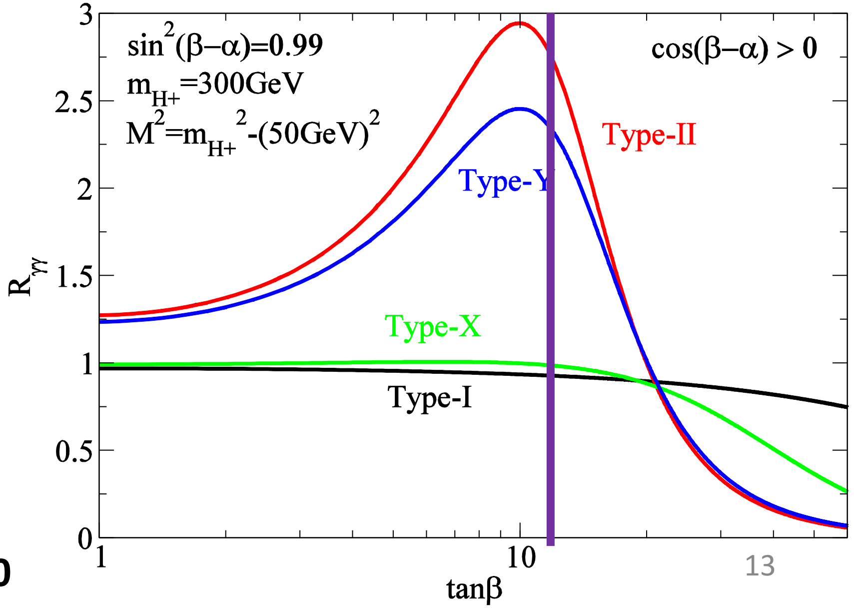
ATLAS 1.2 – 1.8 , CMS 0.3 – 1.3

◆ ***Rγγ* depends on types of Yukawa interaction.**

◆ **Magnitudes of *Rγγ* are different by the sign of cos(β−α).**



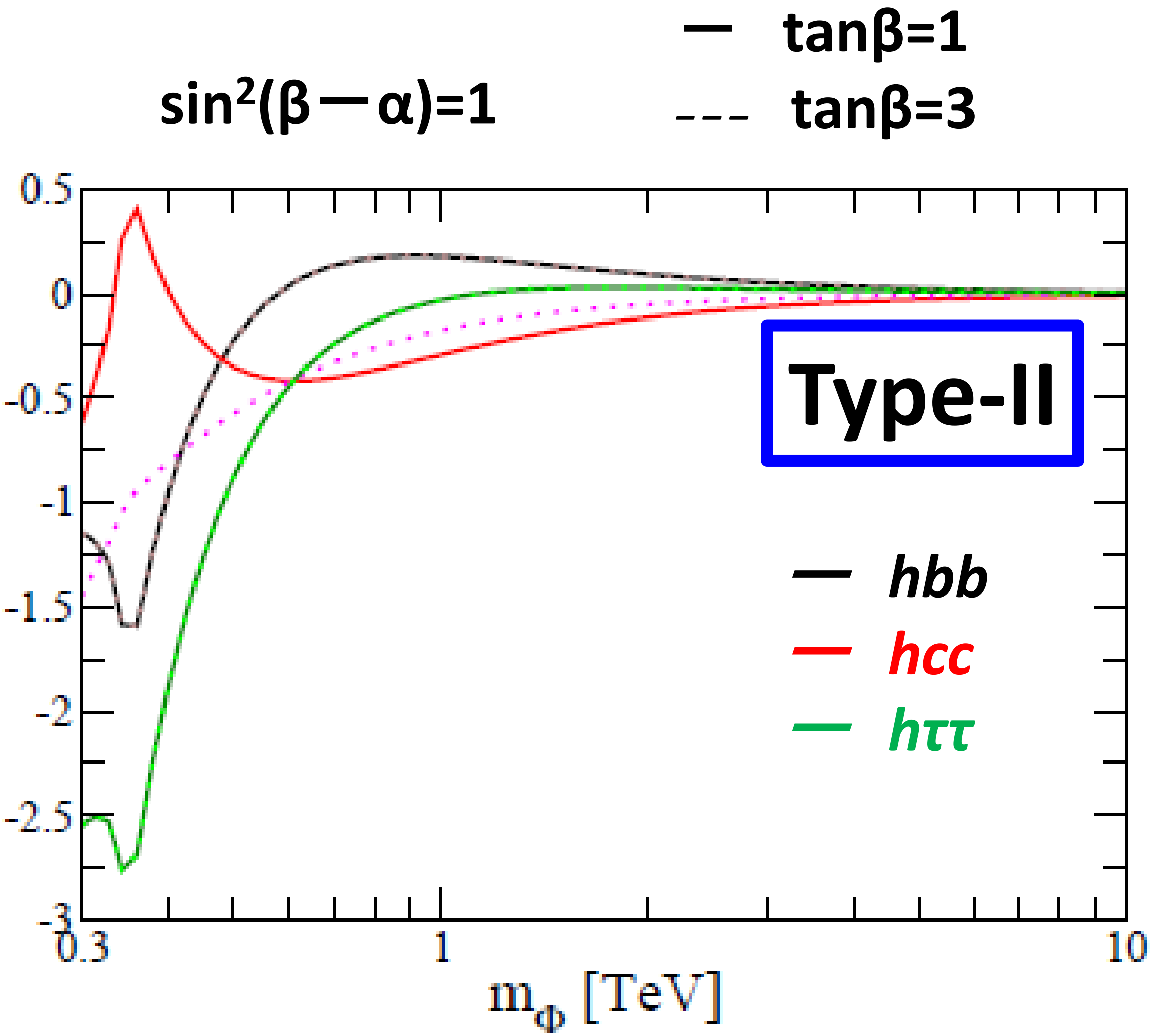




Deviations in *hff* (1)

$$\Delta\Gamma_{hff} \equiv \frac{\Gamma^{\rm THDM}_{hff} - \Gamma^{\rm SM}_{hff}}{\Gamma^{\rm SM}_{hff}}$$

$m_\Phi^2 = M^2 + (300\text{GeV})^2$



We have checked consistency of our calculation.

Kanemura, Kikuchi, Yagyu(2013)

Deviations in *hff* (2)

$$\Delta\Gamma_{hff} \equiv \frac{\Gamma^{\rm THDM}_{hff} - \Gamma^{\rm SM}_{hff}}{\Gamma^{\rm SM}_{hff}}$$

$\sin^2(\beta - \alpha) = 1$

Type-II

Radiative corrections are maximum by Non-decoupling effect.

$M^2 = 0$

— ***hbb***

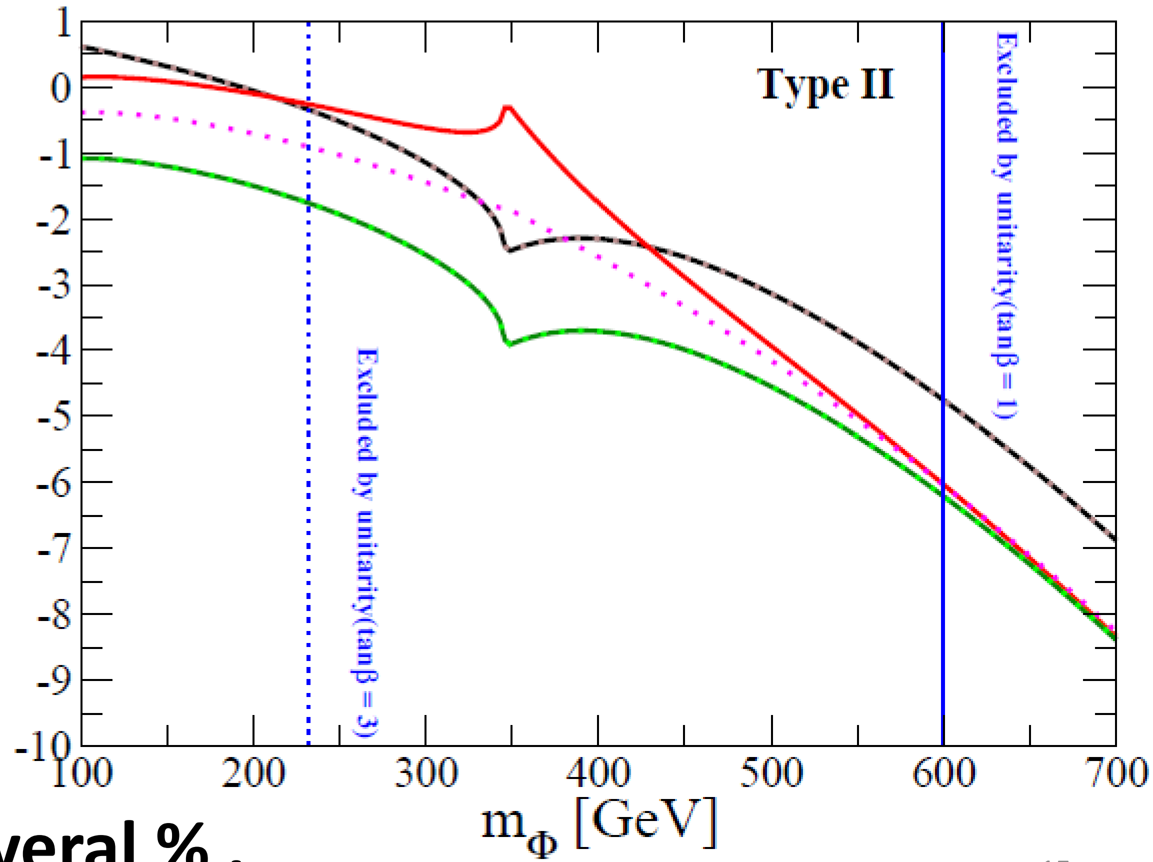
— ***hcc***

— ***hττ***

— **tanβ=1**

--- **tanβ=3**

$\Delta\Gamma_{hff}$ (%)



Deviation can be several % .

Kanemura, Kikuchi, Yagyu(2013)

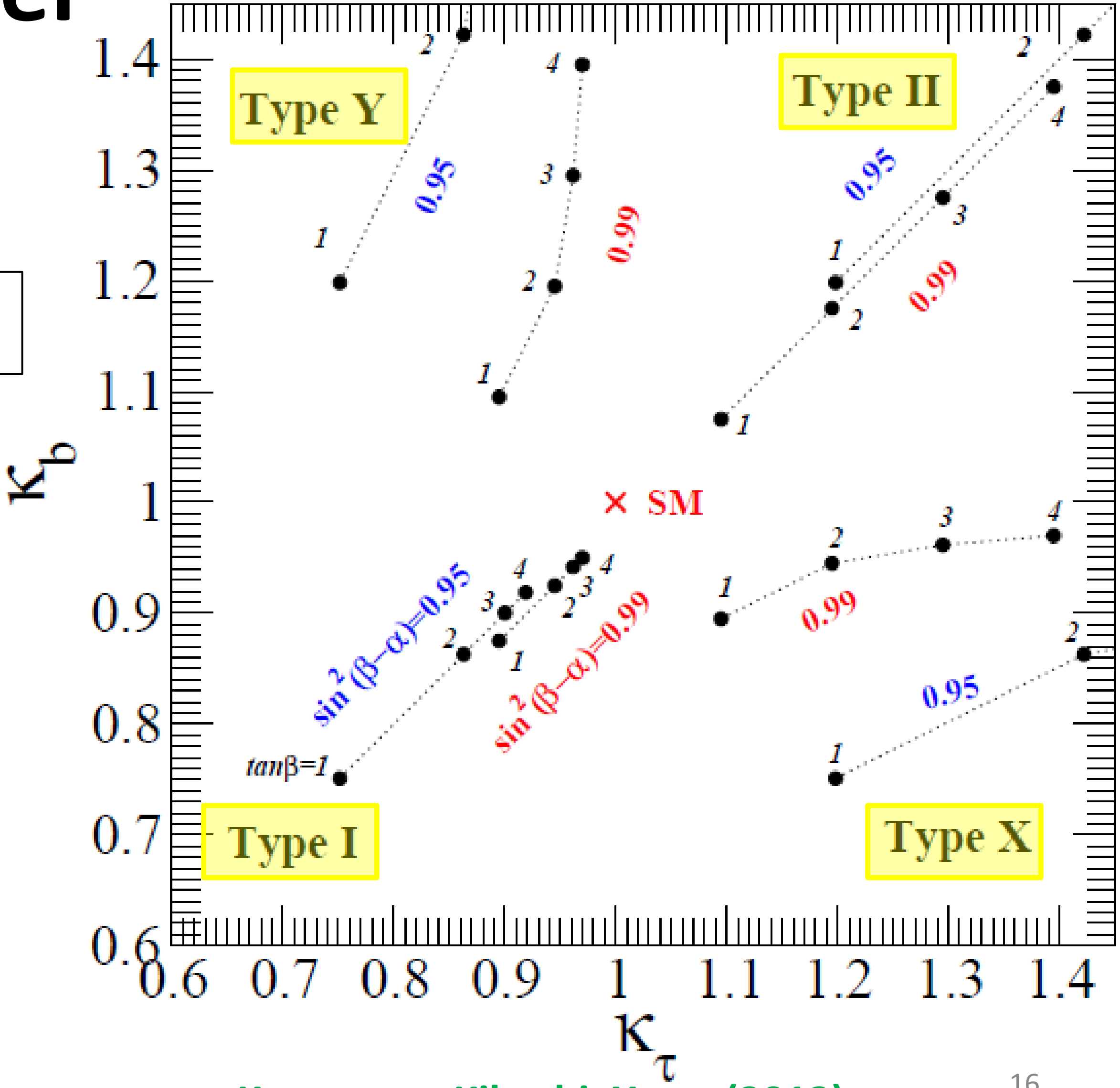
Finger printing
at the tree level

κ_b vs κ_τ

$\cos(\beta-\alpha) \leq 0$

$$g_{hXX} = g_{hXX}{}^{SM} \times \kappa_{hXX}$$

How about one-loop level ?



