Radiative corrections to Higgs coupling constants in two Higgs doublet models

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S. Kanemura, M. Kikuchi, K. Yagyu, Physics Letters B731 (2014) 27-35

ICHEP2014, Valencia, 2014/07/02 - 09

Contents

Introduction

- Is there only one Higgs boson ? No principle for SM Higgs !
- There is a possibility of an extended Higgs sector.
- Only experiment can determine the Higgs sector.

New physics scenarios often require extended Higgs sectors

B-L Gauge, Dark Matter, ···	● Φ (Doublet) + S (Singlet)
MSSM, Dark Matter, m_ν (Radiative Seesaw), ···	● Φ (Doublet) + Φ′ (Doublet)
m_ν (Type II Seesaw), LR models, ···	● Φ (Doublet) + Δ (Triplet)

The Higgs sector is a probe of new physics!

How we can explore the second Higgs boson ?

- Direct discovery of extra Higgs bosons (H, A, H^+, $H^{++}\cdots$) at LHC
- Indirect searches via precision measurements of couplings of the discovered (SM-like) Higgs boson h (hVV, hff, hhh,$\cdots$)
- These couplings can deviate from the predictions in SM by new physics effects.

  Pattern in deviations depends on the model !
- Higgs couplings can be measured with high precision by future pp and e^+e^- colliders (HL-LHC, ILC, TLEP, ⋯).
- Higgs sector can be determined by comparing precision measurements with precise calculation with radiative corrections.

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

Two Higgs doublet models

Φ_1, Φ_2 (I=1/2, Y=1/2)

In general, there is the possibility to cause dangerous FCNCs.

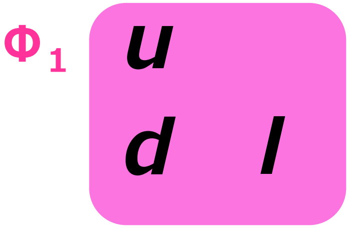
To avoid FCNCs, Φ_1 and Φ_2 should have different quantum numbers with each other.

Discrete Z_2 symmetry

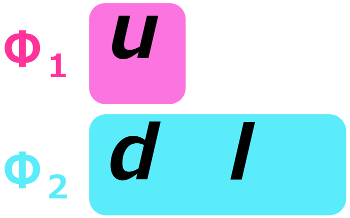
$$\Phi_1 \to +\Phi_1$$
$$\Phi_2 \to -\Phi_2$$

4 types of Yukawa interactions

Barger, Hewett, Phillips(1990), Grossman (1993);
Aoki, Kanemura, Tsumura, Yagyu(2009);
Logan, MacLennan(2009);
Su, Thomas(2009)

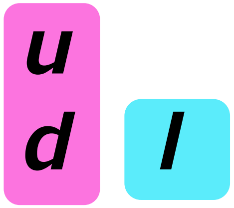


Type I

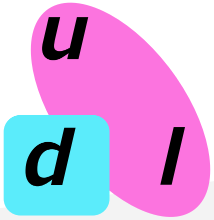


Type II

MSSM



Type X
(Lepton specific)
e.g. Radiative seesaw



Type Y
(Flipped)

Higgs potential

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \phi_i \end{pmatrix}, \quad \phi_i = \frac{1}{\sqrt{2}}(h_i + v_i + z_i).$$

Soft-breaking scale of Z_2 sym.

$$M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$$

- CP invariance & softly broken Z_2

$$V_{\mathrm{THDM}} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - \boxed{m_3^2}(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.})$$
$$+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right].$$

- Mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \boxed{\begin{pmatrix} H \\ h \end{pmatrix}}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} z \\ \boxed{A} \end{pmatrix},$$

$$\begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \omega^+ \\ \boxed{H^+} \end{pmatrix}.$$

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

SM-like Higgs Extra Higgs

- Parameters(8)

$v^2 = v_1^2+v_2^2 = (246\mathrm{GeV})^2$, $\tan\beta = \frac{v_2}{v_1}$

$v \quad m_h \quad \underline{m_H \quad m_A \quad m_{H+} \quad \alpha \quad \beta \quad M^2}$ 6 free parameters

Coupling constants of *h*

- Gauge couplings (*hVV* = *hWW*, *hZZ*)

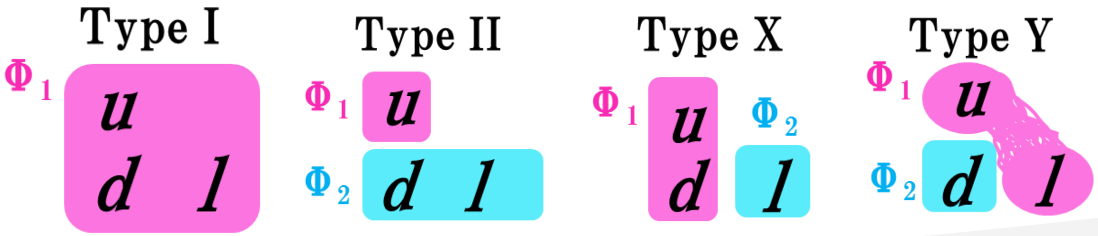
$g_{hVV}{}^{\mathrm{2HDM}} = \sin(\beta-\alpha)\, g_{hVV}{}^{\mathrm{SM}}$ $\kappa_V \equiv \dfrac{g_{hVV}{}^{\mathrm{2HDM}}}{g_{hVV}{}^{\mathrm{SM}}} = \sin(\beta - \alpha)$

SM like limit ; $\kappa_V = \sin(\beta-\alpha) \rightarrow 1$

- Yukawa couplings (*htt*, *hbb*, *hττ*)

If *f* couples to Φ_1 $\kappa_f = \sin(\beta-\alpha) + \cot\beta \cos(\beta-\alpha)$

If *f* couples to Φ_2 $\kappa_f = \sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha)$

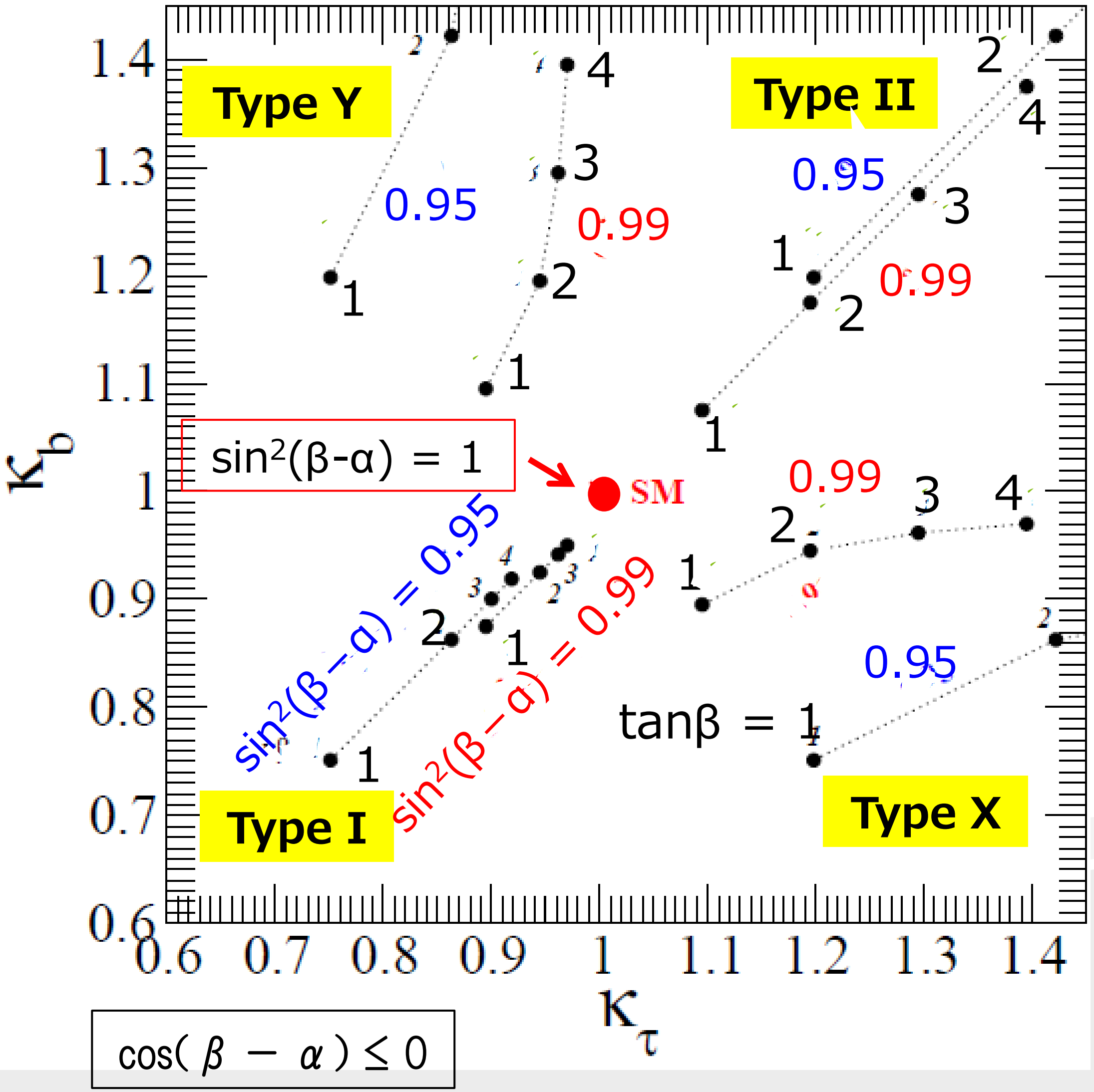


The pattern of deviations in Yukawa couplings depends on the Type of the 2HDM.

The pattern of deviations in hττ and hbb (tree level)

$$\kappa_f \equiv \frac{g_{hff(2HDM)}}{g_{hff(SM)}}$$

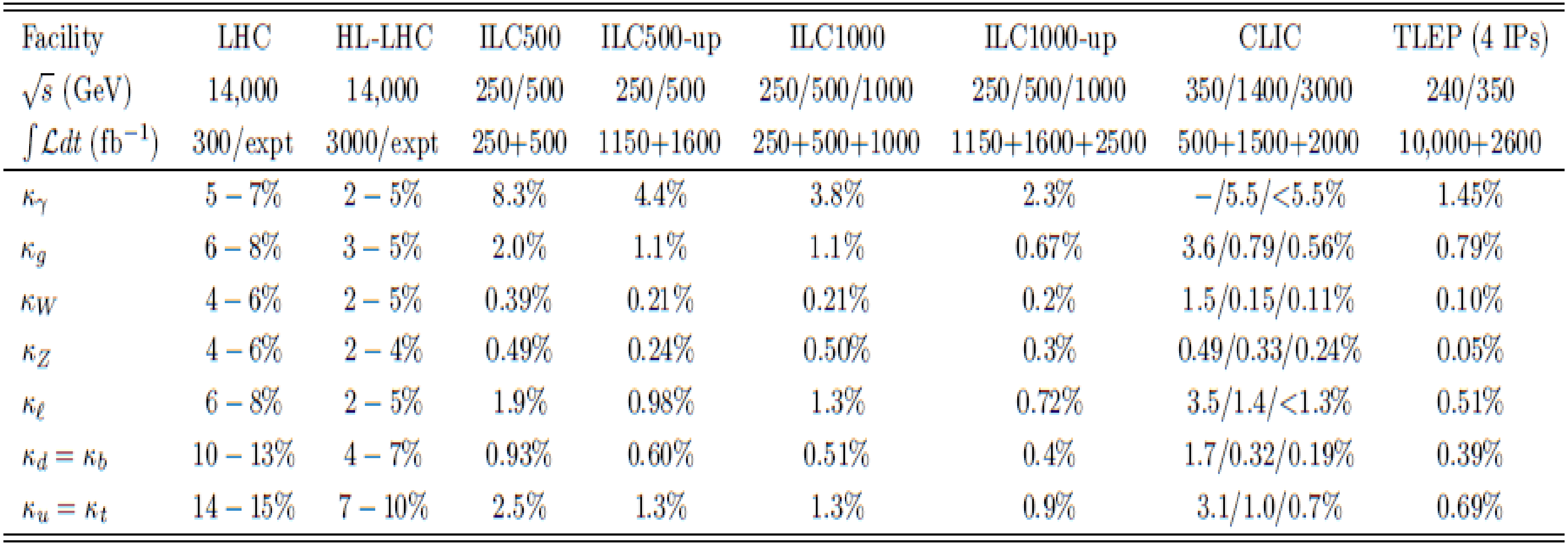
We can discriminate all types of 2HDM, if $\sin^2(\beta-\alpha)$ slightly differs from unity.



