

Radiative corrections to the Higgs coupling constants in extended Higgs sectors

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1. S. K., M. Kikuchi, K. Yagyu, Physics Letters B731 (2014) 27
2. S. K., M. Kikuchi., K. Yagyu, In preparation

Linear Collider Workshop 2014, 7-10 October 2014, Belgrade, Serbia

Higgs sector remains unknown

The Higgs boson h was found at LHC, and the SM was confirmed to be a good approximation.

However, the minimal Higgs sector of the SM is just a guess without any theory principle

On the other hand, most of non-minimal Higgs sectors can also explain current LHC data as well.

Current Situation: although the Higgs boson was found, we know very little about the Higgs sector yet

- Essence (Scalar? or Composite?)
- Multiplet Structure (1DM, 2HDM, additional Singlet, Triplet, ...)

These are strongly connected to new physics BSM!

Higgs as a Probe of New Physics

Determination of Higgs sector by experiments

- Direct search of the 2nd Higgs (H, A, H^+, H^{++}, \dots)

Yokoya's talk

- Indirect search via detecting deviations in the discovered Higgs boson coupling

$hVV, hff, h\gamma\gamma, hhh, \dots$

Task at LCs!!

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Task at LCs!!

This talk

Future measurement of Higgs Couplings

| Facility | LHC | HL-LHC | ILC500 | ILC500-up |
|-------------------------------------|----------|-----------|---------|-----------|
| \sqrt{s} (GeV) | 14,000 | 14,000 | 250/500 | 250/500 |
| $\int \mathcal{L} dt$ (fb $^{-1}$) | 300/expt | 3000/expt | 250+500 | 1150+1600 |
| κ_γ | 5 – 7% | 2 – 5% | 8.3% | 4.4% |
| κ_g | 6 – 8% | 3 – 5% | 2.0% | 1.1% |
| κ_W | 4 – 6% | 2 – 5% | 0.39% | 0.21% |
| κ_Z | 4 – 6% | 2 – 4% | 0.49% | 0.24% |
| κ_ℓ | 6 – 8% | 2 – 5% | 1.9% | 0.98% |
| $\kappa_d = \kappa_b$ | 10 – 13% | 4 – 7% | 0.93% | 0.60% |
| $\kappa_u = \kappa_t$ | 14 – 15% | 7 – 10% | 2.5% | 1.3% |

Snowmass Report
1310.8361

Coupling constants can be typically
Measured with better than 1 % at ILC

Radiative Corrections

In future, the Higgs couplings will be measured with much better accuracies

Clearly, tree level analyses are not enough

Analysis with Radiative Corrections (including quantum effect of the 2nd Higgs/BSM particles) is necessary

Theoretical predictions
at loop levels

×

Precision measurements
at future colliders



New Physics !

This talk

We discuss *Higgs Couplings* for fingerprinting extended Higgs sectors by future precision data

We here focus on 2HDMs as an example

Radiative correction to the Higgs couplings

Scale Factors: $\kappa_V = g_{hVV}/g_{hVV}^{\text{SM}} \quad (V=W,Z)$
 $\kappa_f = Y_{hff}/Y_{hff}^{\text{SM}} \quad (f=b, \tau, c, \dots)$

Questions:

Model discrimination

Extract properties of the 2nd Higgs boson indirectly
decoupling property/Mass/mixing angles etc

FCNC Suppression

Multi-doublet model: **FCNC appears via Higgs mediation**

2 Higgs doublet model:

To avoid FCNC, give different charges to Φ_1 and Φ_2

ex) Discrete sym. $\Phi_1 \rightarrow +\Phi_1, \quad \Phi_2 = -\Phi_2$

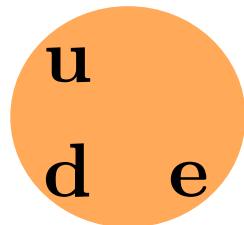
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

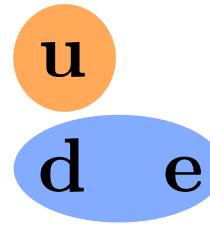
Four Types of Yukawa coupling

Barger, Hewett, Phillips

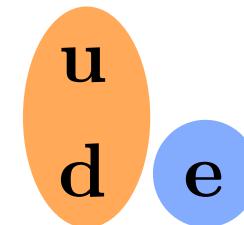
Classified by Z_2 charge assignment



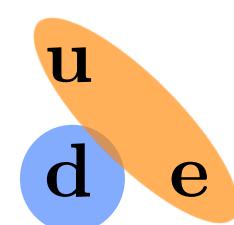
Type-I



Type-II



Type-X



Type-Y

Neutrino Philic etc

SUSY etc

Radiative seesaw etc

2HDM with softly broken Z_2

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

Φ_1 and $\Phi_2 \Rightarrow h, H, A^0, H^\pm \oplus$ Goldstone bosons

\uparrow \uparrow $\uparrow^{\text{charged}}$

CPeven CPodd

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

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

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

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

M_{soft} : soft breaking scale

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i a_i) \end{bmatrix} \quad (i = 1, 2)$$