Kanemura, Kikuchi, Yagyu(2013)

Finger printing at the 1-loop level for each tanβ

κ_b VS κ_τ

cos(β−α) ≤ 0

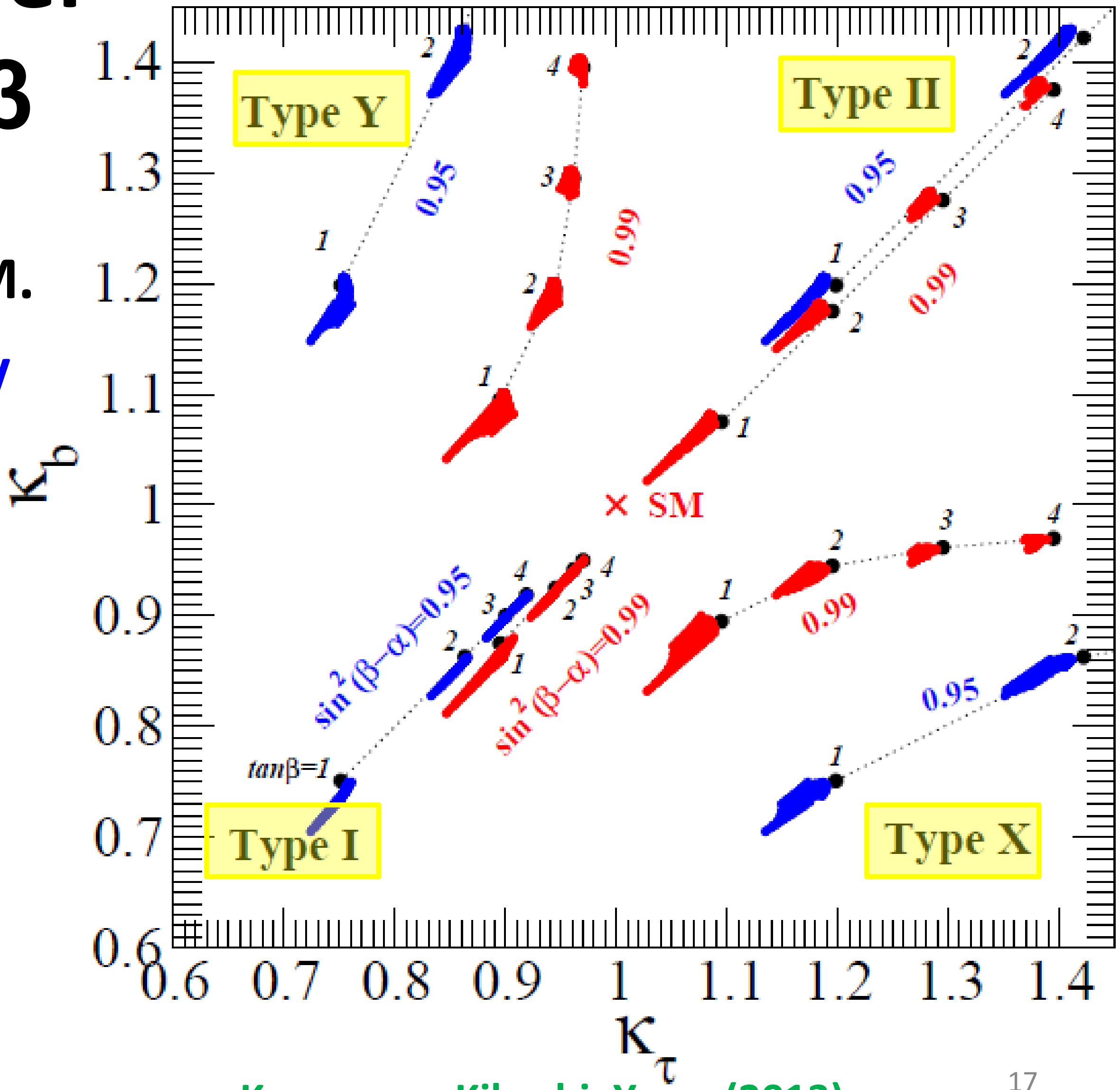
- We perform a scan analysis for m_Φ and M.

$100\text{ GeV} \leq m_\Phi \leq 1000\text{GeV}$

$0 \leq M \leq m_\Phi$

We take into account constraints from the unitarity and the vacuum stability.

In the maximum radiative correction case
→ deviation become prediction with smaller tanβ at the tree level



Kanemura, Kikuchi, Yagyu(2013)

Finger printing at the 1-loop level

- ◆ We perform a scan analysis for m_Φ, M and tanβ.

  $100\ \mathrm{GeV} \le m_\Phi \le 1000\mathrm{GeV}$

  $0 \le M \le m_\Phi$

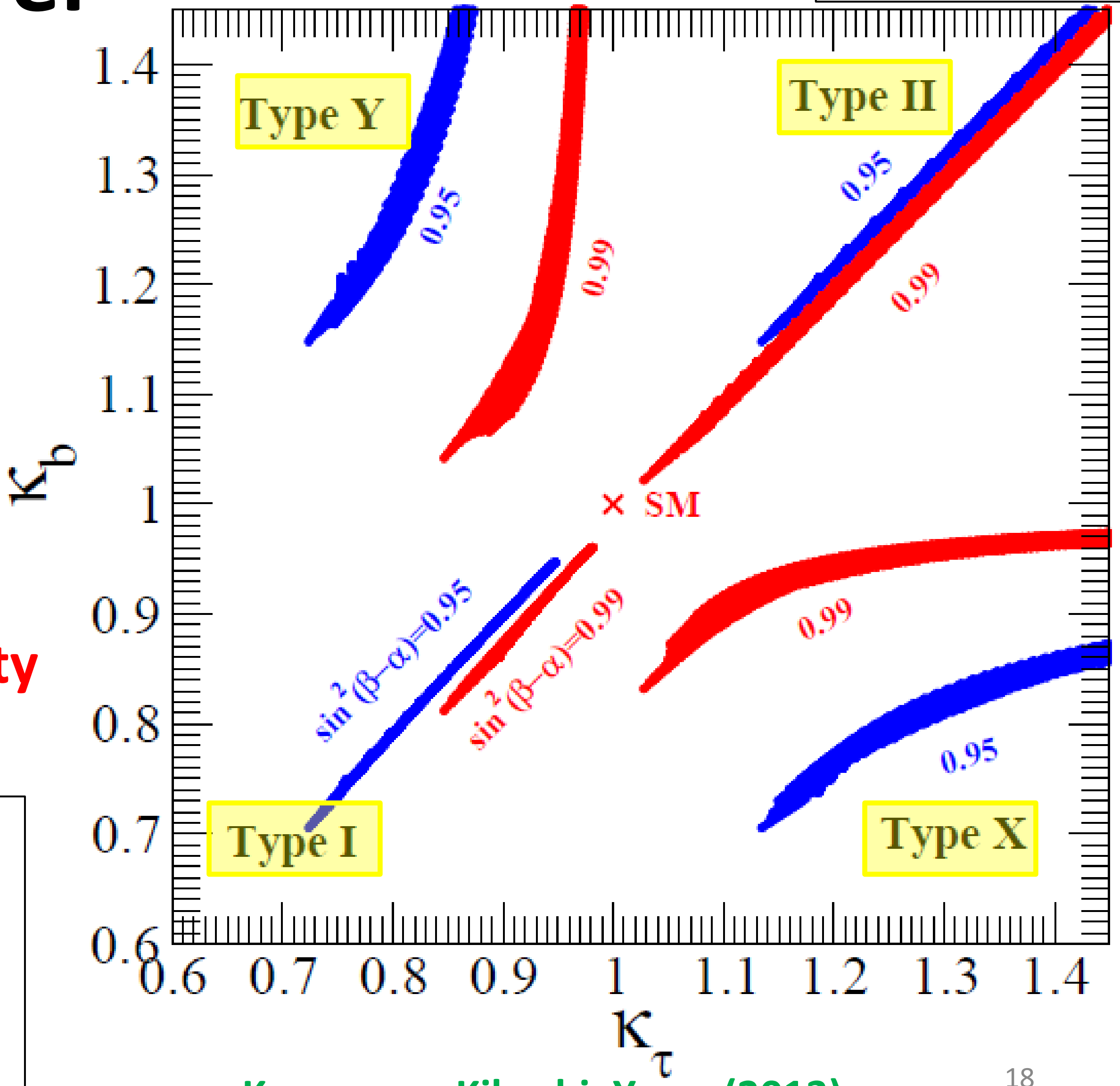
  $1 \le \tan\beta$

We take into account constraints from unitarity and vacuum stability.

We can discriminate all type in the case with the maximum radiative corrections.

κ_b VS κ_τ

cos(β−α) ≤ 0



Kanemura, Kikuchi, Yagyu(2013)

Finger printing at the 1-loop

- - - - *LHC300*

- - - - *LHC3000*

- - - - *ILC250*

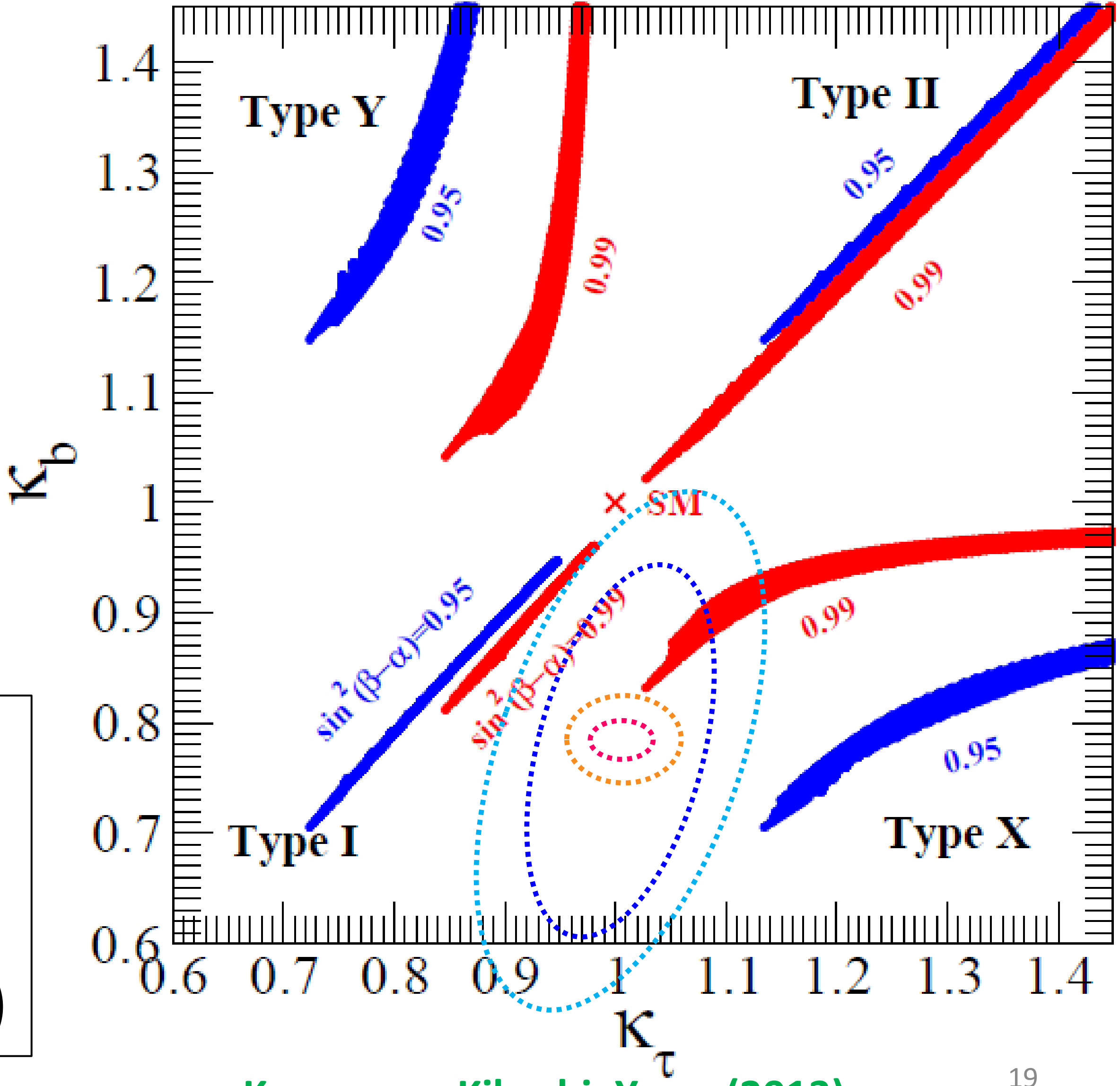
- - - - *ILC500*

(68% C.L.)