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

Higgs coupling measurements

h-couplings can be measured with high precision at future collider experiments!!



Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Higgs Working Group Report (2014)

Higgs coupling measurements

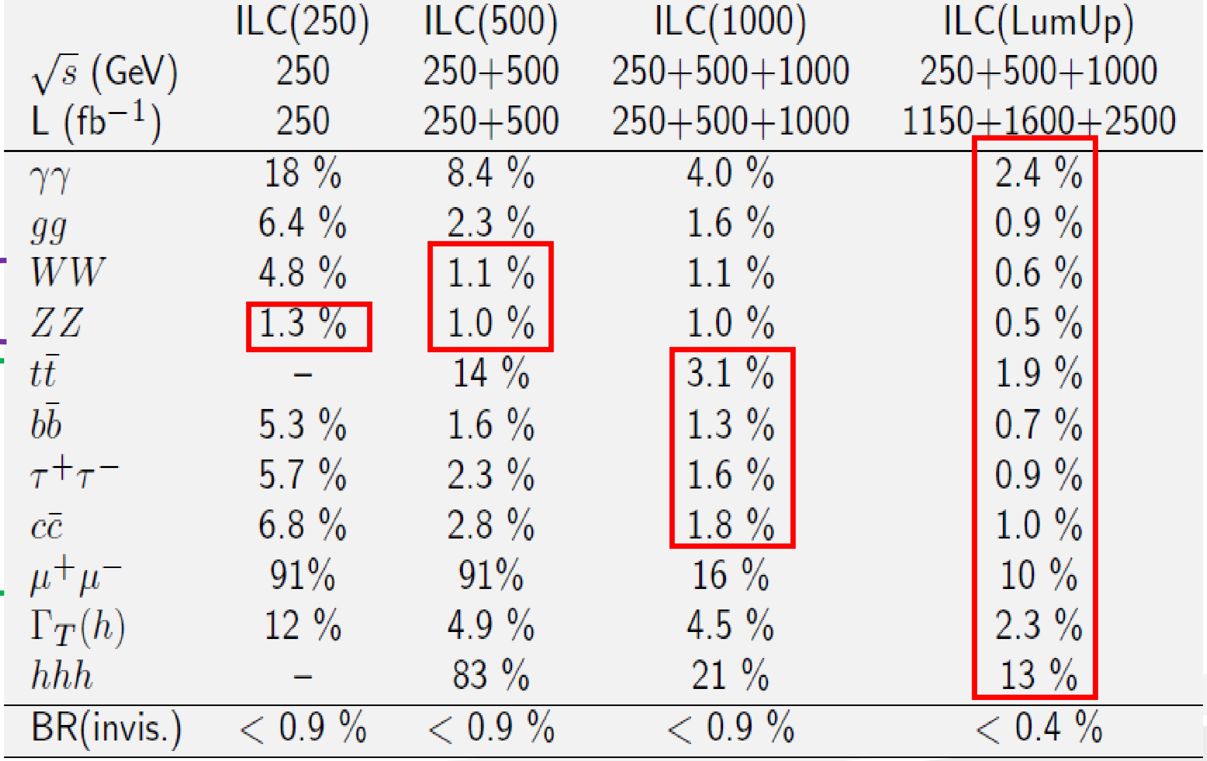
h-couplings can be measured typically by O(1) % !!

All couplings are important !

ILC WHITE PAPER 1303.3570.

Gauge coupling *hVV*
$\sin(\beta-\alpha)$

All types of Yukawa couplings *hff*



	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91%	91%	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %
hhh	–	83 %	21 %	13 %
BR(invis.)	$<$ 0.9 %	$<$ 0.9 %	$<$ 0.9 %	$<$ 0.4 %

To compare with future precision measurements, it is essentially important to evaluate loop contributions.

Renormalized couplings

We calculate Yukawa couplings *hff* at one loop in 2HDMs for all types of Yukawa interaction.

- Renormalized couplings by on-shell scheme

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

Guasch, Hollik, Penaranda (2001);
Kanemura, Kikuchi, Yagyu (2014)

- Counter terms

$$\delta\Gamma_{hff}=-i\frac{m_f}{v}\xi_h^f\left[\frac{\delta m_f}{m_f}+\delta Z_V^f+\frac{1}{2}\delta Z_h+\frac{\delta\xi_h^f}{\xi_h^f}+\frac{\xi_H^f}{\xi_h^f}(\delta C_h+\delta\alpha)-\frac{\delta v}{v}\right]$$

If *f* couples to Φ_1,

$$\boxed{-\frac{\cos\alpha}{\sin\beta}(\cot\beta\delta\beta+\tan\alpha\delta\alpha)}$$

or

If *f* couples to Φ_2,

$$\boxed{-\frac{\sin\alpha}{\cos\beta}(\tan\beta\delta\beta+\cot\alpha\delta\alpha)}$$

- Deviations and scale factors at one loop

$$\Delta\hat{\Gamma}_{hff}=\frac{\hat{\Gamma}_{hff}(p_1,p_2,q)_{THDM}-\hat{\Gamma}_{hff}(p_1,p_2,q)_{SM}}{\hat{\Gamma}_{hff}(p_1,p_2,q)_{SM}}$$

$$\hat{\kappa}_f\equiv\frac{\hat{\Gamma}_{hff}(m_f^2,m_f^2,m_h^2)_{\rm THDM}}{\hat{\Gamma}_{hff}(m_f^2,m_f^2,m_h^2)_{\rm SM}}$$

Renormalized conditions in Yukawa interactions

Hollik(1993);
Kanemura, Kikuchi, Yagyu(2014)

$$m_f \to m_f + \delta m_f, \quad \psi_L \to \left(1+\frac{1}{2}\delta Z_L^f\right)\psi_L, \quad \psi_R \to \left(1+\frac{1}{2}\delta Z_R^f\right)\psi_R,$$

Two point functions

$$\hat{\Pi}_{ff}(p^2) = \hat{\Pi}_{ff,V}(p^2) + \hat{\Pi}_{ff,A}(p^2),$$

- $\hat{\Pi}_{ff,V}(p^2) = \not{p}\left[\Pi^{\rm 1PI}_{ff,V}(p^2) + \delta Z_V^f\right] + m_f\left[\Pi^{\rm 1PI}_{ff,S}(p^2) - \delta Z_V^f - \frac{\delta m_f}{m_f}\right],$
- $\hat{\Pi}_{ff,A}(p^2) = -\not{p}\gamma_5\left[\Pi^{\rm 1PI}_{ff,A}(p^2) + \delta Z_A^f\right],$

$$\boxed{\delta Z_V^f = \frac{\delta Z_L^f + \delta Z_R^f}{2}, \quad \delta Z_A^f = \frac{\delta Z_L^f - \delta Z_R^f}{2}.}$$

We obtain δm_f and δZ_V^f by imposing on-shell conditions.

$$\hat{\Pi}_{ff,V}(m_f^2) = 0, \quad \Longrightarrow \quad \frac{\delta m_f}{m_f} = \Pi^{\rm 1PI}_{ff,V}(m_f^2) + \Pi^{\rm 1PI}_{ff,S}(m_f^2),$$

$$\frac{d}{d\not{p}}\hat{\Pi}_{ff,V}(p^2)\Big|_{p^2=m_f^2} = 0, \quad \Longrightarrow \quad \delta Z_V^f = -\Pi^{\rm 1PI}_{ff,V}(m_f^2) - 2m_f^2\left[\frac{d}{dp^2}\Pi^{\rm 1PI}_{ff,V}(p^2)\Big|_{p^2=m_f^2} + \frac{d}{dp^2}\Pi^{\rm 1PI}_{ff,S}(p^2)\Big|_{p^2=m_f^2}\right]$$

Kanemura, Okada, Senaha, Yuan(2002);
Kanemura, Kikuchi, Yagyu(2014)

Renormalized conditions in $V(\Phi_1,\Phi_2)$

Parameters; m_h m_H m_A m_{H+} v α β M

Counter terms; δT_h δT_H δm_h δm_H δm_A δm_{H+} $\delta\alpha$ $\delta\beta$ δM δv

δZ_h δZ_H δZ_A δZ_{H+} δZ_{G0} δZ_{G+} δC_{hH} δC_{GA} δC_{G+H+}

- On-shell conditions in Higgs potential

$\delta\beta$

$$\Pi_{G^0A}(m_A{}^2) = 0$$
$$\Pi_{G^0A}(m_Z{}^2) = 0$$

$$\delta\beta = \frac{1}{2(m_Z{}^2 - m_A{}^2)}\left(\Pi_{GA}^{1\mathrm{PI}}[m_Z{}^2] - \Pi_{GA}^{1\mathrm{PI}}[m_A{}^2] - \frac{2m_Z{}^2}{m_A{}^2}\Pi_{GA}^{1\mathrm{PI}}[m_A{}^2]\right) + \frac{s_\beta}{m_A{}^2}\frac{\delta T_1}{v} - \frac{c_\beta}{m_A{}^2}\frac{\delta T_2}{v}$$

We can determine δC_{hH} by imposing $\Pi_{hH}(p^2)$ same conditions as $\Pi_{G^0A}(p^2)$.