Diagonalization

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

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

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

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

soft-breaking scale
of the discrete symm.

Fingerprinting the 2HDM (tree level)

$$\kappa_V \equiv \frac{g_{hVV(2HDM)}}{g_{hVV(SM)}} = \sin(\beta - \alpha)$$

$x = \cos^2(\beta - \alpha)$ **SM-like:** $x \ll 1$

$$\kappa_V = 1 - (1/2) x^2 + \dots$$

When a Fermion couples to Φ_1 ,

$$K_f = 1 + \cot\beta x + \dots$$

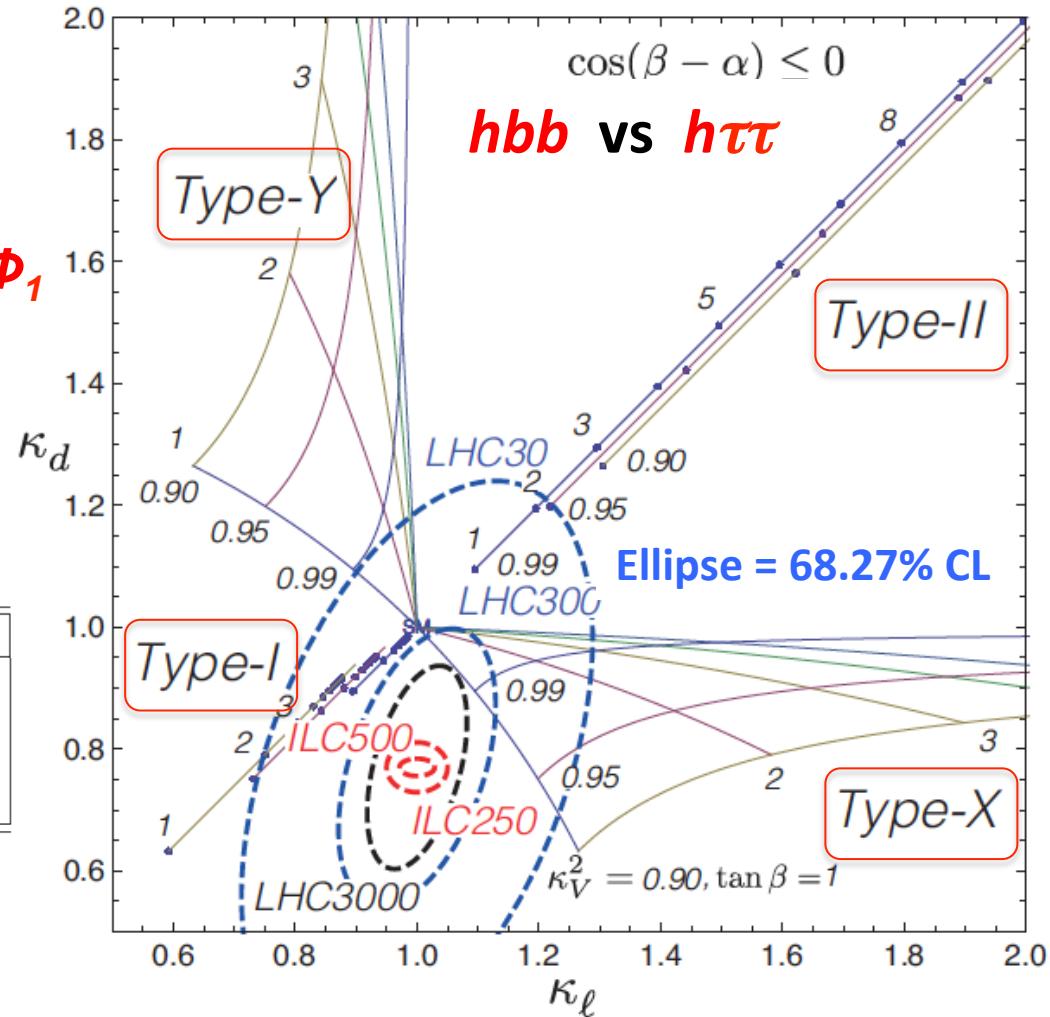
and if it couples to Φ_2

$$K_f = 1 - \tan\beta x + \dots$$

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

How do this result change
with radiative corrections?