We can measure detailed deviations at the ILC (E=250GeV,500GeV)

κ_b VS κ_τ

cos(β−α) ≤ 0



Kanemura, Kikuchi, Yagyu(2013)

1-loop level for each tanβ

κ_b VS κ_c

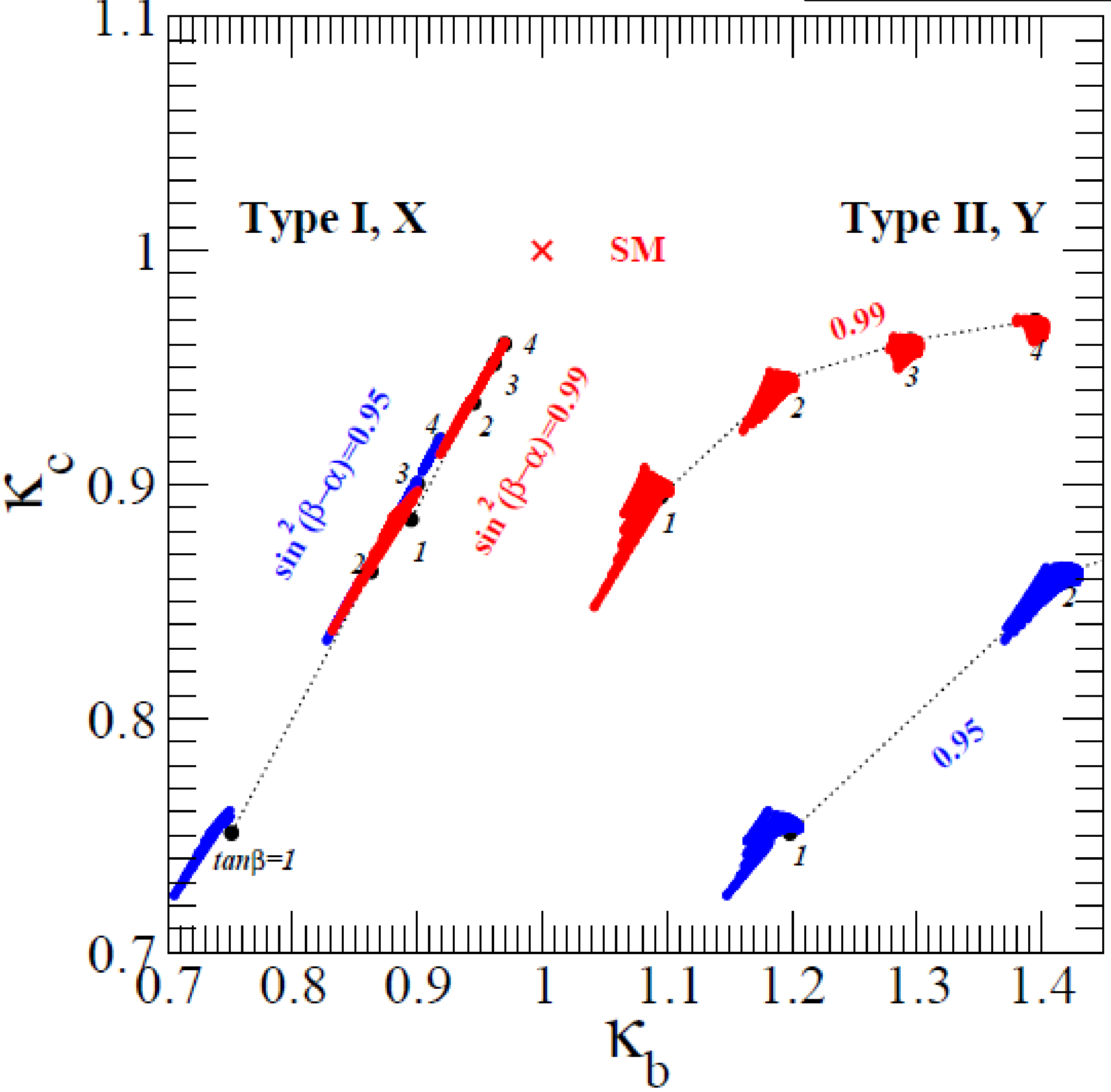
$\cos(\beta - \alpha) \leq 0$

- We perform a scan analysis for m_Φ and M.

$100 \text{ GeV} \leq m_\Phi \leq 1000$

$0 \leq M \leq m_\Phi$

We take into account constraints from the unitarity and the vacuum stability.



Kanemura, Kikuchi, Yagyu(2013)

1-loop level

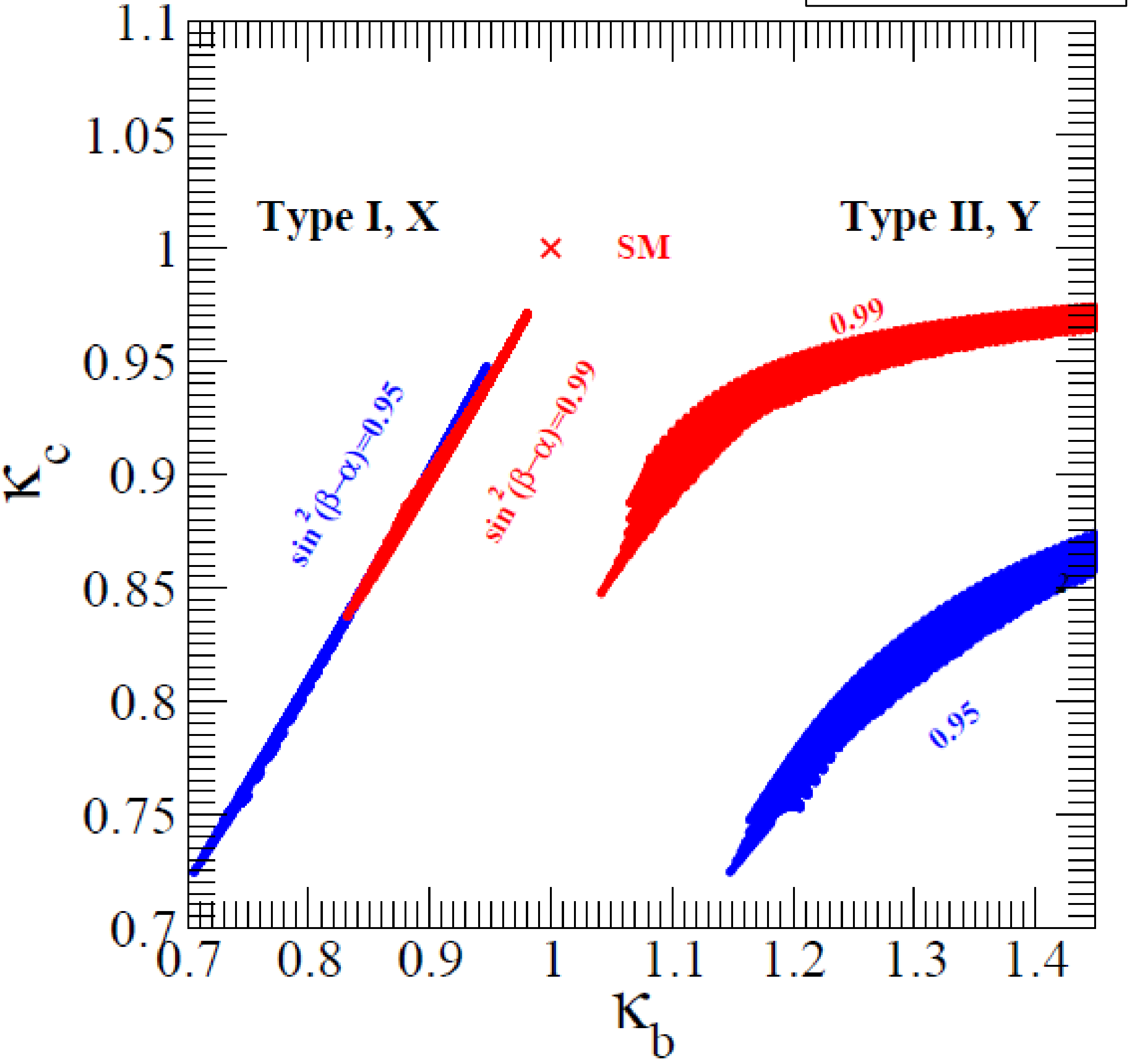
κ_b VS κ_c

cos(β－α) ≤ 0

- We perform a scan analysis for m_{Φ}, tanβ and M.

$100\ \text{GeV} \leq m_{\Phi} \leq 1000$
$0 \leq M \leq m_{\Phi}$
$1 \leq \tan\beta$

We take into account constraints from the unitarity and the vacuum stability.



Kanemura, Kikuchi, Yagyu(2013)

1-loop level

κ_b VS κ_c

cos(β − α) ≤ 0

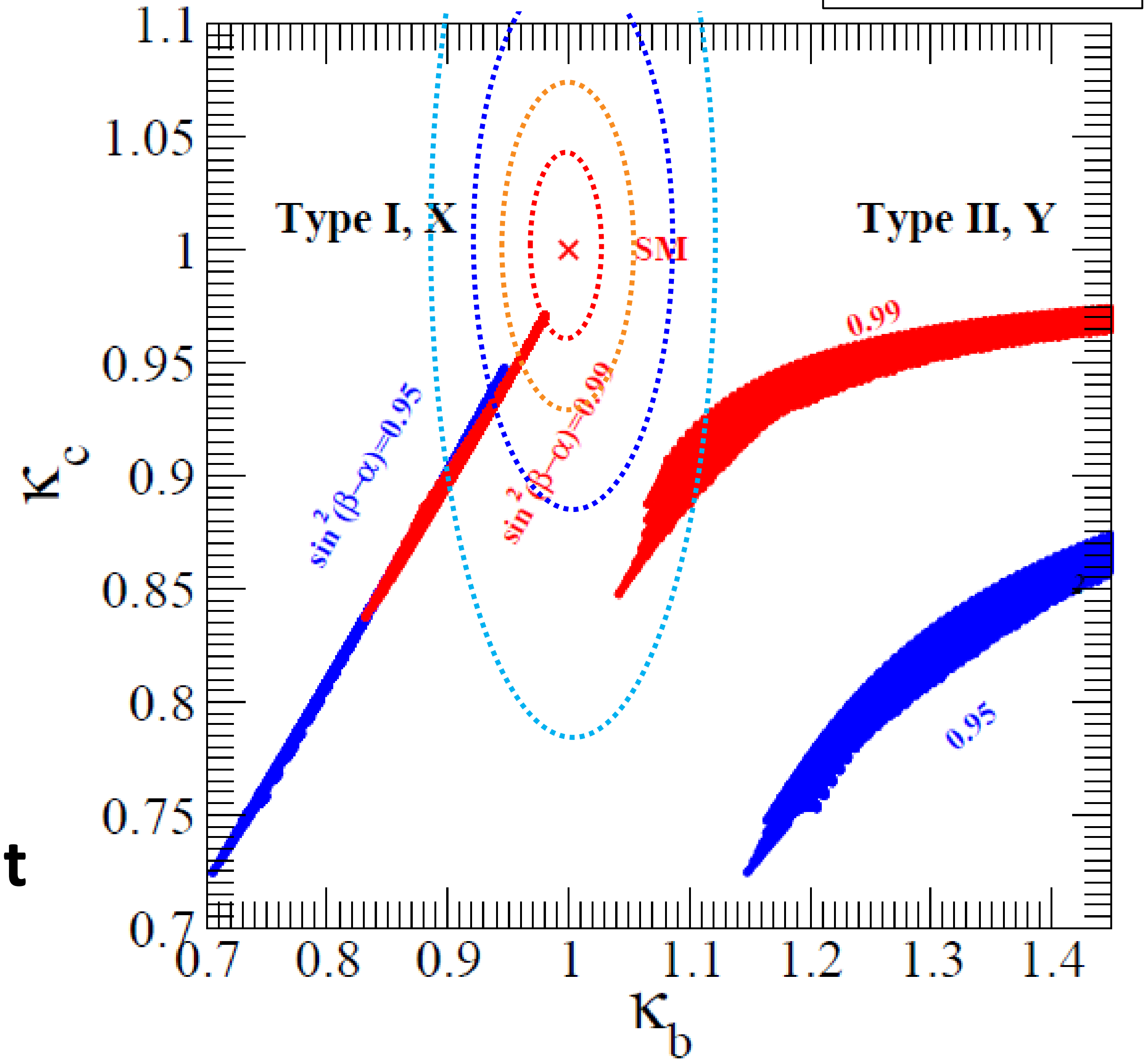
- - - - *LHC300*

- - - - *LHC3000*

- - - - *ILC250*

- - - - *ILC500*

(68%C.L.)



Kanemura, Kikuchi, Yagyu(2013)

We can measure detailed deviations at the ILC (E=250GeV,500GeV).

Summary

- **There is no principle for the minimal SM Higgs sector. Extended Higgs models can deviate *h*-couplings from the SM**
- **At the ILC, couplings of the SM-like Higgs boson (*h*) will be measured quite precisely**
- **For comparison with such future precision data, we evaluate EW radiative corrections to the *h*-couplings in 2HDMs with 4 types of Yukawa interactions**

hcc, hbb, hττ, hWW, hZZ, hγγ, hgg, hγZ, hhh

- **Even in the case with maximal non-decoupling loop effects, 4 types of Yukawa interactions can be well discriminated at the ILC, as long as the *hVV* coupling slightly differs from the SM value (**κ_V**<0.99 or more close to 1, but ≠1)**
- **We can make fingerprinting of new physics models at the ILC**

Higgs is a probe of new physics!!!

Back UP

Renormalization

$$\rho = \frac{m_W{}^2}{m_Z{}^2 cos^2\theta_W} = 1$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2},$$

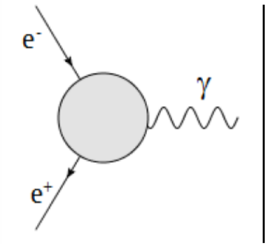
$$G_F = \frac{\pi\alpha_{em}}{\sqrt{2} m_W^2 \sin^2\theta_W}$$

➢ Kinetic term

- Parameters in Lagrangian ･･･ g, g', v
- Physical parameters ･･･ m_W , m_Z , $sin\theta_W$, G_F , α_{em} .
- Counter-terms ･･･ δm_W, δm_Z, δs_W, δG_F, $\delta\alpha_{em}$,
- Renormalized conditions ･･ $Re\Pi_{WW}(p^2)|_{p^2=m_W^2} = 0,$ $\delta m_W^2 = Re\Pi_{WW}^{1PI}(m_W^2),$

$$Re\Pi_{ZZ}(p^2)|_{p^2=m_Z^2} = 0, \qquad \delta m_Z^2 = Re\Pi_{ZZ}^{1PI}(m_Z^2),$$

On-shell conditions



$$= -ie\gamma^{\mu}$$

$$\frac{\delta\alpha_{em}}{\alpha_{em}} = \frac{d}{dp^2}\Pi_{\gamma\gamma}^{1PI}(p^2)|_{p^2=0} - \frac{2s_W}{c_W}\frac{\Pi_{\gamma Z}^{1PI}(0)}{m_Z^2}$$

- Counter term of v

$$v^2 = \frac{m_W{}^2 \, sin^2\vartheta_W}{\pi \, \alpha_{em}} \Rightarrow \frac{\delta v}{v} = \frac{1}{2}\left(\frac{\delta m_W^2}{m_W^2} - \frac{\delta\alpha_{\rm em}}{\alpha_{\rm em}} + \frac{\delta s_W^2}{s_W^2}\right)$$