δZ_h

$$\frac{d}{dp^2}\Pi_{hh}(m_h{}^2) = 1$$

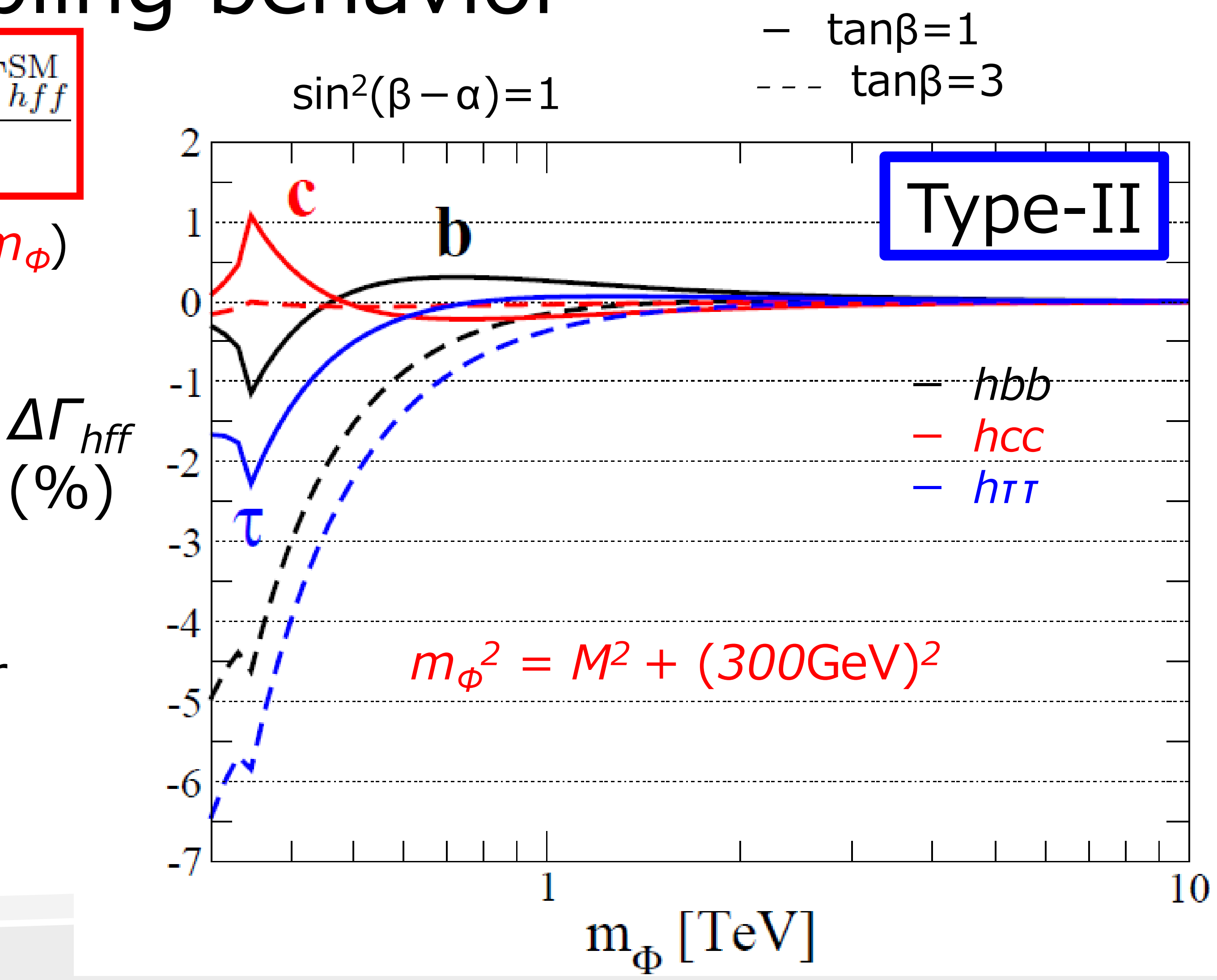
$$\delta Z_h = -\frac{d}{dp^2}\Pi_{hh}(m_h{}^2)$$

Decoupling behavior

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

$m_H = m_A = m_{H+}$ $(= m_\Phi)$

We have checked consistency of our calculation.



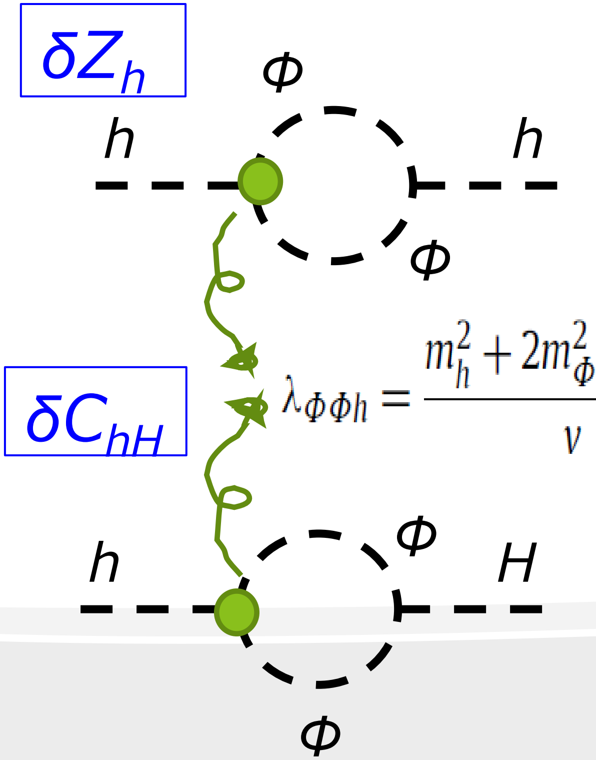
Kanemura, Kikuchi, Yagyu(2014)

Non decoupling effects

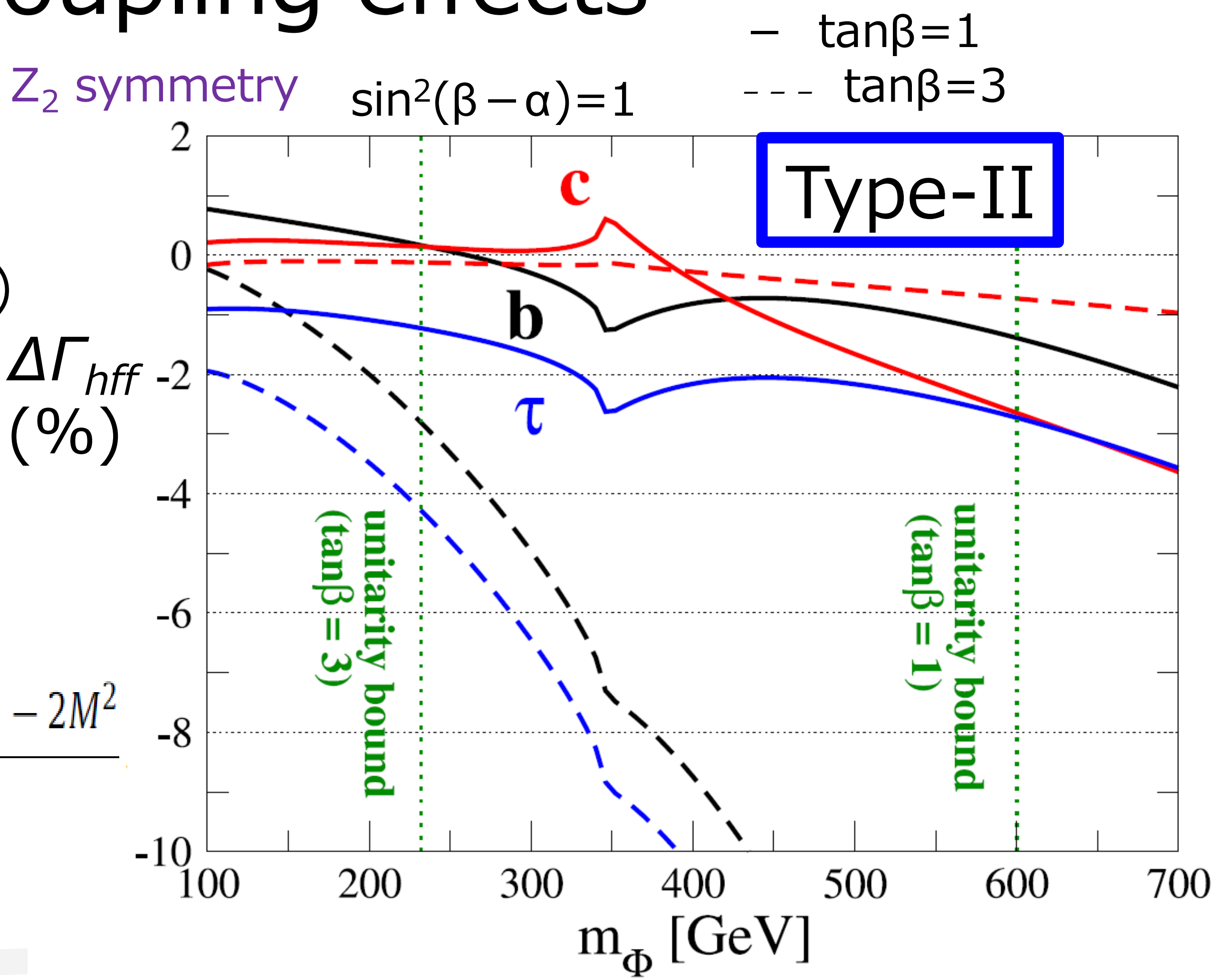
Soft breaking scale of Z_2 symmetry

$M^2 = 0$

$m_H = m_A = m_{H+}$ (=m_Φ)



$$\lambda_{\Phi\Phi h} = \frac{m_h^2 + 2m_\Phi^2 - 2M^2}{v}$$



Kanemura, Kikuchi, Yagyu(2014)

κ_τ vs κ_b at 1 loop level

◆ Scan analysis

$100\ \mathrm{GeV} \leq m_{H+,\ H,\ A} \leq 1000\mathrm{Ge}$

$0 \leq M \leq m_{H+,\ H,\ A}$

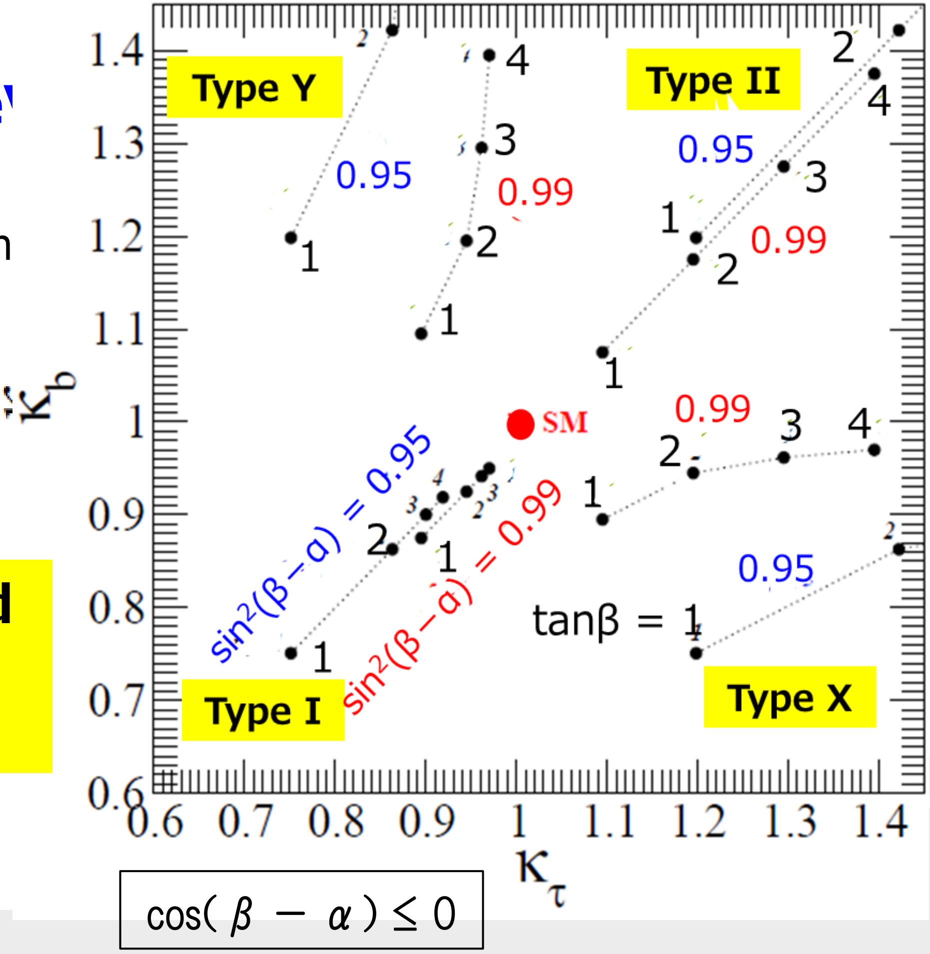
↳ Soft breaking scale of Z_2 sym

◆ Constraints

- Perturbative Unitarity
- Vacuum Stability

***hff* couplings can be modified as large as several % from tree level predictions.**

Tree Level



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

Kanemura, Kikuchi, Yagyu(2014)