SK, K. Tsumura, K. Yagyu, H. Yokoya 2014
ILC Higgs White Paper 2013



Radiative Corrections to the Higgs couplings in the 2HDM

We calculate them in *the modified on-shell scheme*

hZZ hWW

Hollik, Penaranda, Eur. Phys. J. C23 (2002) [in the MSSM]

SK, Kiyoura, Okada, Senaha, Yuan PLB558, (2003);

SK, Okada, Senaha, Yuan, PRD70 (2004).

SK, Kikuchi, Yagyu, in preparation

hbb htt hcc

Guasch, Hollik, Penaranda, PLB515 (2001) [in the MSSM]

Guasch, Hafliger, Spira, PRD68 (2003) [in the MSSM]

SK, Kikuchi, Yagyu, PLB731 (2014)

hhh, ...

SK, Okada, Senaha, Yuan, PRD70 (2004).

Parameters in Higgs potential ; $m_h \ m_H \ m_A \ m_{H^\pm} \ M^2 \ \sin(\beta - \alpha) \ \tan\beta \ v$

Tadpole ; $T_1 \ T_2$

Field mixing ;

Mass Eigenstates ; $h \ H \ A \ H^\pm, \ G^0 \ G^\pm$ $h\text{-}H, \ G^0\text{-}A, \ G^\pm\text{-}H^\pm$

Counter terms; $\delta m_h \ \delta m_H \ \delta m_A \ \delta m_{H^\pm} \ \delta\alpha \ \delta\beta \ (\delta\beta') \ \delta M \ \delta v \ \delta T_h \ \delta T_H$
 $\delta Z_h \ \delta Z_H \ \delta Z_A \ \delta Z_{H^\pm} \ \delta Z_{G^0} \ \delta Z_{G^\pm} \ \delta C_{hH} \ \delta C_{Hh} \ \delta C_{GA} \ \delta C_{AG} \ \delta C_{G^+H^-} \ \delta C_{H^+G^-}$

23 counter terms
in Higgs potential

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} \rightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{G^0} & \delta C_{GA} + \delta\beta \\ -\delta\beta + \delta C_{AG} & 1 + \frac{1}{2}\delta Z_A \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$
 11

Renormalization conditions

Tadpole
2

$$\text{---} \circlearrowleft + \text{---} \otimes = 0$$

2 by vacuum conditions

δT_h δT_H

Mass
4

$$\text{---} \circlearrowleft + \text{---} \otimes \text{---} = 0$$

@ $p^2 = m_\phi^2$

4 by on-shell

δm_h^2 δm_H^2
 δm_A^2 $\delta m_{H^\pm}^2$

mixing
9

$$\text{---} \circlearrowleft + \text{---} \otimes \text{---} = 0$$

@ $p^2 = m_\phi^2 = m_{\phi'}^2$

6 by on-shell + 3 MS for gauge inv.

$\delta\alpha, \delta C_{hH}, \delta C_{Hh}$
 $\delta\beta, \delta C_{GA}, \delta C_{AG},$
 $\delta\beta', \delta C_{G^+H^-}, \delta C_{H^+G^-}$

Wave function renormalization (on-shell)