Deviations in *hff*

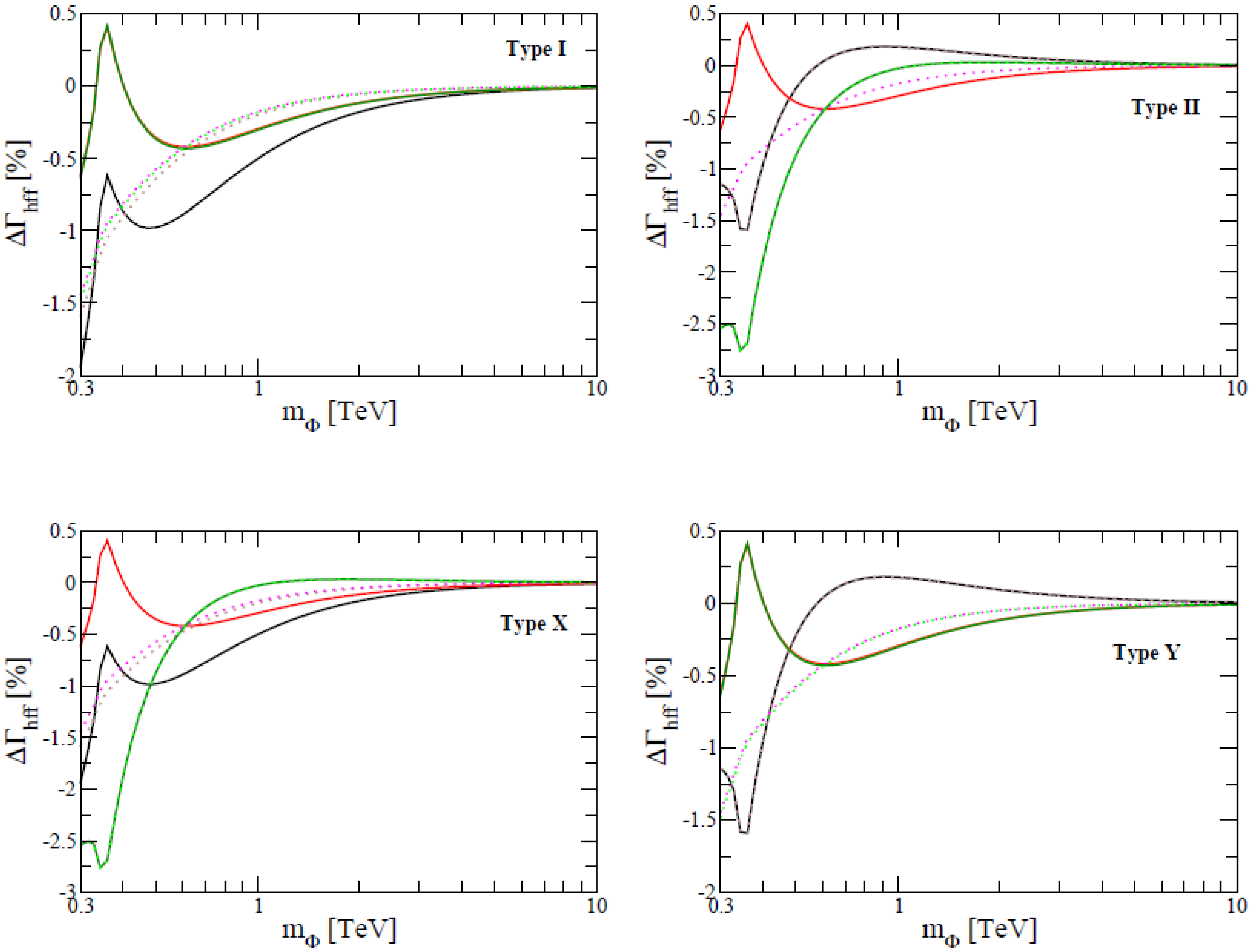
Kanemura, Kikuchi, Yagyu(2013)

$\sin^2(\beta - \alpha) = 1$

— $\tan\beta = 1$

--- $\tan\beta = 3$

$M^2 = m_\Phi^2 - (300\text{GeV})^2$



Deviations in *hff*

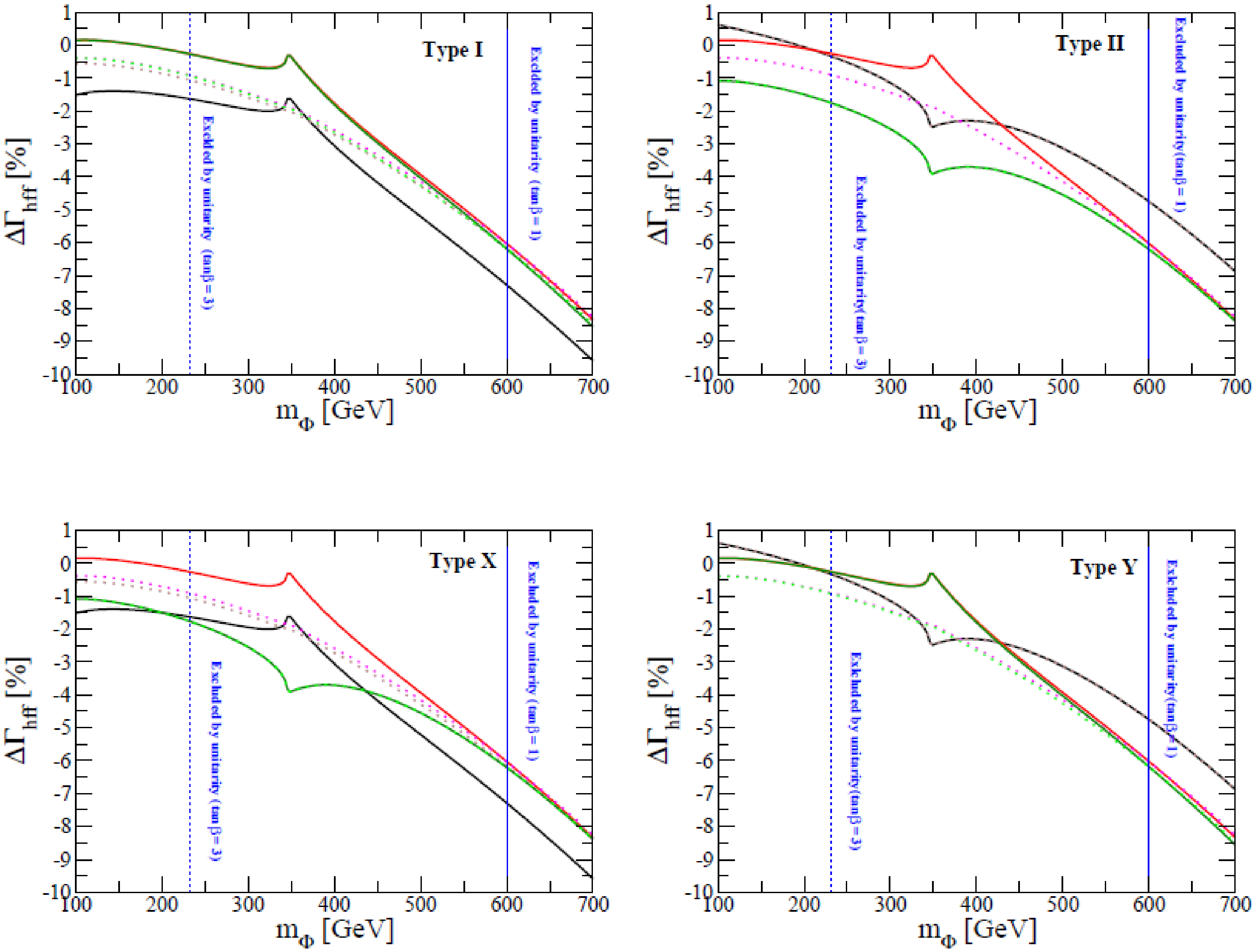
$\sin^2(\beta-\alpha)=1$

— tanβ=1

--- tanβ=3

Kanemura, Kikuchi, Yagyu(2013)

M = 0



Deviations in *htt*

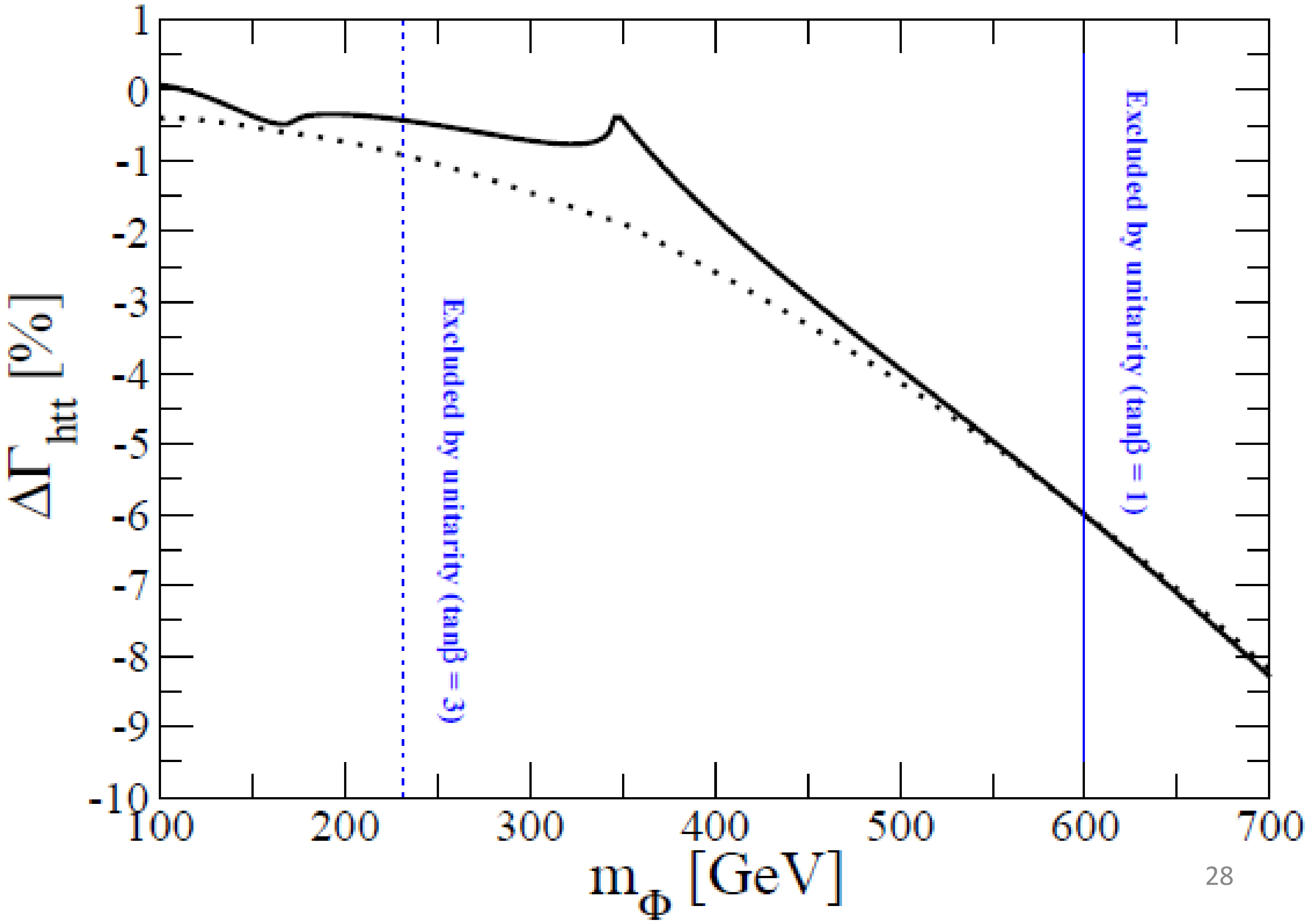
$\sin^2(\beta - \alpha) = 1$

— tanβ=1

--- tanβ=3

M = 0

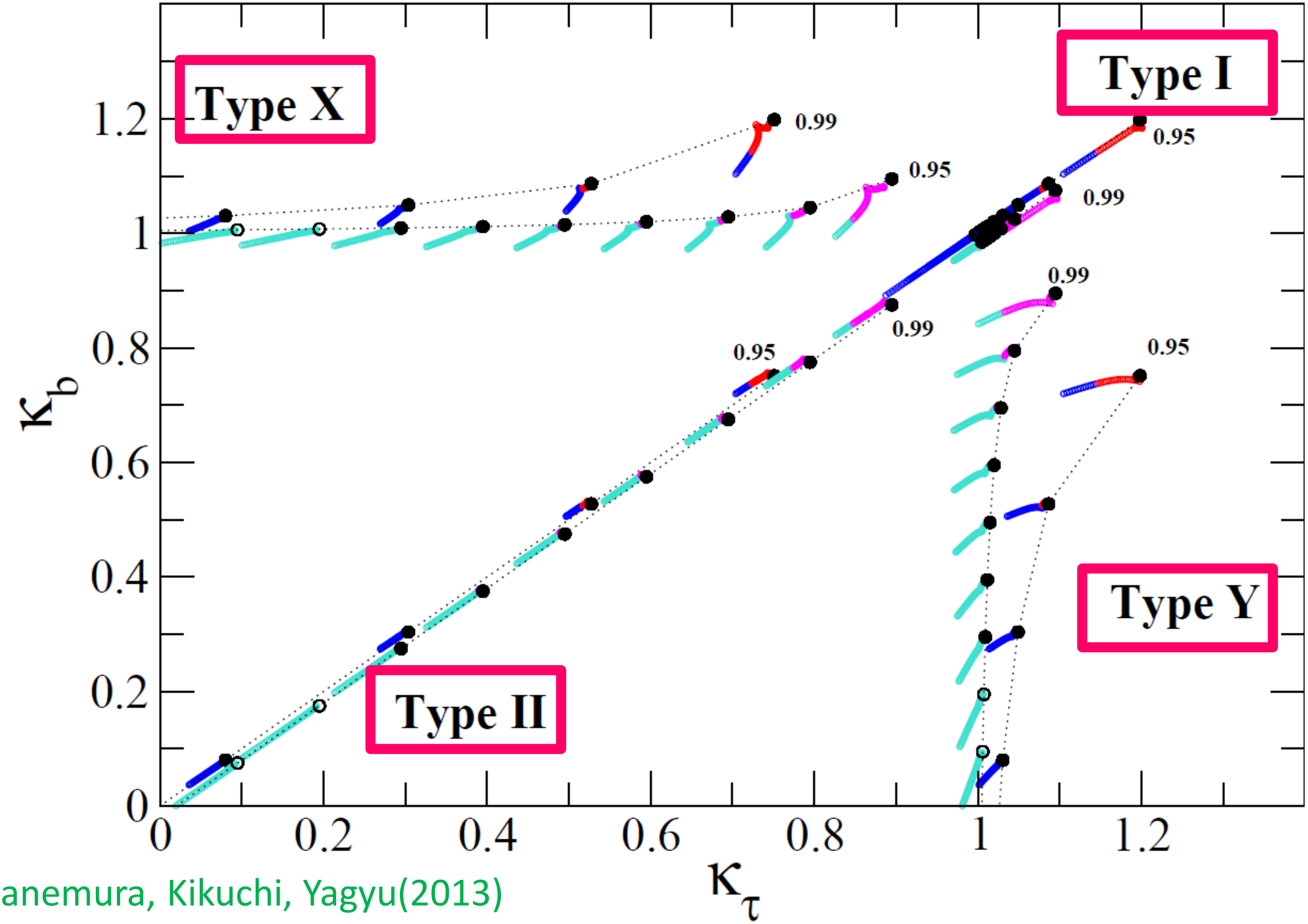
Kanemura, Kikuchi, Yagyu(2013)