κ_τ vs κ_b at 1 loop level

- Scan analysis

$100\ \mathrm{GeV} \leq m_{H+,\ H,\ A} \leq 1000\mathrm{GeV}$

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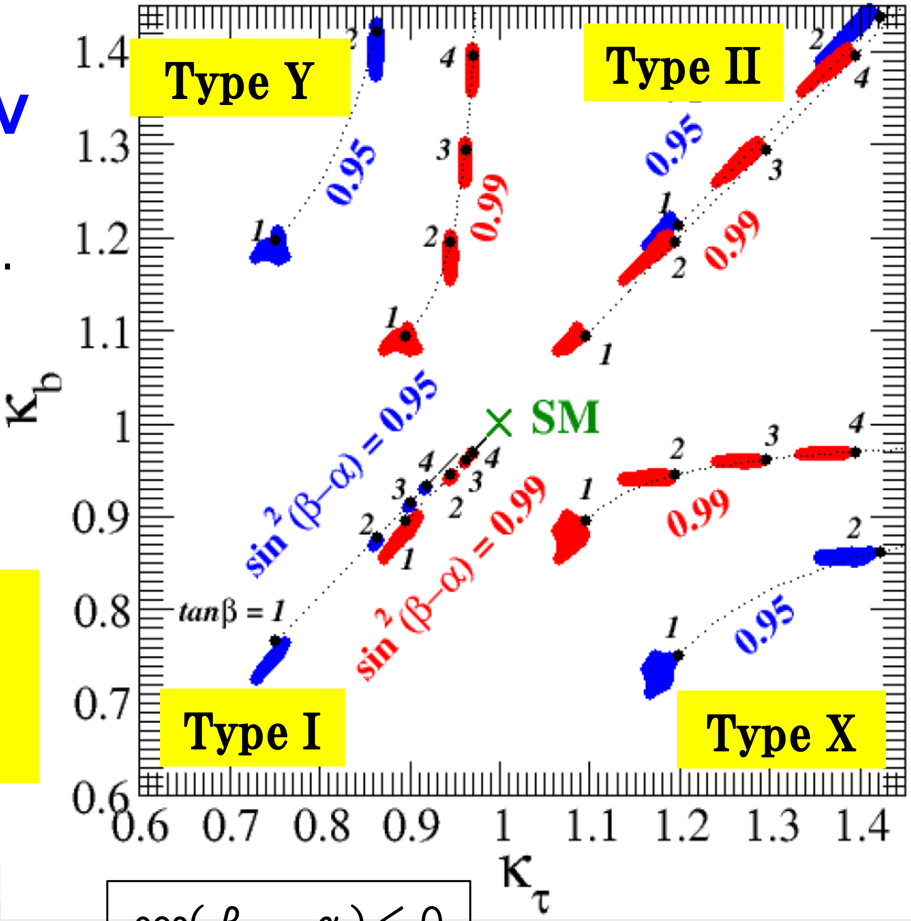
- Constraints
  - Perturbative Unitarity
  - Vacuum Stability

***hff* couplings can be modified as large as several % from tree level predictions.**

Radiative correction



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Kanemura, Kikuchi, Yagyu(2014)

κ_τ vs κ_b at 1 loop level

- ◆ Scan analysis

$100\ \mathrm{GeV} \le m_{H+,\ H,\ A} \le 1000\mathrm{GeV}$

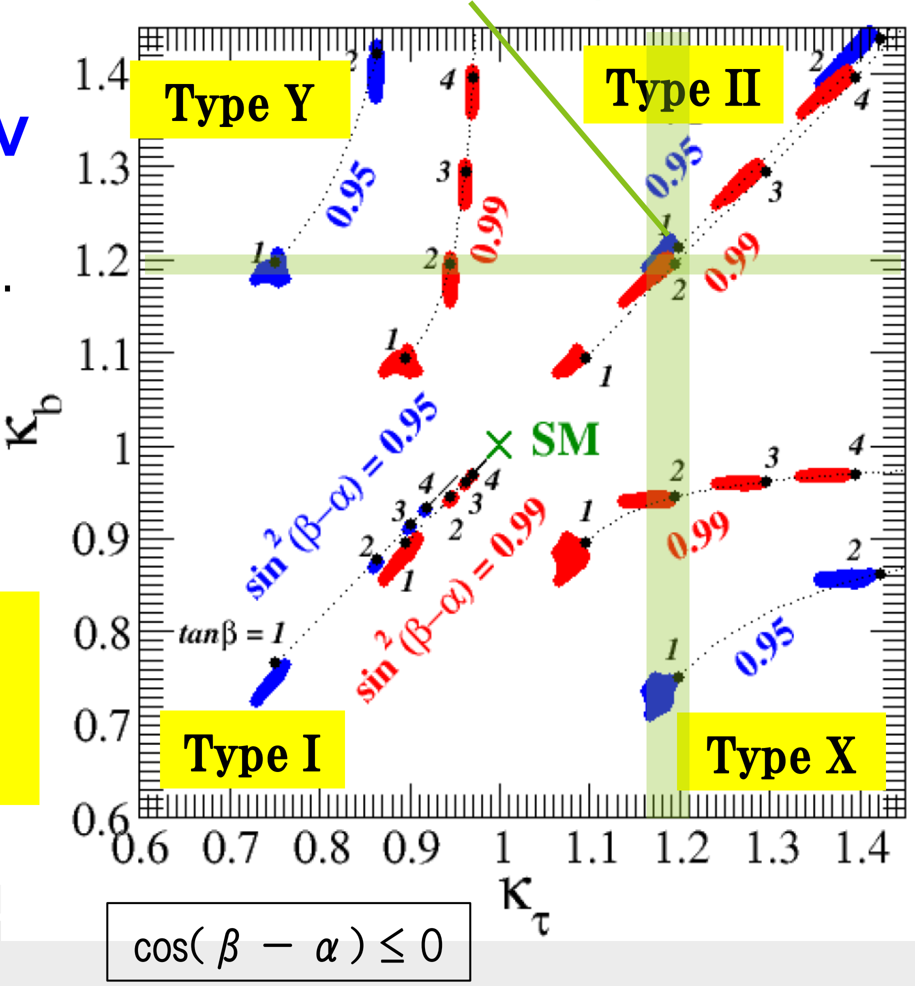
$0 \le M \le m_{H+,\ H,\ A}$

Soft breaking scale of Z_2 sym.

- ◆ Constraints
  - Perturbative unitarity
  - Vacuum stability

***hff* couplings can be modified as large as several % from tree level predictions.**

Measurement accuracy at ILC500



Kanemura, Kikuchi, Yagyu(2014)

Summary

- In this talk, we focused on 2HDMs with softly broken Z_2 symmetry. We calculate all Yukawa couplings with radiative corrections.

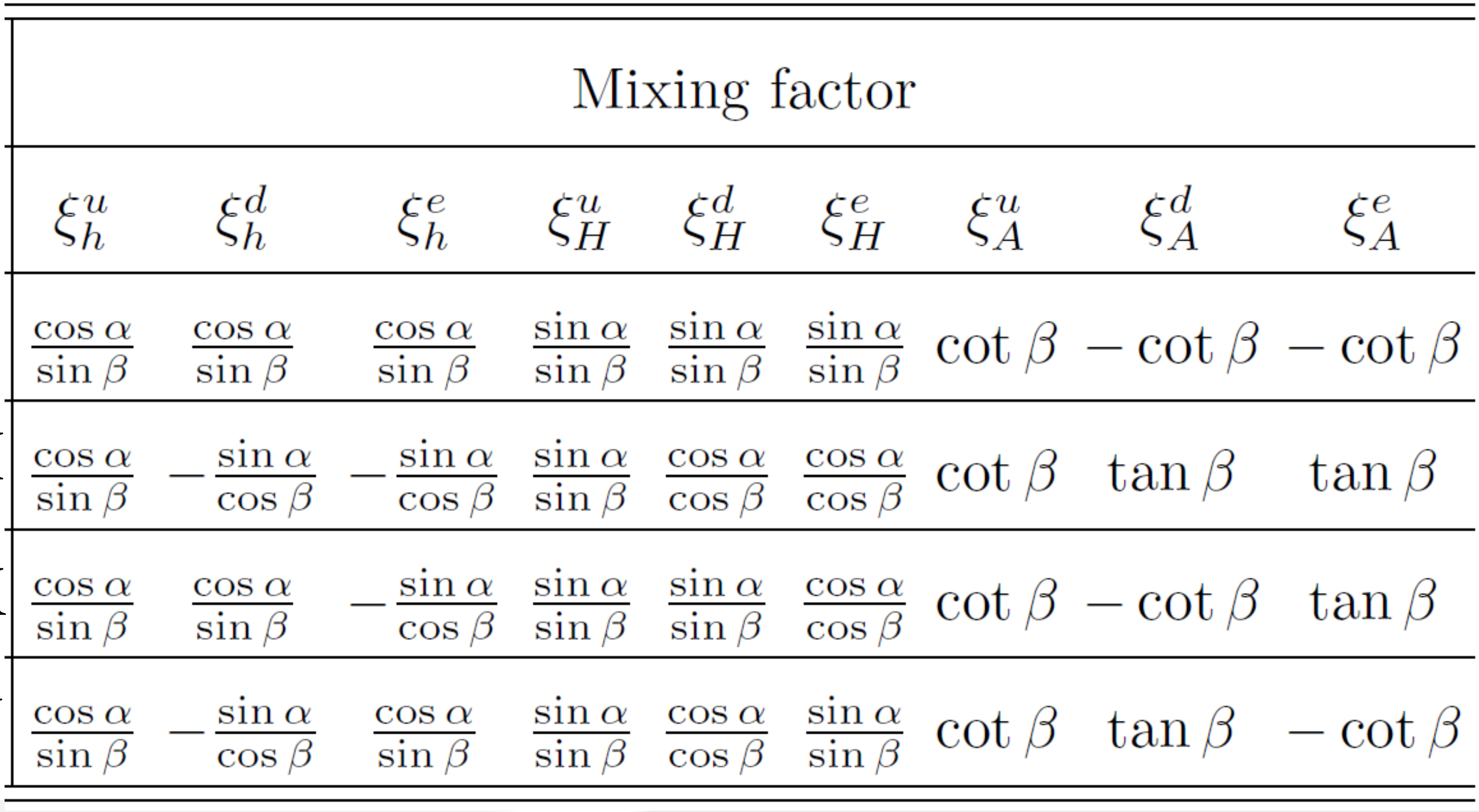
- Yukawa couplings can deviate by several % from SM predictions by extra Higgs loop contributions, so that we should take into account these contributions when we compare theory predictions with precision data.

- The pattern in deviations does not change even with radiative corrections. Namely, we can discriminate the type of 2HDMs when gauge couplings hWW(hZZ) slightly deviate from SM predictions (as long as $\kappa_V \simeq 0.99$).

- Furthermore, by comparing loop corrections with precision data, we may obtain information of inner parameters (e.g.; Mass of extra Higgs boson).

BUCK UP

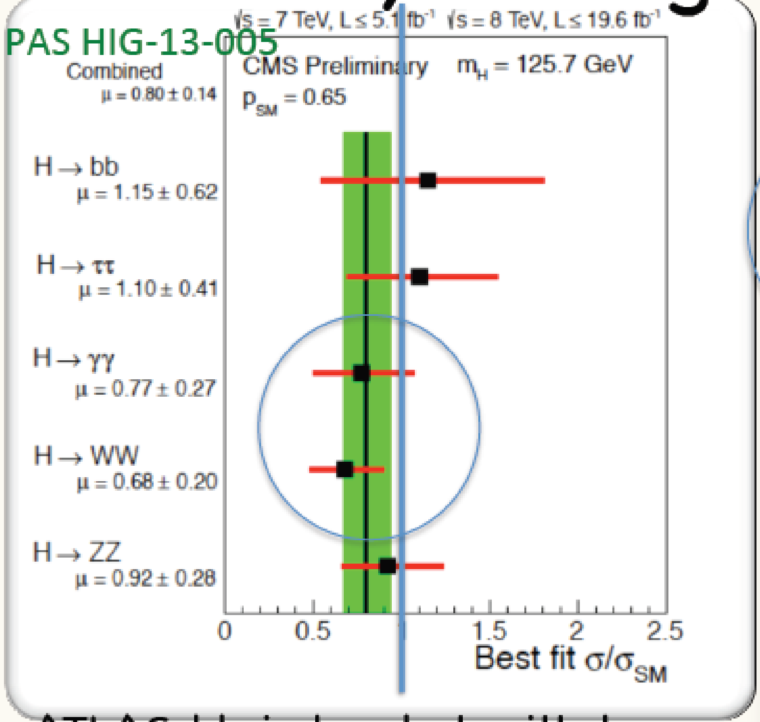
Mixing factor



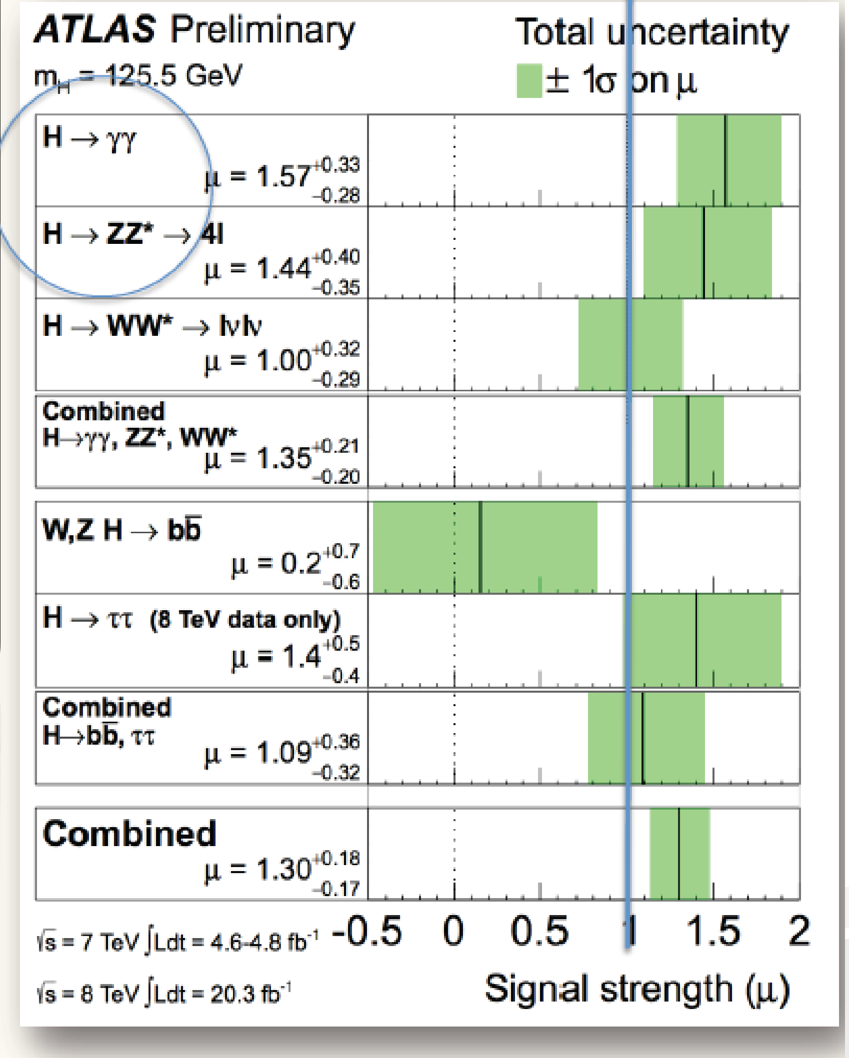
	Mixing factor								
	ξ_h^u	ξ_h^d	ξ_h^e	ξ_H^u	ξ_H^d	ξ_H^e	ξ_A^u	ξ_A^d	ξ_A^e
Type-I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Summary of Signal Strength

CMS PAS HIG-13-005



ATLAS-CONF-2014-009



ATLAS bb is low but with large error.

$$k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$

Moriond 2014,
Eilam Gross

Renormalization

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

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

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

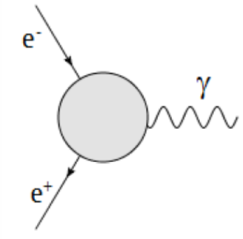
➢ Kinetic term

- Parameters in Lagrangian ･･･ g, g', v
- Physical parameters ･･･ m_W , m_Z , $\sin\theta_W$, G_F , α_{em} .
- Counter-terms ･･･ $\delta m_W, \delta m_Z, \delta s_W, \delta G_F, \delta\alpha_{em}$,･･･
- Renormalized conditions ･･･

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

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

On-shell conditions



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

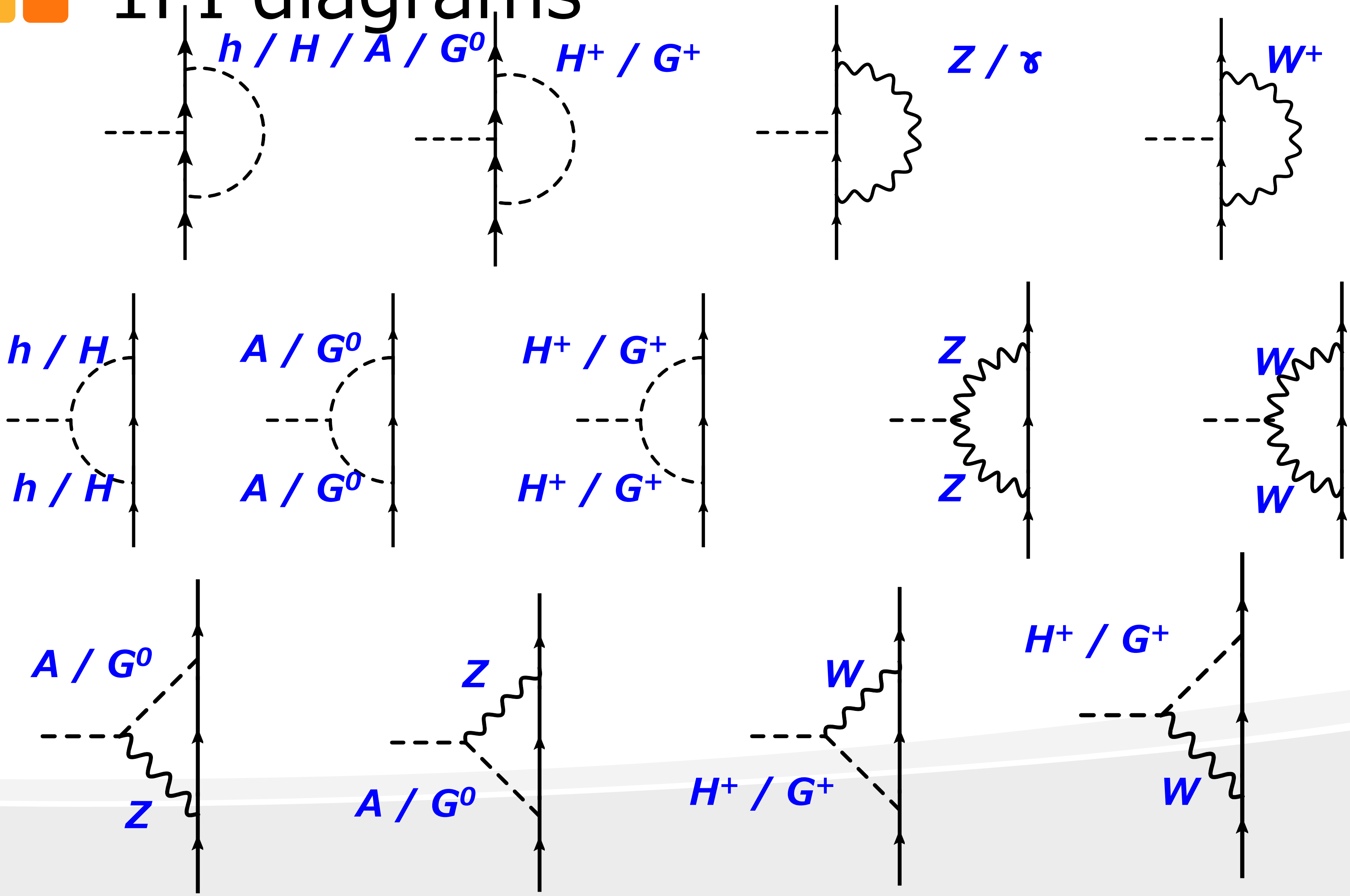
$$\frac{\delta\alpha_{em}}{\alpha_{em}} = \frac{d}{dp^2}\Pi_{\gamma\gamma}^{1PI}(p^2)|_{p^2=0} - \frac{2s_W}{c_W}\frac{\Pi_{\gamma Z}^{1PI}(0)}{m_Z^2}$$

- Counter term of v

$$v^2 = \frac{m_W{}^2 \sin^2\theta_W}{\pi\,\alpha_{em}}$$

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

1PI diagrams



SM like limit

$\sin^2(\beta-\alpha) = 1$, $m_{H+} = m_A = m_H = m_\Phi$

ξ_A^u	ξ_A^d	ξ_A^e
$\cot\beta$	$-\cot\beta$	$-\cot\beta$
$\cot\beta$	$\tan\beta$	$\tan\beta$
$\cot\beta$	$-\cot\beta$	$\tan\beta$
$\cot\beta$	$\tan\beta$	$-\cot\beta$

$$\begin{aligned}
&\hat{\Gamma}^{\rm THDM}_{hff}(m_f^2, m_f^2, m_h^2)\\
&\simeq \hat{\Gamma}^{\rm SM}_{hff}(m_f^2, m_f^2, m_h^2) + \frac{m_f}{v}\frac{1}{16\pi^2}\Bigg\{\frac{2m_{f'}^2}{v^2}\xi_A^d \cot\beta\Big[(m_h^2 - 2m_f^2)C_{12}(m_{f'}, m_\Phi, m_{f'})\\
&+ (2m_{f'}^2 - m_f^2)C_0(m_{f'}, m_\Phi, m_{f'}) + v\lambda_{\Phi\Phi h}C_0(m_\Phi, m_{f'}, m_\Phi)\Big]\\
&+ 4\lambda^2_{\Phi\Phi h}\frac{d}{dp^2}B_0(p^2; m_\Phi, m_\Phi)\Big|_{p^2=m_h^2} - \frac{6m_t^2}{v^2}I_f\xi_A^f \cot\beta B_0(m_\Phi^2; m_t, m_t)\\
&+ \frac{6m_t^4}{v^2(m_\Phi^2 - m_h^2)}I_f\xi_A^f \cot\beta\left[\left(4 - \frac{m_h^2}{m_t^2}\right)B_0(m_h^2; m_t, m_t) - \left(4 - \frac{m_\Phi^2}{m_t^2}\right)B_0(m_\Phi^2; m_t, m_t)\right]\\
&+ \frac{6\lambda_{\Phi\Phi h}\lambda_{\Phi\Phi H}}{m_\Phi^2 - m_h^2}I_f\xi_A^f\left[B_0(m_h^2; m_\Phi, m_\Phi) - B_0(m_\Phi^2; m_\Phi, m_\Phi)\right]\Bigg\},
\end{aligned}$$

$$\lambda_{\Phi\Phi h} = \frac{m_h^2 + 2m_\Phi^2 - 2M^2}{v}, \qquad \lambda_{\Phi\Phi H} = \frac{M^2 - m_\Phi^2}{v}\cot 2\beta.$$