κτ vs *κb*

cos(β − α) ≥ 0

M = 0

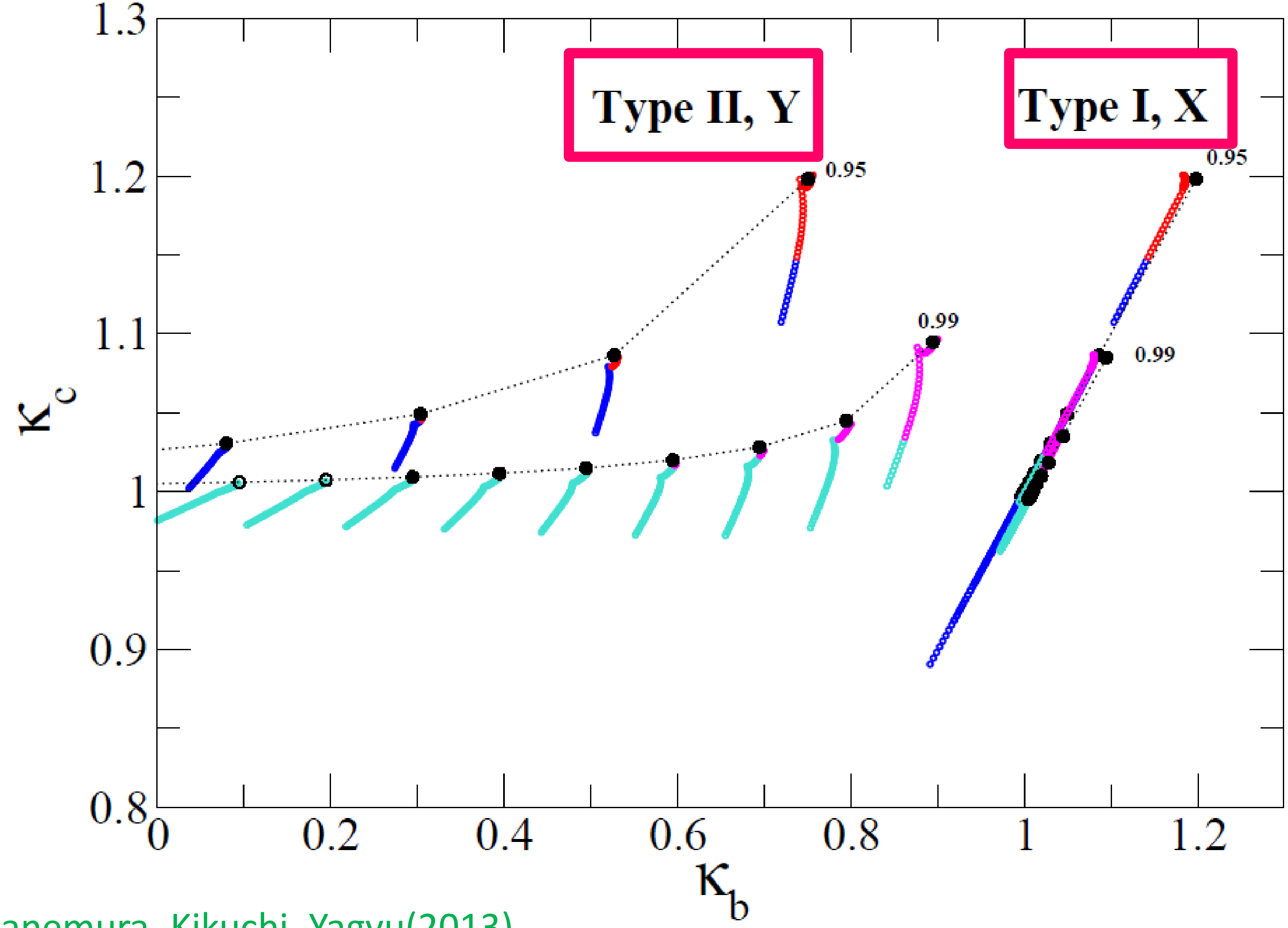


Kanemura, Kikuchi, Yagyu(2013)

κc vs *κb*

cos(β − α) ≥ 0

M = 0

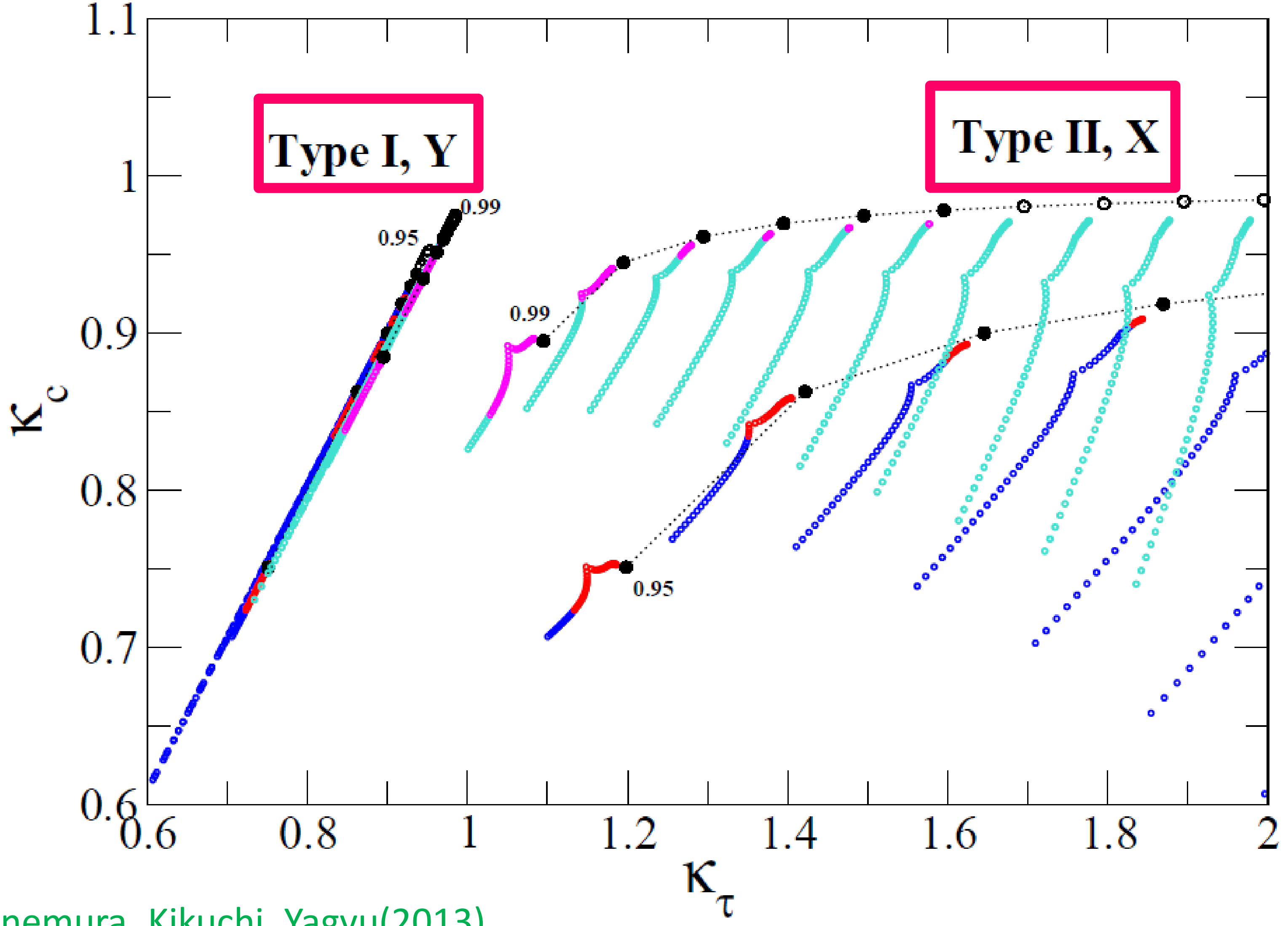


Kanemura, Kikuchi, Yagyu(2013)

$\kappa\tau$ VS κc

$\cos(\beta - \alpha) \leq 0$

$M = 0$

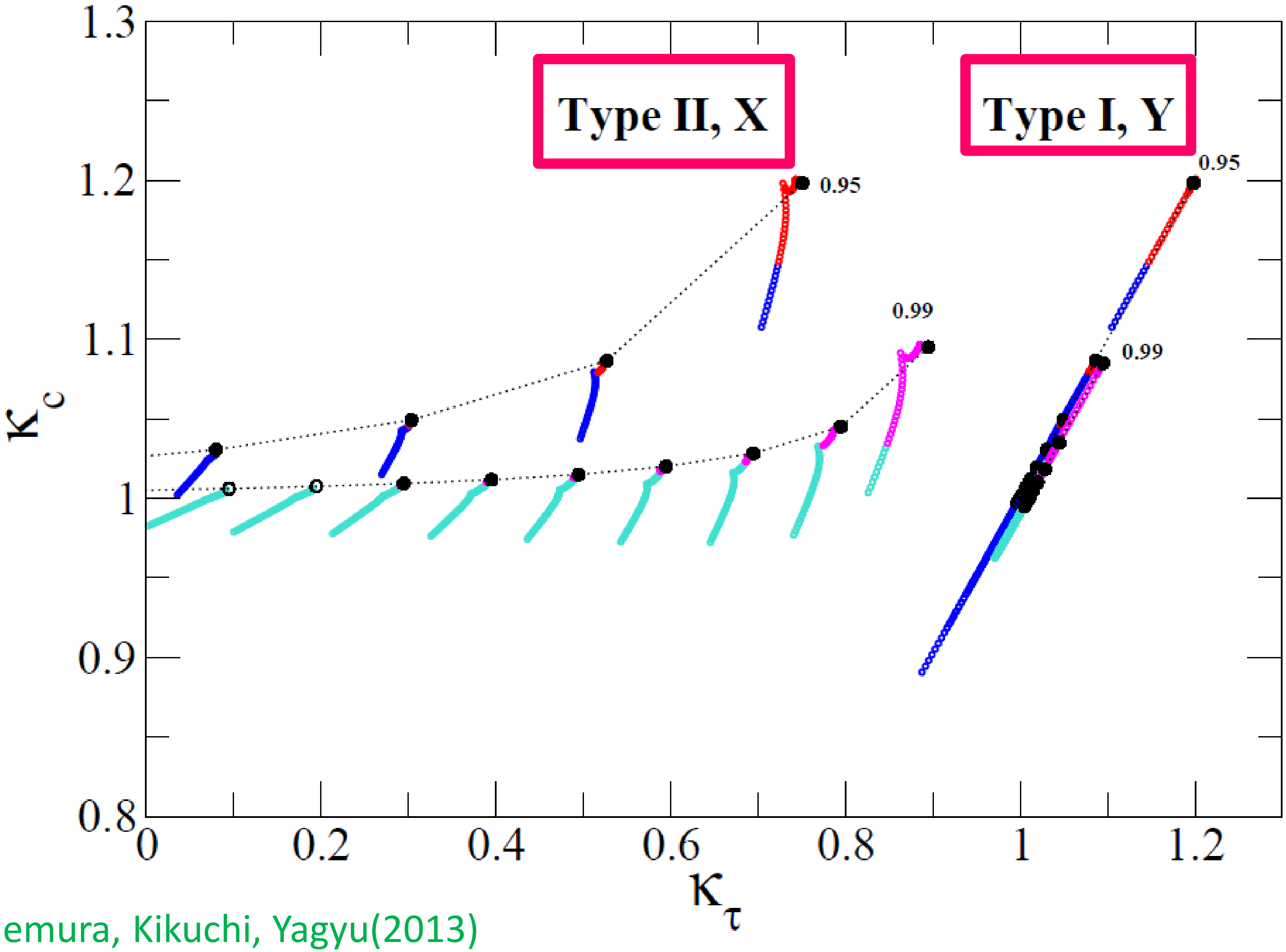


Kanemura, Kikuchi, Yagyu(2013)

κτ VS κc

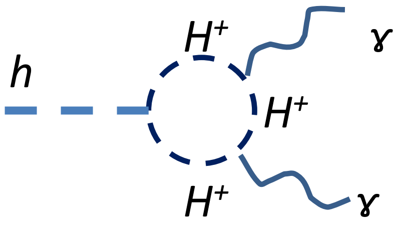
cos(β − α) ≥ 0

M = 0

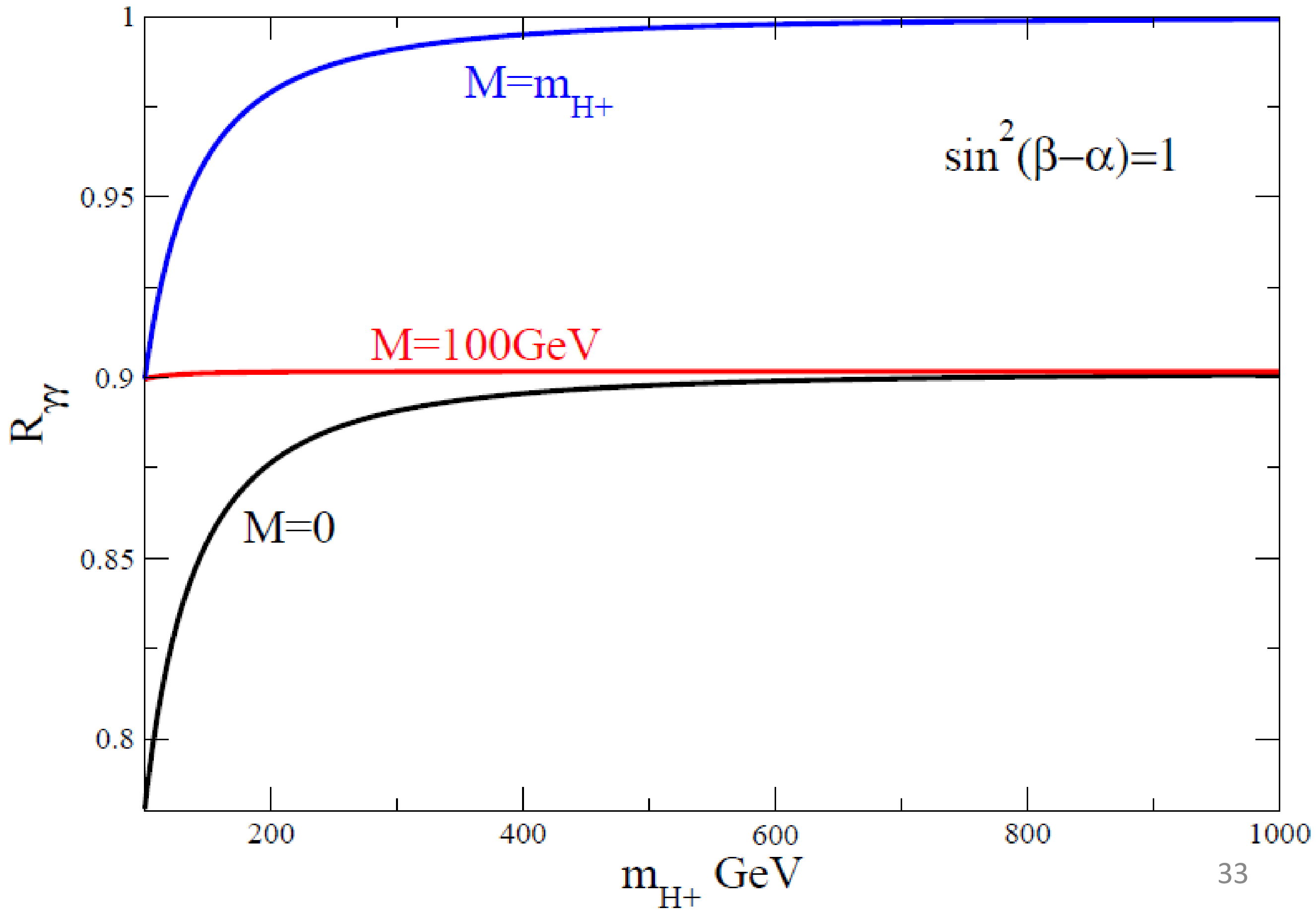


Kanemura, Kikuchi, Yagyu(2013)

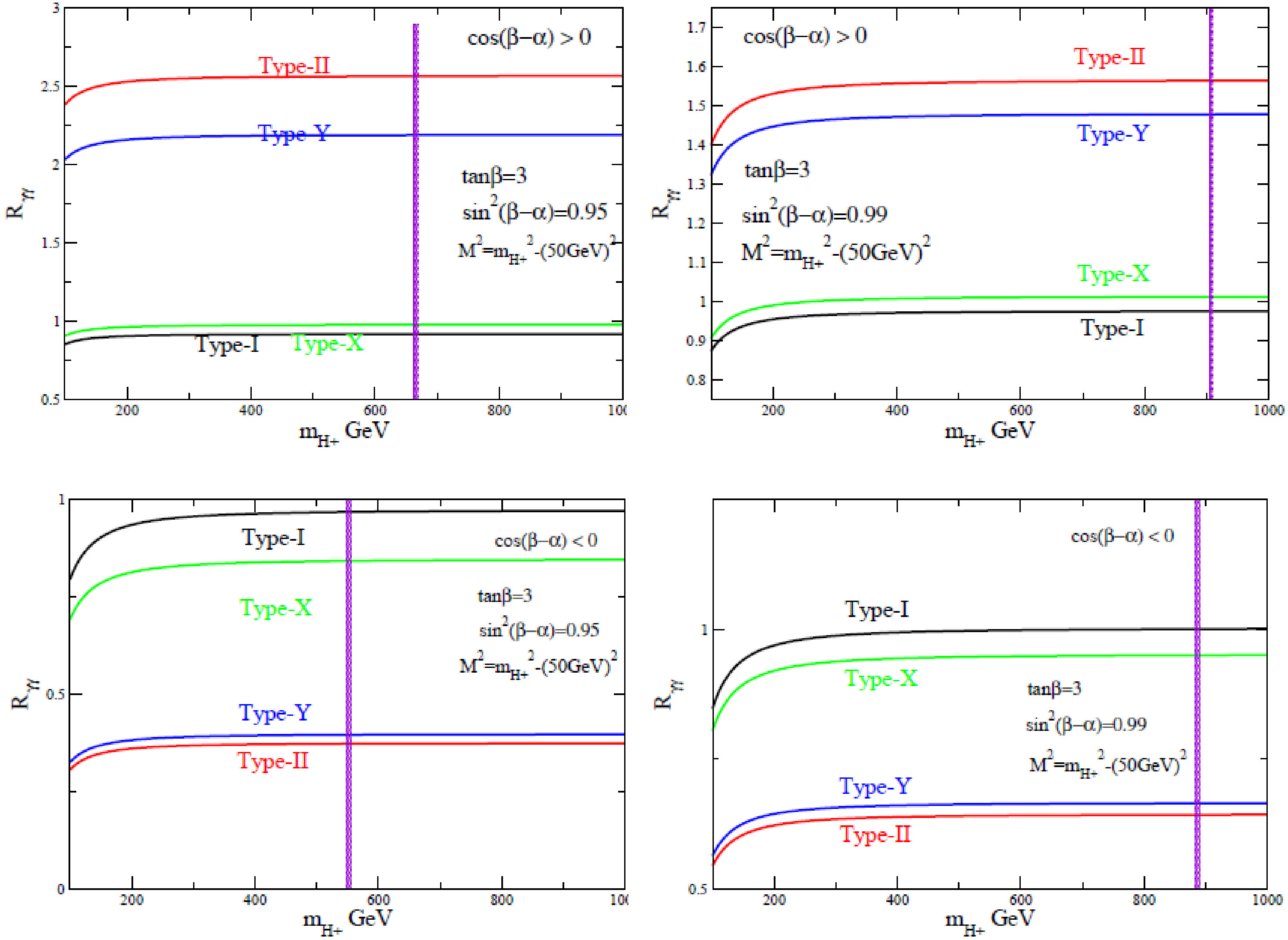
$R_{\gamma\gamma}$ *in* $\sin^2(\beta-\alpha)=1$

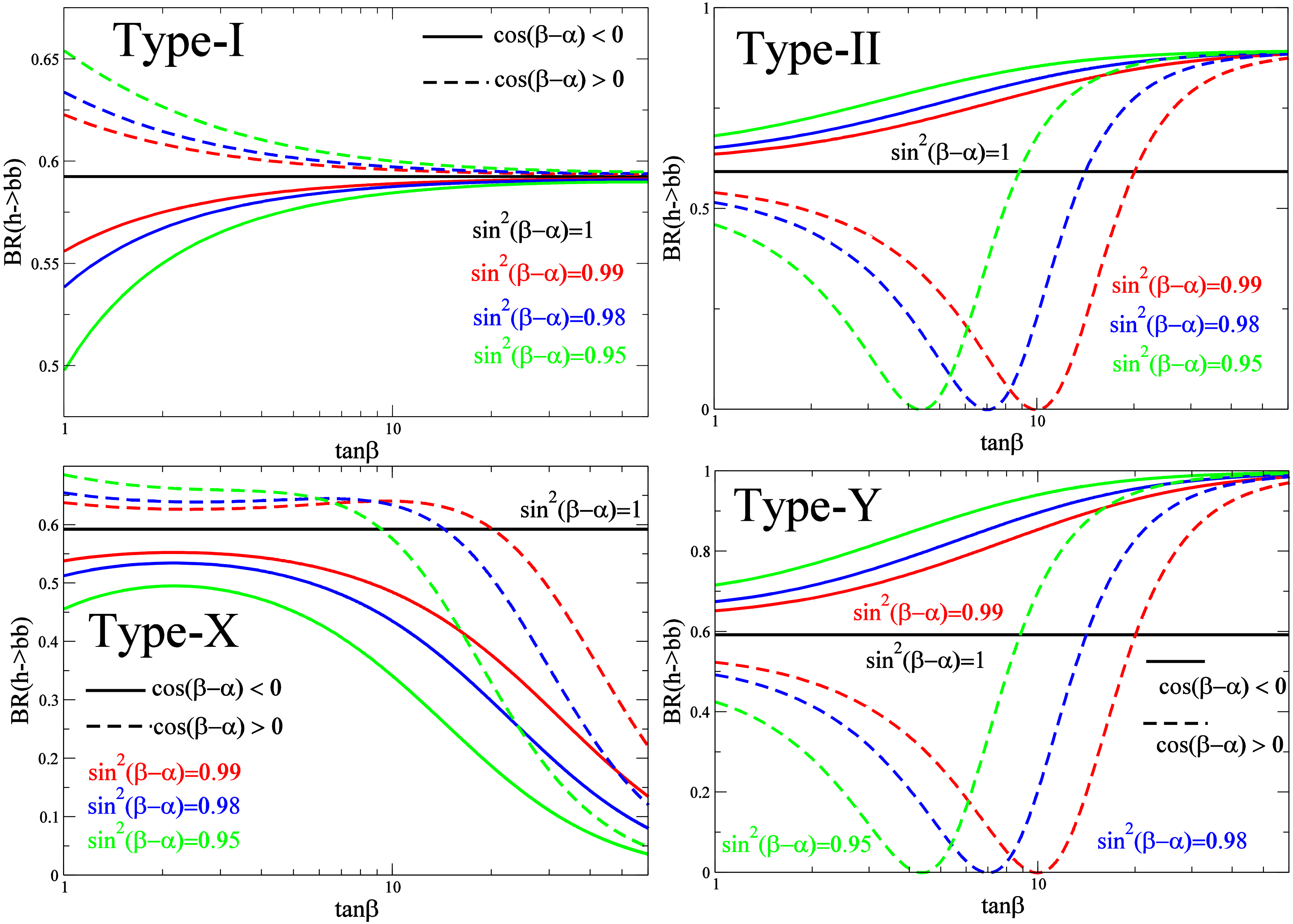


$$\lambda_{hH+H-} = M^2 + v^2\lambda'$$

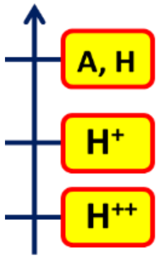


Mass dependence of $R_{\gamma\gamma}$



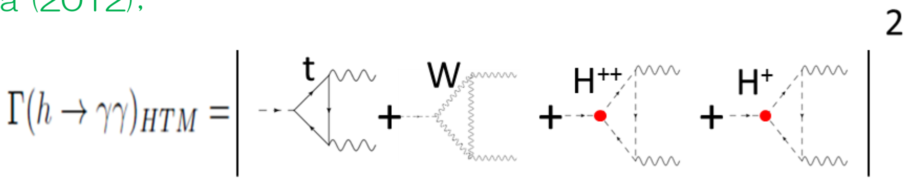

Type-I
cos(β−α) < 0
cos(β−α) > 0
$\sin^2(\beta-\alpha)=1$
$\sin^2(\beta-\alpha)=0.99$
$\sin^2(\beta-\alpha)=0.98$
$\sin^2(\beta-\alpha)=0.95$
BR(h->bb)
0.65
0.6
0.55
0.5
1
10
tanβ
Type-II
$\sin^2(\beta-\alpha)=1$
$\sin^2(\beta-\alpha)=0.99$
$\sin^2(\beta-\alpha)=0.98$
$\sin^2(\beta-\alpha)=0.95$
BR(h->bb)
1
0.5
0
1
10
tanβ
Type-X
$\sin^2(\beta-\alpha)=1$
cos(β−α) < 0
cos(β−α) > 0
$\sin^2(\beta-\alpha)=0.99$
$\sin^2(\beta-\alpha)=0.98$
$\sin^2(\beta-\alpha)=0.95$
BR(h->bb)
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
tanβ
Type-Y
$\sin^2(\beta-\alpha)=0.99$
$\sin^2(\beta-\alpha)=1$
cos(β−α) < 0
cos(β−α) > 0
$\sin^2(\beta-\alpha)=0.95$
$\sin^2(\beta-\alpha)=0.98$
BR(h->bb)
1
0.8
0.6
0.4
0.2
0
1
10
tanβ