Kanemura, Kikuchi, Yagyu(2013)

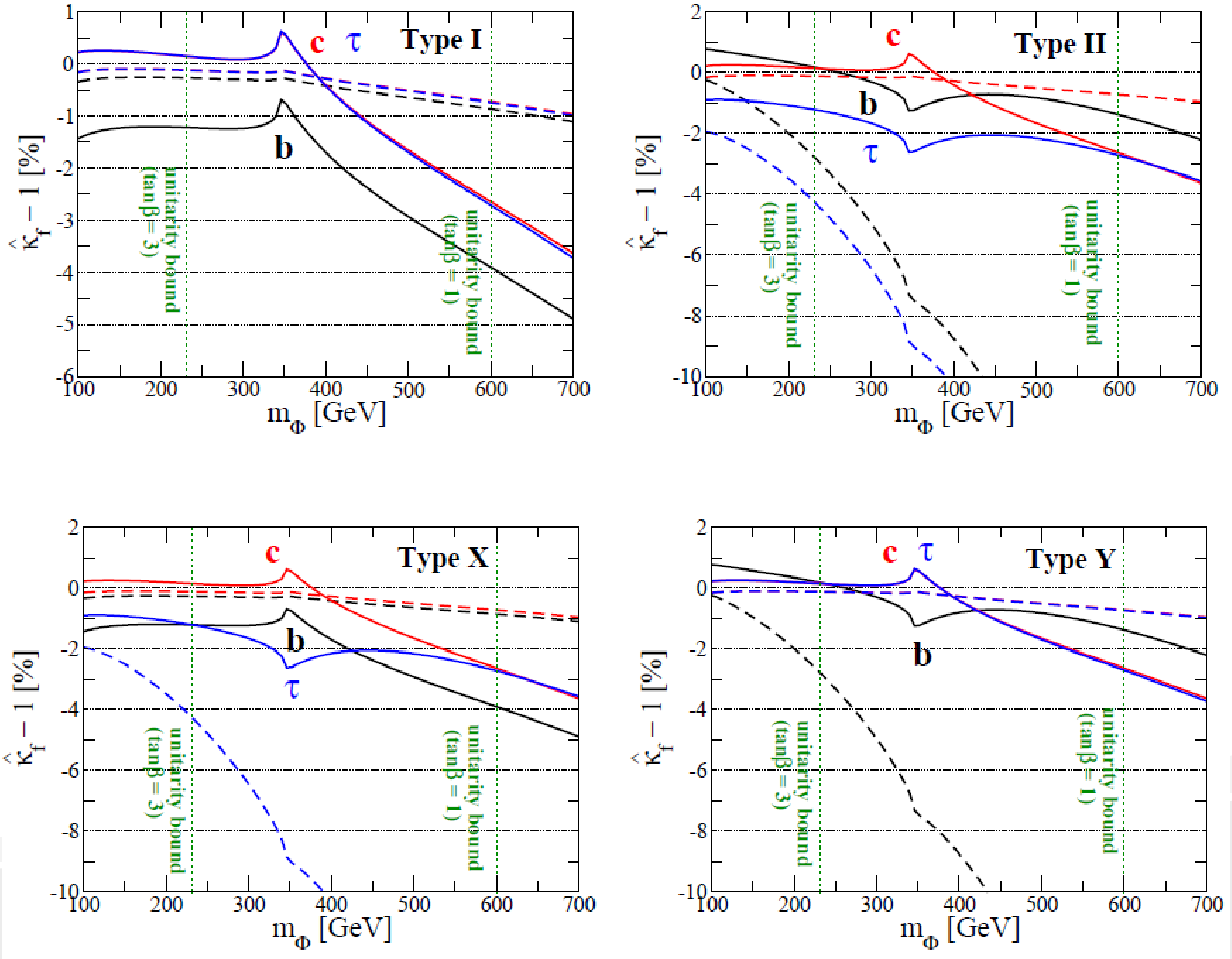
$\sin^2(\beta-\alpha)=1$

— **$\tan\beta=1$**

- - - **$\tan\beta=3$**

Deviations in *hff*

***M* = 0**



Kanemura, Kikuchi, Yagyu(2013)

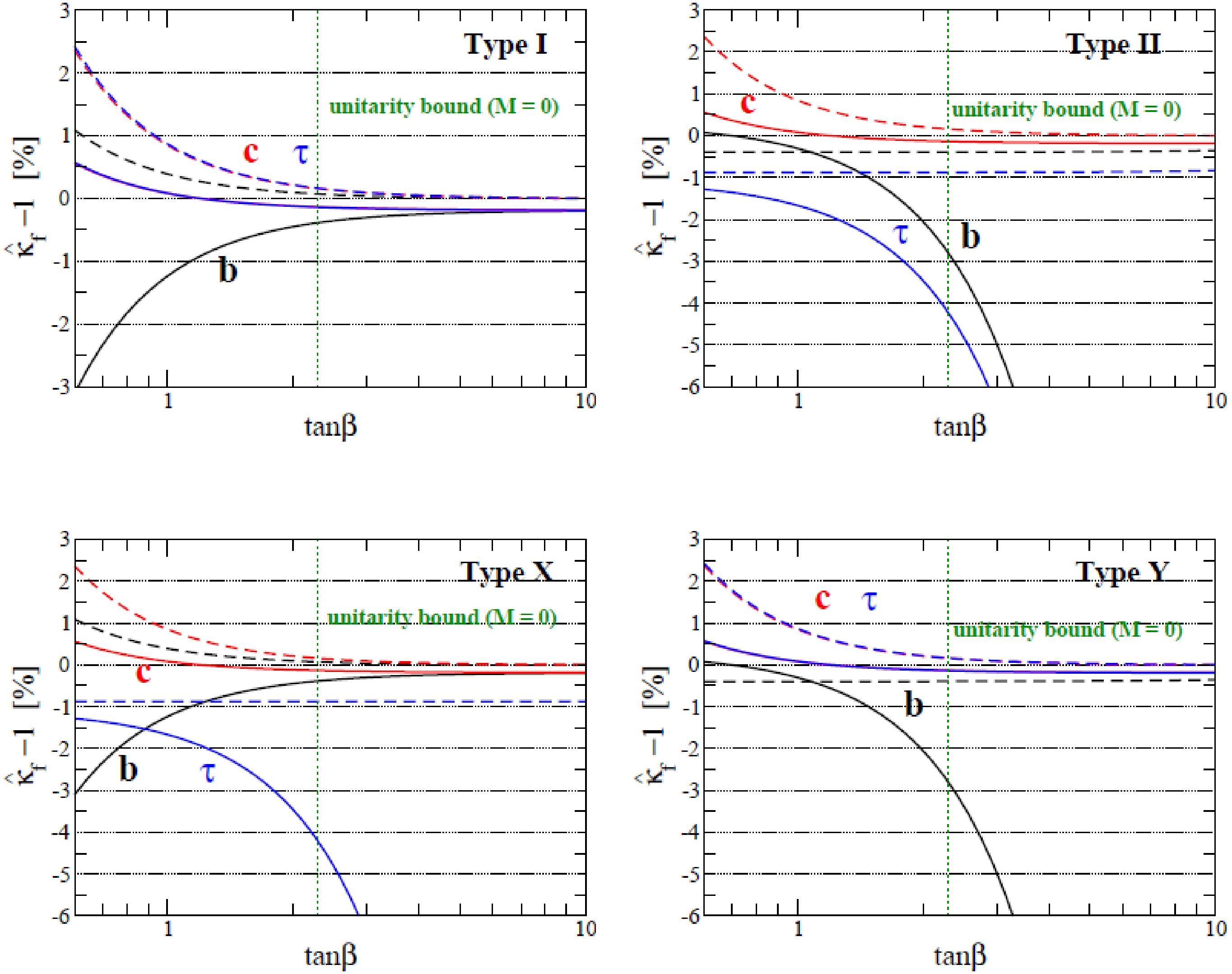
Deviations in *hff*

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

— tanβ=1

- - - tanβ=3

$m_\Phi = 300$ GeV, $M = 0$



Deviations in *htt*

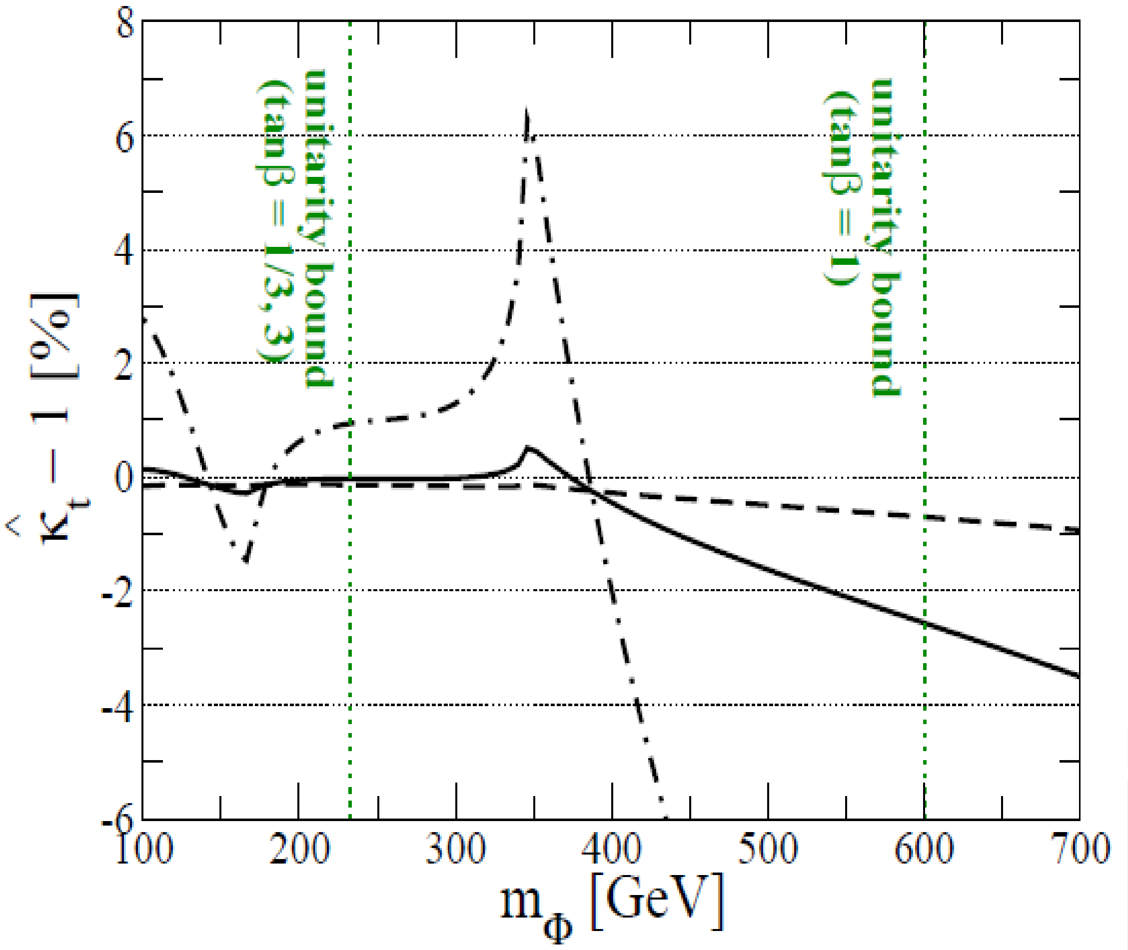
$\sin^2(\beta - \alpha) = 1$

Kanemura, Kikuchi, Yagyu(2013)

— tanβ=1

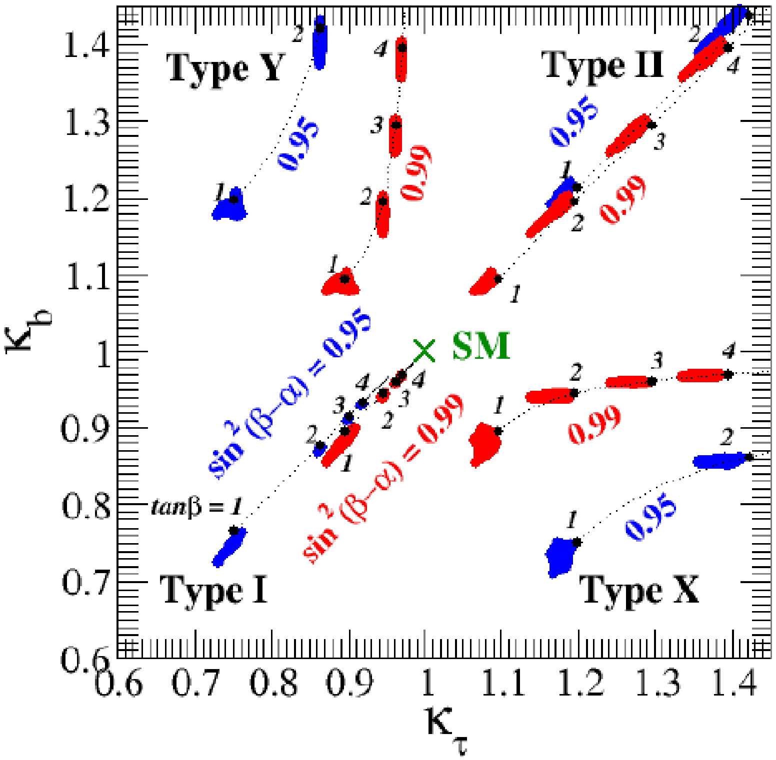
- - - tanβ=3

***M* = 0**

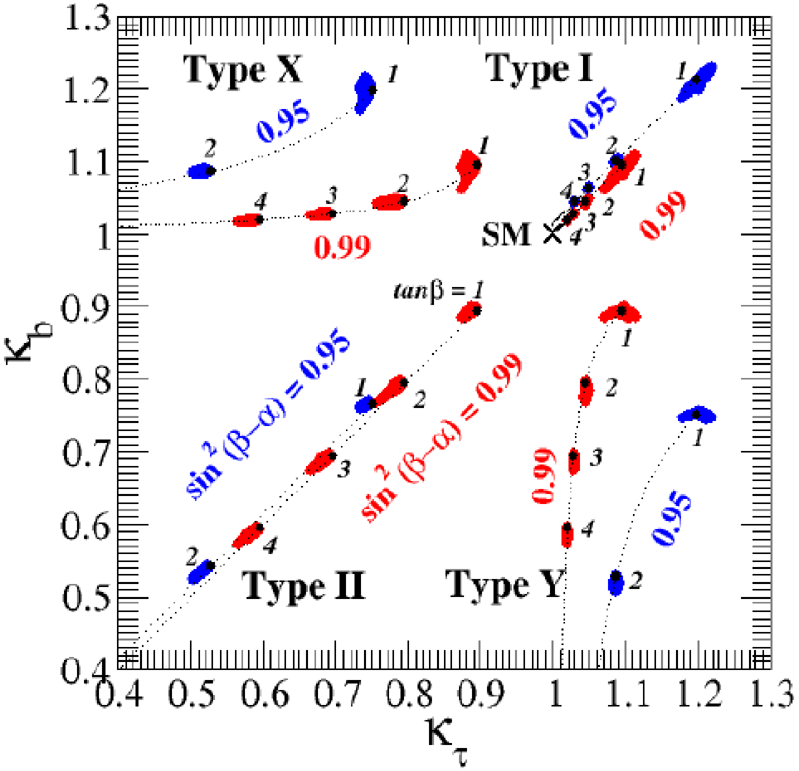


κ_b VS κ_τ

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

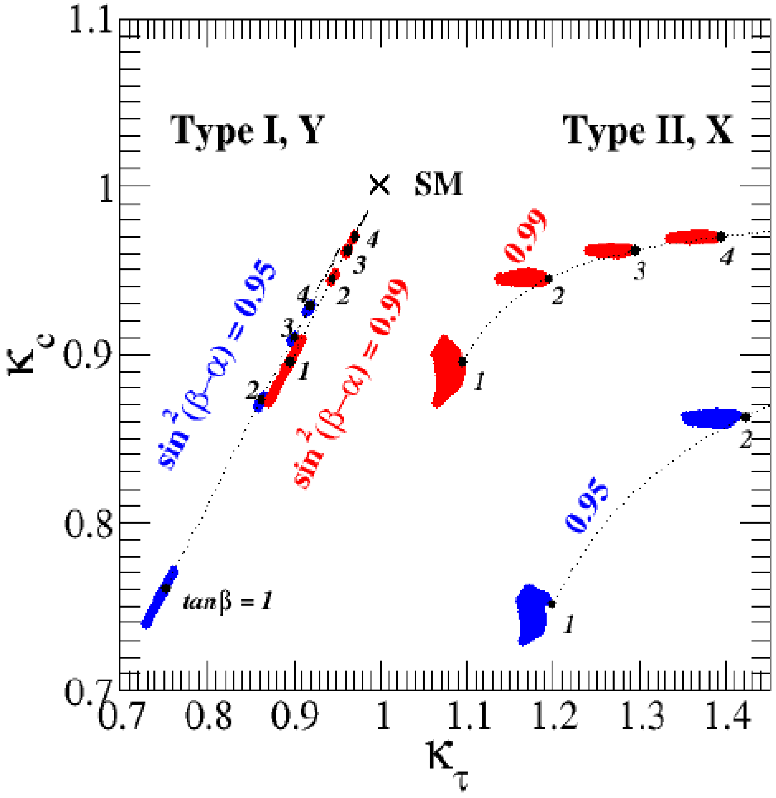


$\cos(\beta-\alpha) > 0$

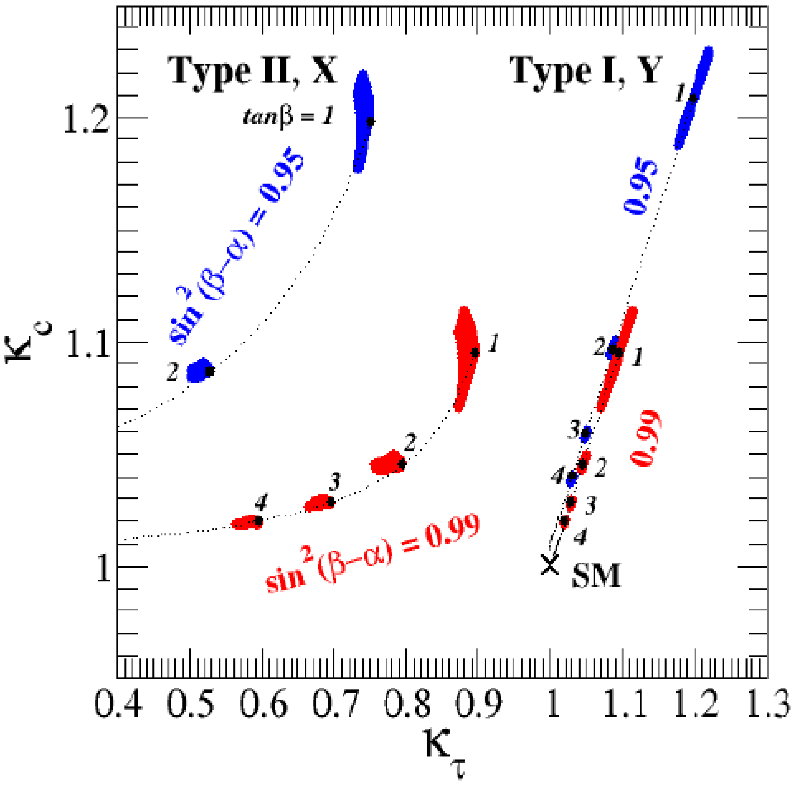


κ_τ VS κ_c

cos(β-α) < 0

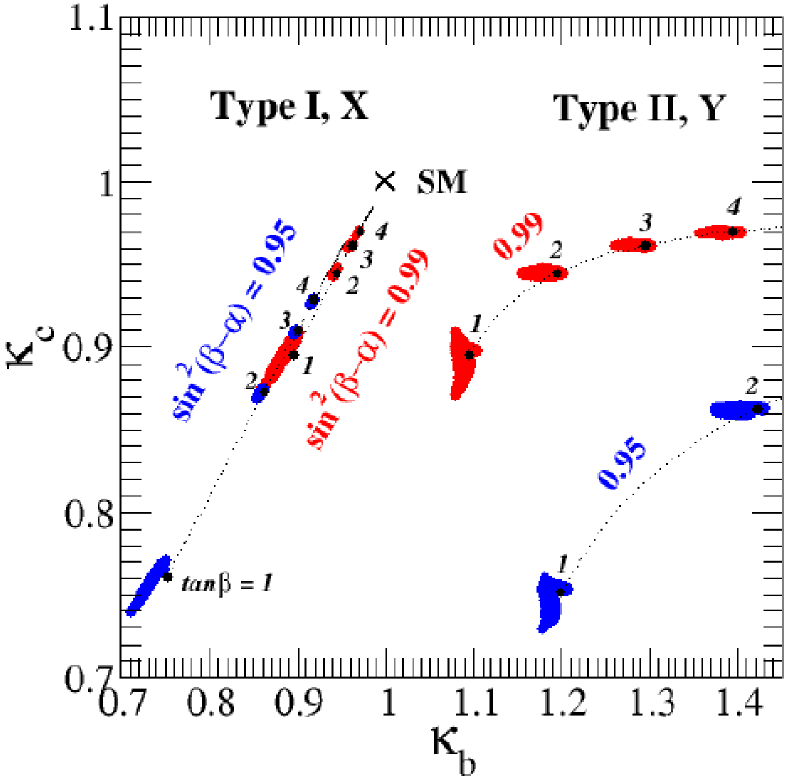


cos(β-α) > 0

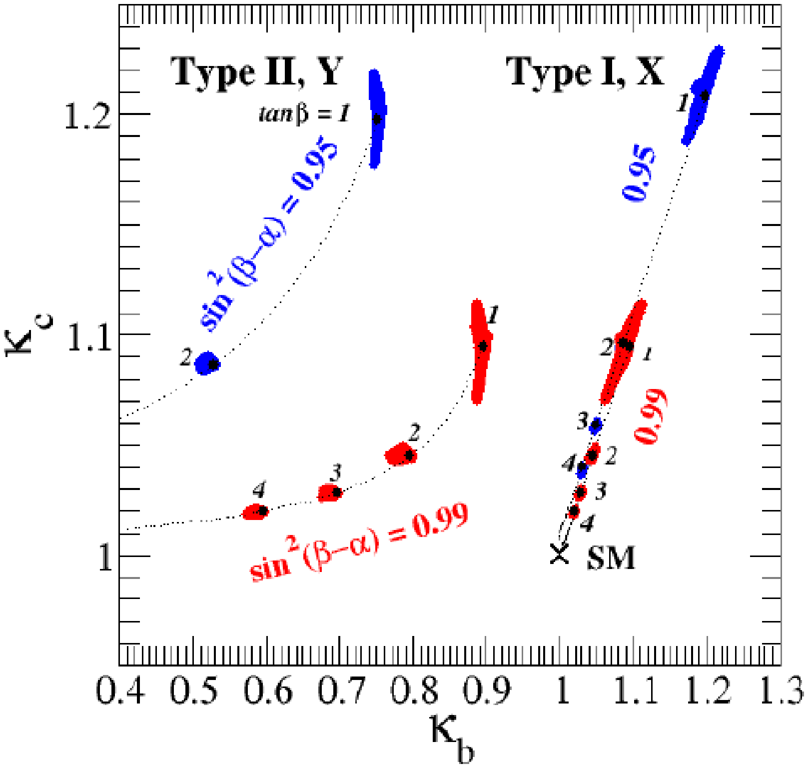


κ_b VS κ_c

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



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



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$v_{\Delta} / v_{\varphi} << 1$

→ 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

Perturbative unitarity

S-wave amplitude

$$a_\pm = \frac{1}{16\pi}\left\{\frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2+(2\lambda_3+\lambda_4)^2}\right\},$$

$$b_\pm = \frac{1}{16\pi}\left\{\frac{1}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{1}{4}(\lambda_1-\lambda_2)^2+\lambda_4^2}\right\},$$

$$c_\pm = d_\pm = \frac{1}{16\pi}\left\{\frac{1}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{1}{4}(\lambda_1-\lambda_2)^2+\lambda_5^2}\right\},$$

$$e_1 = \frac{1}{16\pi}(\lambda_3+2\lambda_4-3\lambda_5),$$

$$e_2 = \frac{1}{16\pi}(\lambda_3-\lambda_5),$$