Ratio of the event rate for $h\to\gamma\gamma$

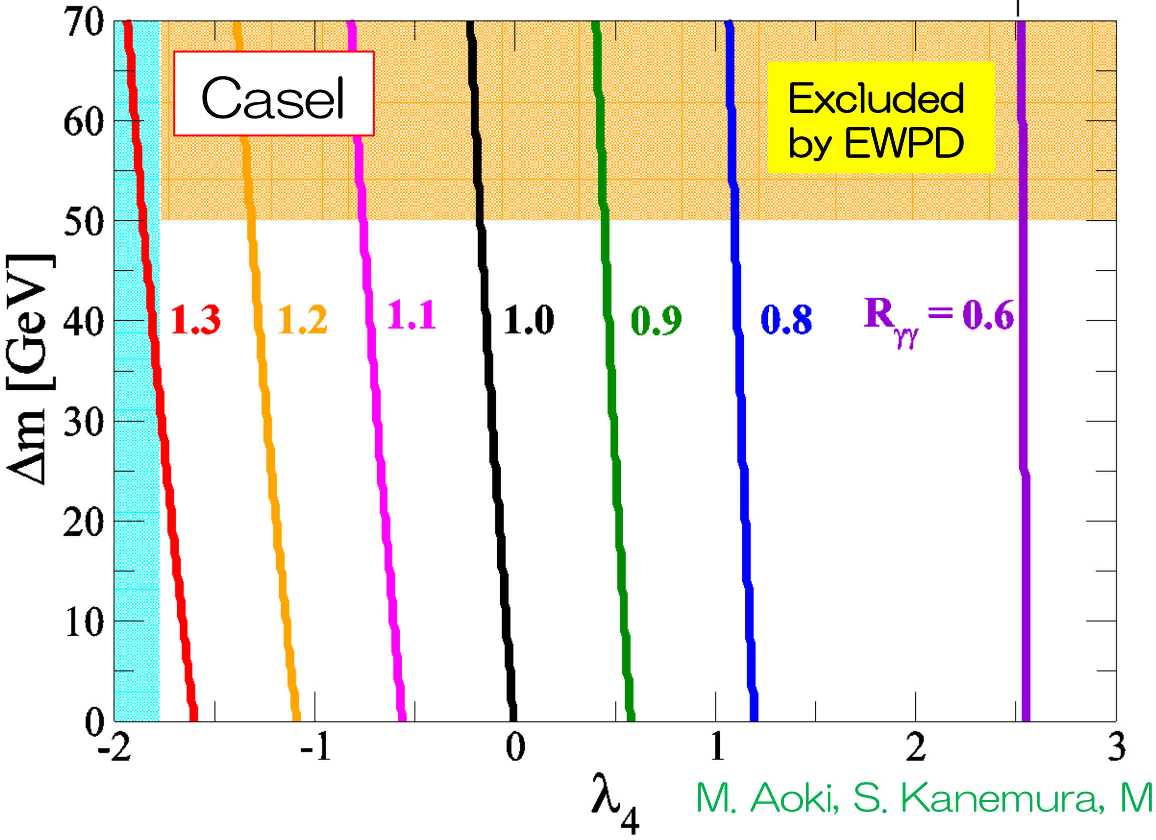


A. Arhrib, R. Benbrik, M. Chabab, G. Moultaka (2012);
A. G. Akeroyd, S. Moretti (2012);

$m_{H^{++}}$=300GeV, v_Δ=1MeV



$\Gamma(h\to\gamma\gamma)_{HTM} = \left| \cdots + \cdots + \cdots + \cdots \right|^2$



M. Aoki, S. Kanemura, M. K, K. Yagyu (2013)

$R_{\gamma\gamma}$ depends on λ_4.

$$\lambda_{hH^{++}H^{--}} \approx -\lambda_4 v$$

$$\lambda_{hH^{+}H^{-}} \approx -(\lambda_4 + \frac{\lambda_5}{2})v$$

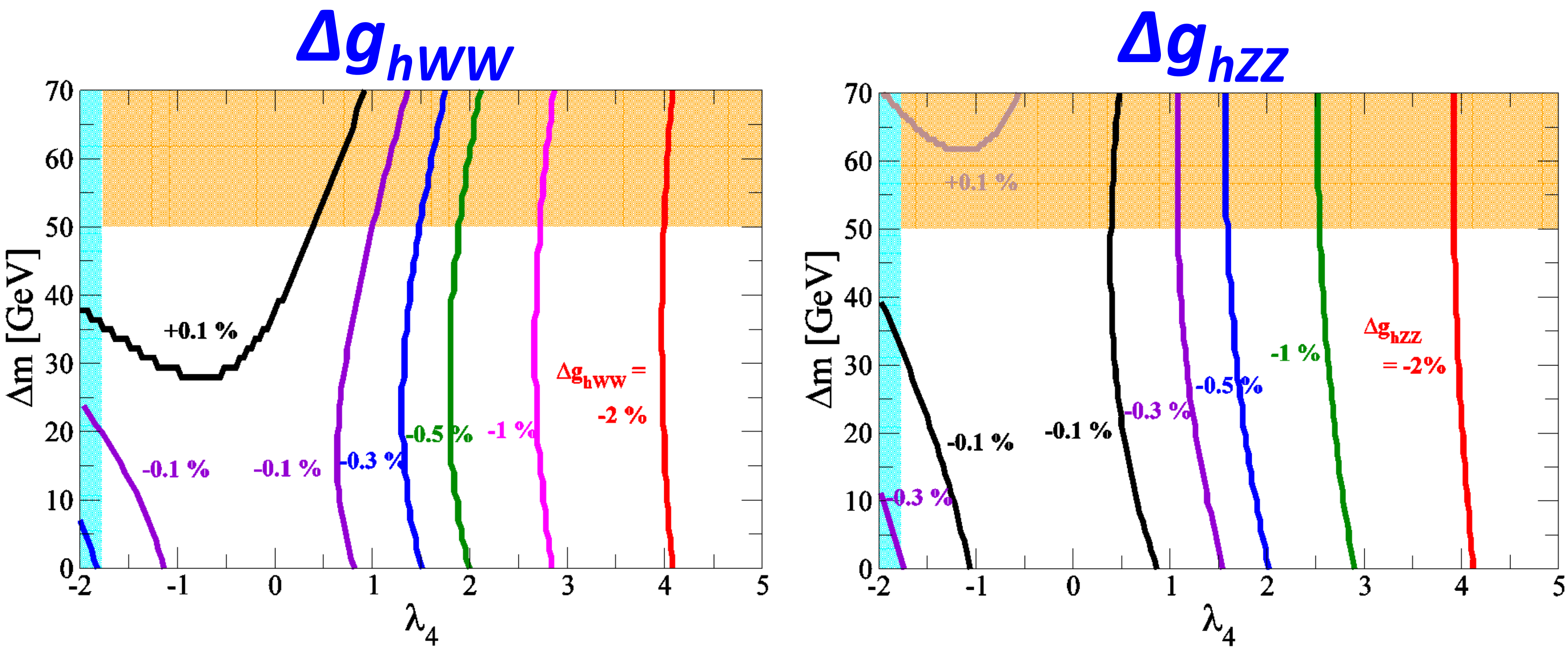
$R_{\gamma\gamma}$ can be enhanced or reduced depending on the sign of $\lambda_{hH^{++}H^{--}}$.

Deviations for *hVV*

$$\Delta g_{hVV} \equiv \frac{\mathrm{Re}M_1^{hVV} - \mathrm{Re}M_1^{hVV}(\mathrm{SM})}{\mathrm{Re}M_1^{hVV}(\mathrm{SM})}$$

CaseI

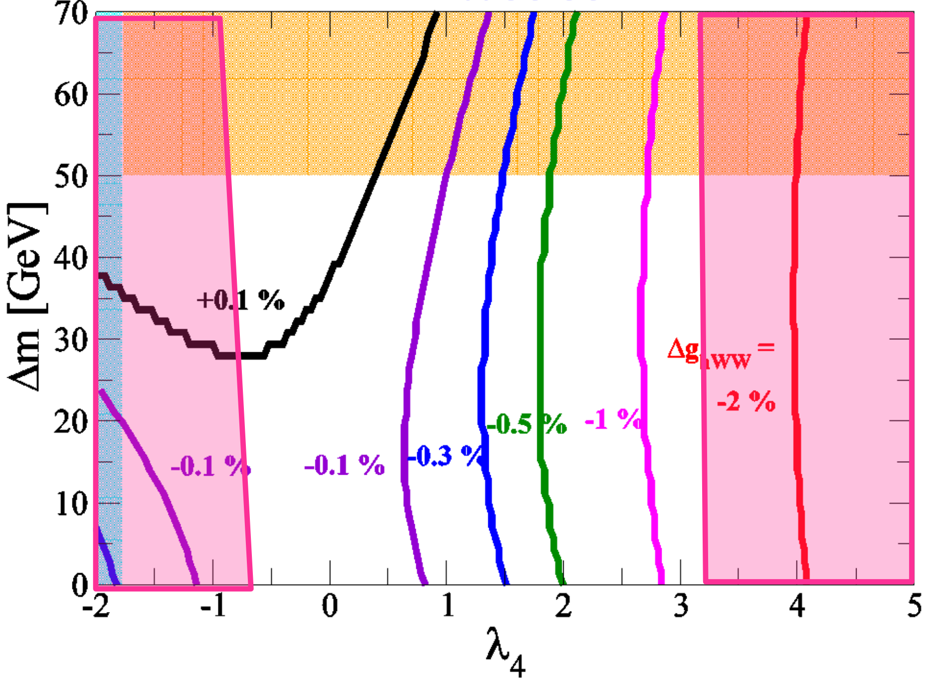
$m_{H^{++}}$=300GeV, v_Δ=1MeV



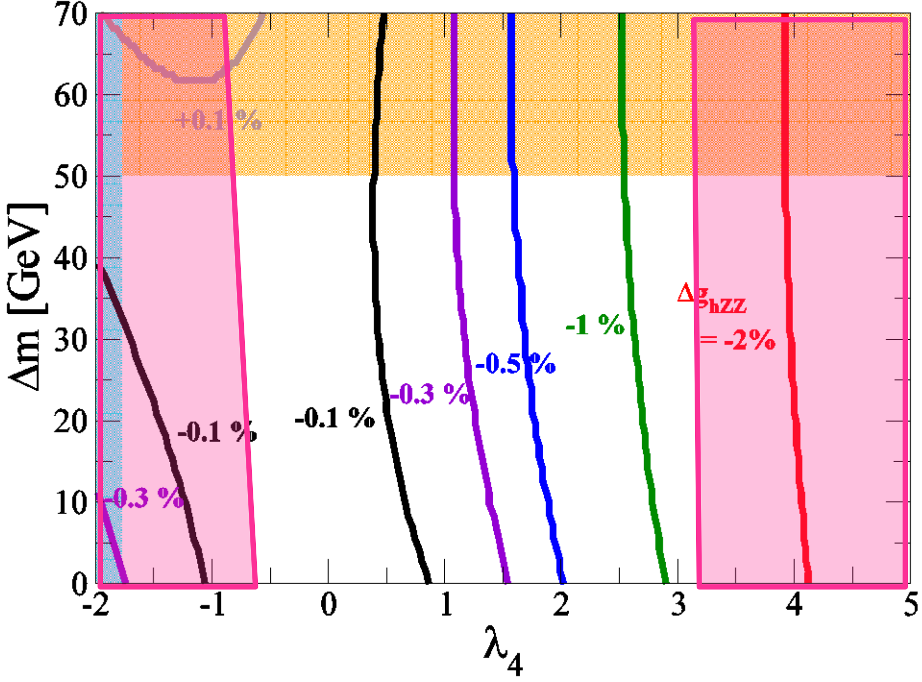
M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu (2013)

Deviations for *hWW* from the SM predictions can be several %.

If we take into account the CMS data for $R_{\gamma\gamma}$, pink regions are excluded.



Δg_{hWW}



Δg_{hZZ}

M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu (2013)

Δg_{hVV} can be 1%.

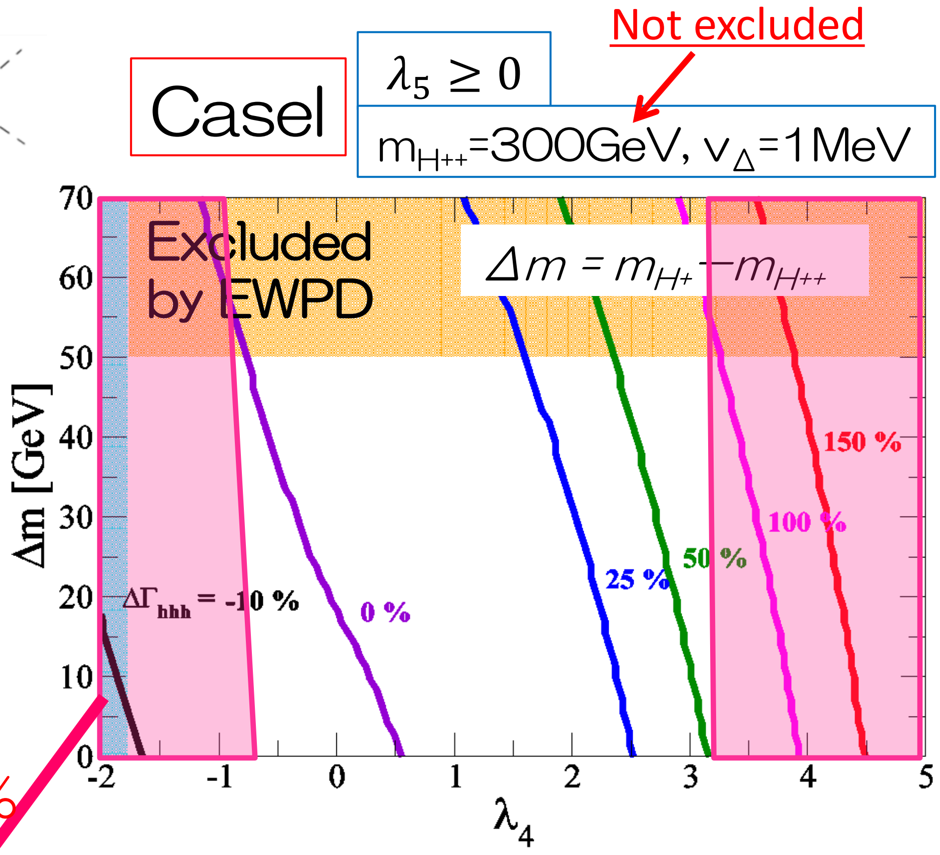
hhh

- Deviations for *hhh* from the SM predictions

$$\Delta\Gamma_{hhh} \equiv \frac{\mathrm{Re}\Gamma_{hhh} - \mathrm{Re}\Gamma_{hhh}^{\mathrm{SM}}}{\mathrm{Re}\Gamma_{hhh}^{\mathrm{SM}}}$$

$$\Delta\Gamma_{hhh} \simeq \frac{-v}{48\pi^2 m_h{}^2}\left(\frac{\lambda_{H++H--h}{}^3}{m_{H++}{}^2} + \frac{\lambda_{H+H-h}{}^3}{m_{H+}{}^2} + \frac{4\lambda_{hAA}{}^3}{m_A{}^2} + \frac{4\lambda_{hHH}{}^3}{m_H{}^2}\right)$$

$$\simeq \frac{v^4}{48 m_h{}^2\pi^2}\left[\frac{\lambda_4{}^3}{m_{H++}{}^2} + \frac{\left(\lambda_4+\frac{\lambda_5}{2}\right)^3}{m_{H+}{}^2} + \frac{(\lambda_4+\lambda_5)^3}{2m_A{}^2} + \frac{(\lambda_4+\lambda_5)^3}{2m_H{}^2}\right]$$



M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu (2013)

Deviations in hhh coupling from the SM prediction can be -10 %~ +150%

If we take into account results of $R_{\gamma\gamma}$, pink region is excluded.