$$f_+ = \frac{1}{16\pi}(\lambda_3+2\lambda_4+3\lambda_5),$$

$$f_- = \frac{1}{16\pi}(\lambda_3+\lambda_5),$$

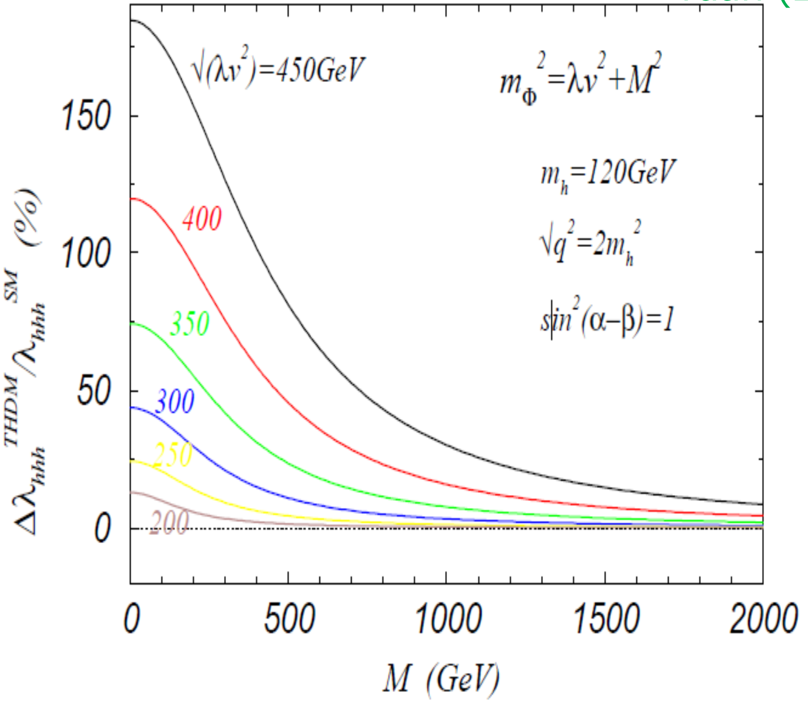
$$f_1 = f_2 = \frac{1}{16\pi}(\lambda_3+\lambda_4).$$

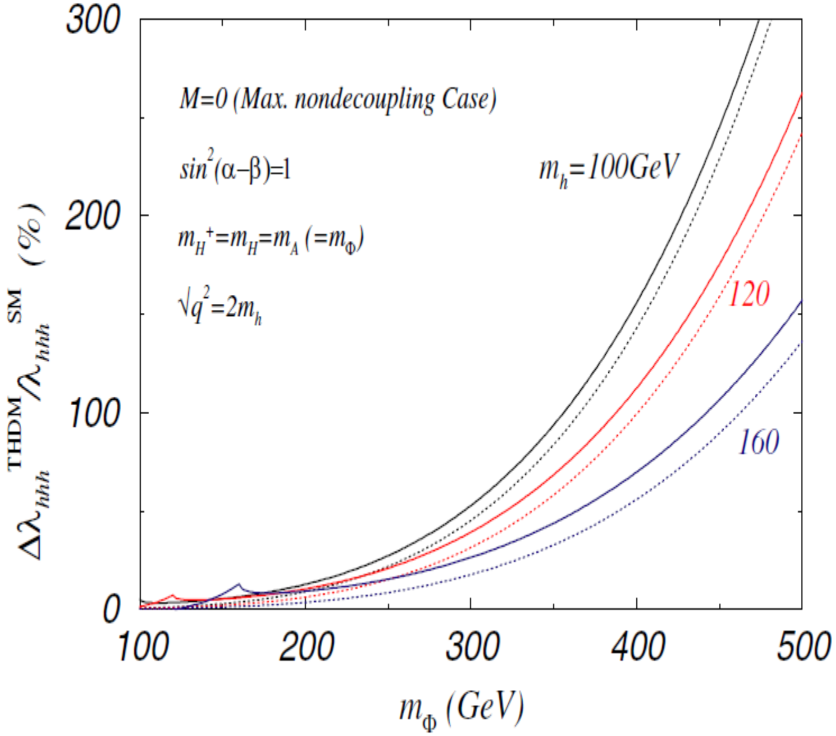
$$|x_i| \leq 1/2$$

Kanemura, Kubota, Takasugi(1993).

hhh coupling in 2HDM

Kanemura, Okada, Senaha, Yuan (2004)





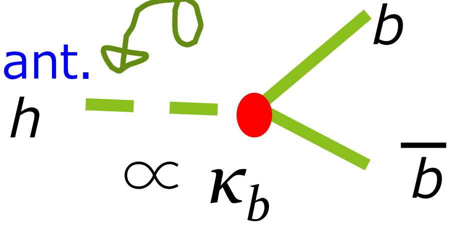
$$m_\Phi^2 = \lambda v^2 + M^2$$

$R_{\gamma\gamma}$

Precision at LHC300fb^{-1} 15%

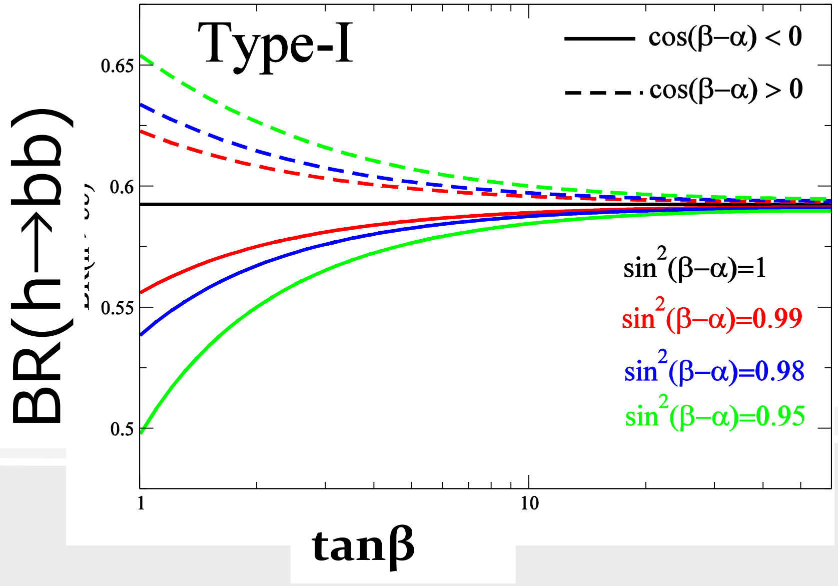
$$R_{\gamma\gamma} \equiv \frac{\sigma(gg\to h)_{\mathrm{THDM}} \times BR(h\to\gamma\gamma)_{\mathrm{TDHM}}}{\sigma(gg\to h)_{\mathrm{SM}} \times BR(h\to\gamma\gamma)_{\mathrm{SM}}} = \frac{\sigma_{\mathrm{THDM}} \times \Gamma(h\to\gamma\gamma)_{\mathrm{THDM}} \times \Gamma(ALL)_{\mathrm{SM}}}{\sigma_{\mathrm{SM}} \times \Gamma(h\to\gamma\gamma)_{\mathrm{SM}} \times \Gamma(\mathrm{ALL})_{\mathrm{THDM}}}$$

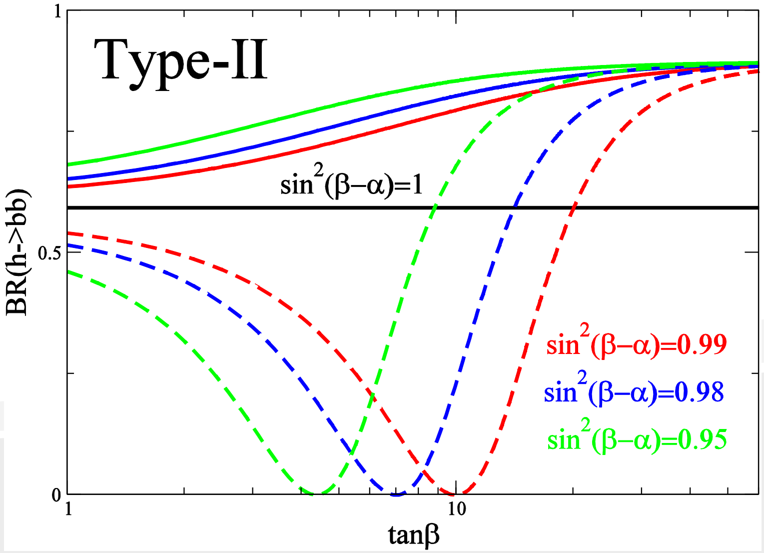
Contribution of h→bb is dominant.



Type I, X $\kappa_b \propto$ sin(β−α) + cotβ cos(β−α)

Type II, Y $\kappa_b \propto$ sin(β-α) − tanβ cos(β−α)





K_f vs $R_{\gamma\gamma}$

We may check the pattern in deviation of *hbb* by evaluating $R_{\gamma\gamma}$.