$\Delta\Gamma_{hhh}$ can be 50%. → Deviations are detectable at ILC !

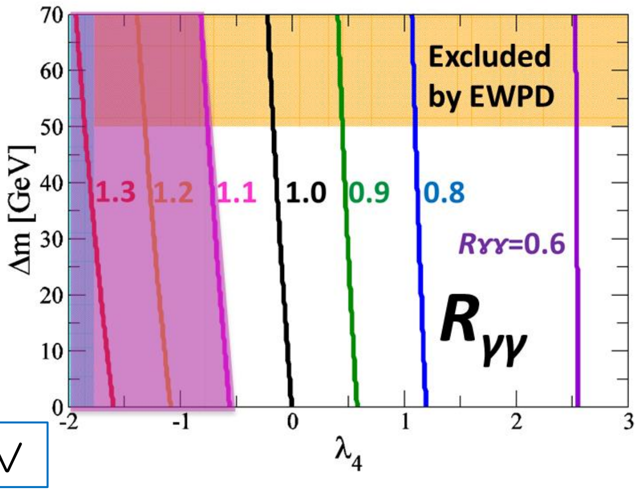
Aoki, Kanemura, M. K. , Yagyu(2012)

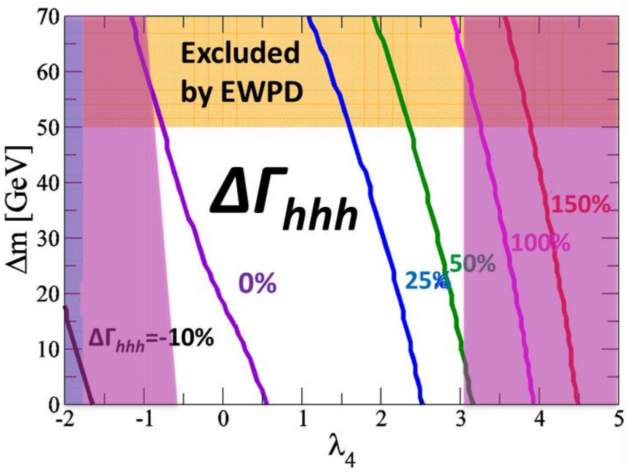
Correlations of the deviation

Contributions to $R_{\gamma\gamma}$ is opposite to one of $\Delta\Gamma_{hhh}$.

Case-I

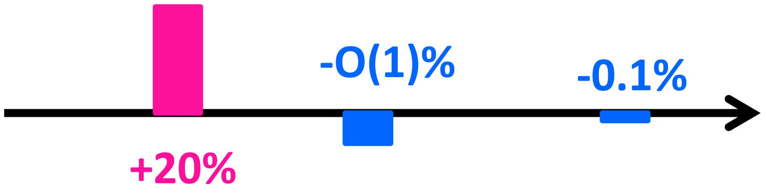
$\Delta m = m_{H+} - m_{H++}$



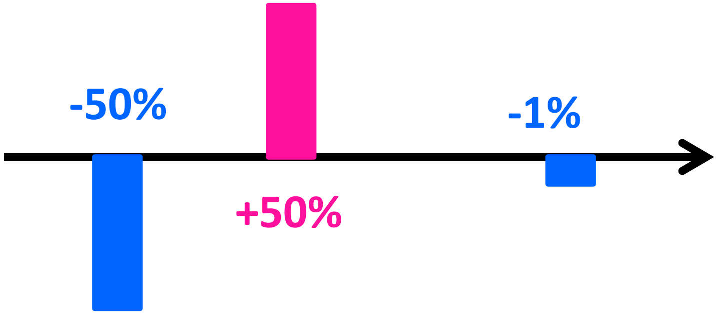


$m_{lightest}$=300GeV, v_Δ=1MeV

$\lambda_4 = -0.5$ $R_{\gamma\gamma}$ $\Delta\Gamma_{hhh}$ $\Delta g_{hWW}, \Delta g_{hZZ}$



$\lambda_4 = 3$ $R_{\gamma\gamma}$ $\Delta\Gamma_{hhh}$ $\Delta g_{hWW}, \Delta g_{hZZ}$



There is a correlation in deviations in $h\gamma\gamma$ and hhh.
By detecting this, we can discriminate the model from the others.

hhh

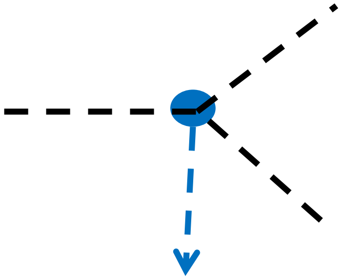
$$m_{H++}{}^2 \simeq M^2 + \frac{1}{2}\lambda_4 v^2$$

$$m_{H+}{}^2 \simeq M^2 + (\frac{1}{2}\lambda_4 + \frac{1}{4}\lambda_5)v^2$$

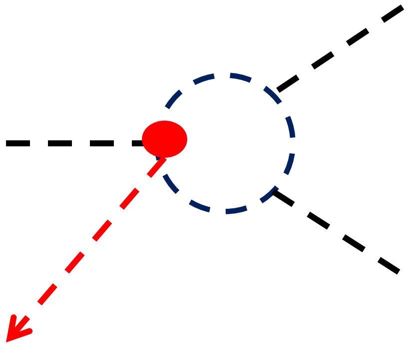
$$m_A{}^2 \simeq m_H{}^2 \simeq M^2 + \frac{1}{2}(\lambda_4 + \lambda_5)v^2$$

$$\lambda^{eff}_{hhh}(THDM) = \frac{3m_h^2}{v}\left\{1 + \frac{m_H^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_H^2}\right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_A^2}\right)^3 + \frac{m_{H\pm}^4}{6\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_{H\pm}^2}\right)^3 - \frac{N_{c_t} m_t^4}{3\pi^2 m_h^2 v^2} + \mathcal{O}\left(\frac{p_i^2 m_\Phi^2}{m_h^2 v^2}, \frac{m_\Phi^2}{v^2}, \frac{p_i^2 m_t^2}{m_h^2 v^2}, \frac{m_t^2}{v^2}\right)\right\},$$

Coupling parameters of the loop diagrams are different from the one of the tree diagram.
So, deviations by loop correction can be large.



$$\lambda_{hhh} \simeq -\lambda_1 v$$



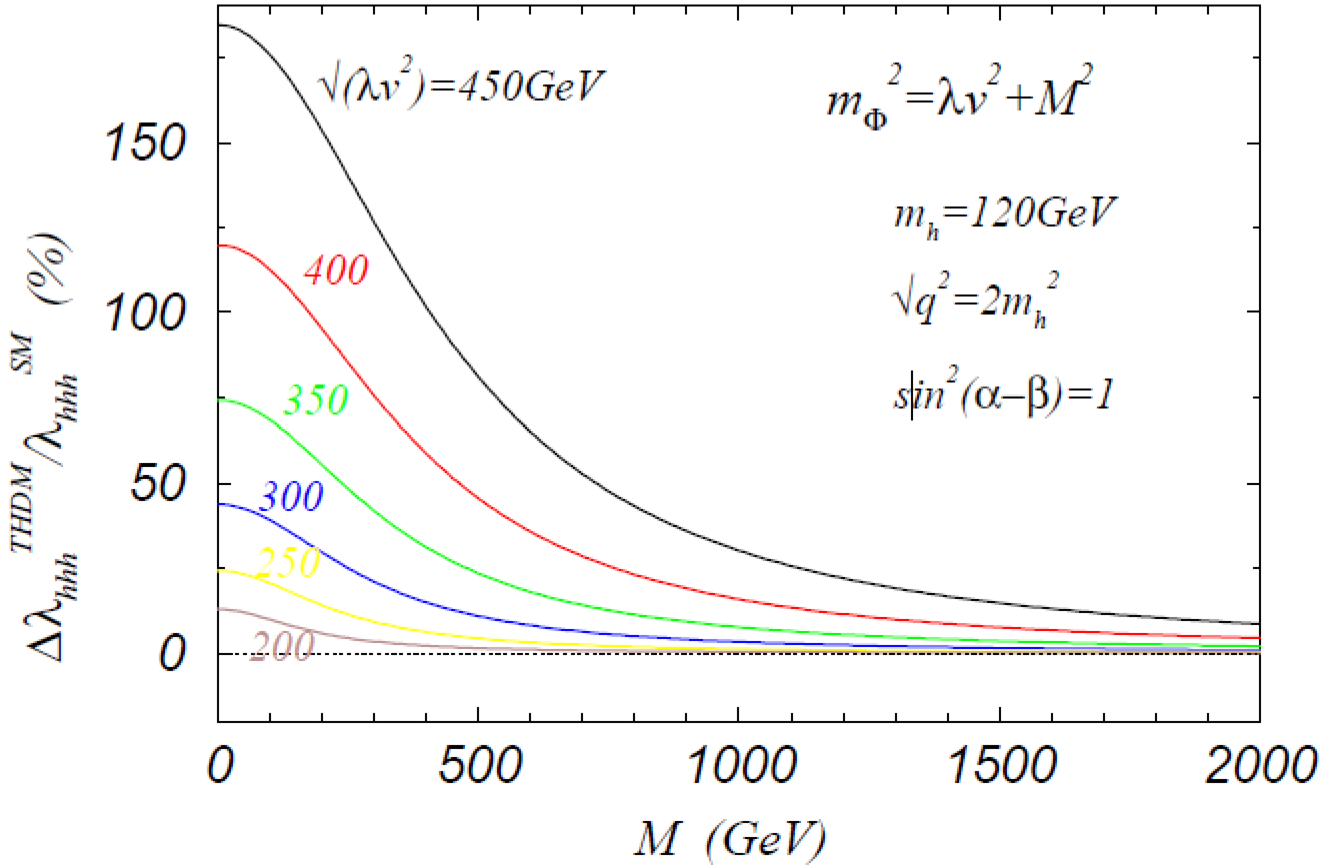
$$\lambda_{hH{+}{+}H{-}{-}} \simeq -\lambda_4 v$$

$$\lambda_{hH+H-} \simeq -\left(\lambda_4 + \frac{1}{2}\lambda_5\right)v$$

$$\lambda_{hAA} \simeq \lambda_{hH+H-} \simeq -\frac{1}{2}(\lambda_4 + \lambda_5)v$$

2HDM の *hhh*結合

Kanemura, Okada, Senaha, Yuan (2004)



$$m_\Phi^2 = \lambda v^2 + M^2$$

FCNC Suppression

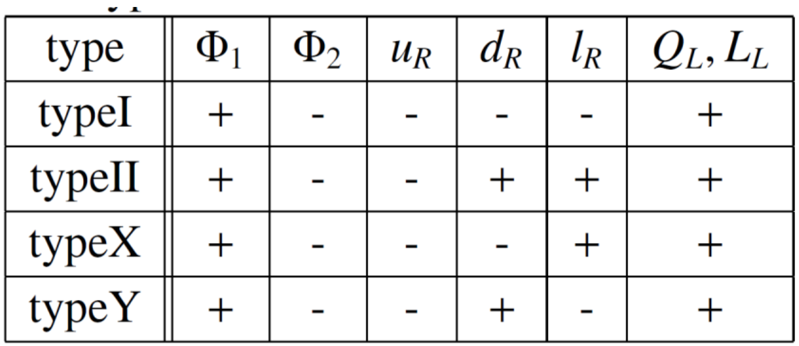
The mechanism suppressed FCNC is required in multi Higgs models.

ex) 2 Higgs doublet models:

- discrete symmetry

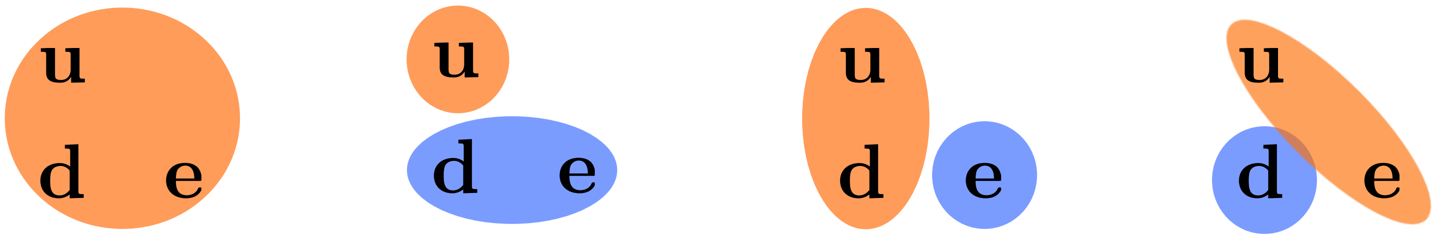
$\Phi_1 \rightarrow +\Phi_{1,} \qquad \Phi_2 \rightarrow -\Phi_2$

Barger, Hewett, Phillips



type	Φ_1	Φ_2	u_R	d_R	l_R	Q_L, L_L
typeI	+	-	-	-	-	+
typeII	+	-	-	+	+	+
typeX	+	-	-	-	+	+
typeY	+	-	-	+	-	+

Four types of Yukawa interaction



Type-I **Type-II** **Type-X** **Type-Y**

Fermio-phobic 2HDM
Neutrino-phillic 2HDM

MSSM,
NMSSM

Lepton-specific 2HDM,
Radiative seesaw

Flipped 2HDM

Characteristic of couplings

2HDM | **Higgs triplet model**

hff

Yukawa couplings

	c	b	τ
I	↓	↓	↓
II	↓	↑	↑
X	↓	↓	↑
Y	↓	↑	↓

cos(β-α)<0

Each type has a different pattern of deviations.

①$v_\Delta / v_\phi \ll 1$

→ **Mixing is very small.**

②Fermion don't couple to Δ.

Deviations are very small.

hVV

Gauge couplings

< Multi-doublet model >

$$g_{hVV} = {g_{hVV}}^{SM} \times \kappa_{hVV}$$

$$\kappa_{hVV} = -\sin\alpha \cos\beta + \cos\alpha \sin\beta$$

$$\kappa_{hVV} \leqq 1$$

Gauge couplings can be larger than SM predictions because of CG coefficient.

$$\kappa_{hWW} = \cos\beta \cos\alpha + \sqrt{2} \sin\beta \sin\alpha$$

$\kappa_{hVV} \geqq$ **1 is possible**