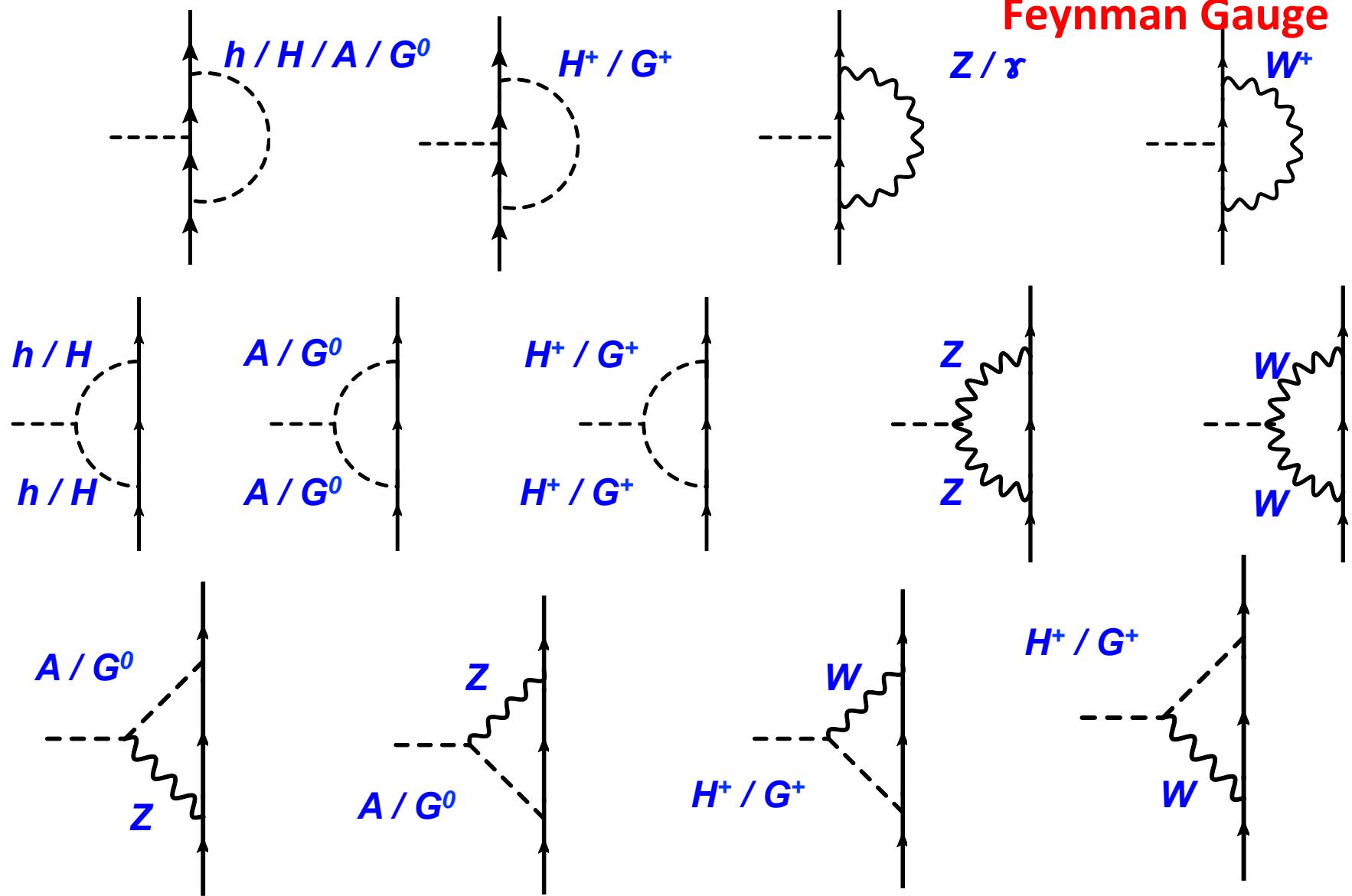
6 δZ_h δZ_H δZ_A δZ_G δZ_{H^+} δZ_{G^+}

VEV **1** δv Renormalize by the condition in the gauge sector

Z_2 breaking scale **1** δM^2 Minimal Subtraction

All 23 counter terms are determined by the 23 conditions

1PI Diagrams for Yukawa Coupling



Scale Factors (1-loop level)

Mixing parameter $x = \cos^2(\beta - \alpha)$ $\left[\sin(\beta - \alpha) = 1 - \frac{x^2}{2} \right]$ **SM-like**
 $x \ll 1$

**Scale Factor
of the hVV Couplings**

$$\Delta\kappa_X = \kappa_X - 1$$

$$\Delta\hat{\kappa}_V \simeq -\frac{1}{2}x^2 - \frac{A(m_\Phi^2, M^2)}{\text{mixing loop}}$$

Loop Effect

$$A(m_\Phi, M) = \frac{1}{16\pi^2} \frac{1}{6} \sum_{\Phi} c_{\Phi} \frac{m_{\Phi}^2}{v^2} \left(1 - \frac{M^2}{m_{\Phi}^2}\right)^2$$

$$m_{\Phi}^2 = M^2 + \lambda_i v^2$$

$(\Phi = H^\pm, A, H)$

where

$$m_{\Phi}^2 \left(1 - \frac{M^2}{m_{\Phi}^2}\right)^2 \begin{cases} \infty & \frac{1}{m_{\Phi}^2} \quad (M \gg v) \\ \infty & m_{\Phi}^2 \quad (M \sim v) \end{cases}$$

Decoupling!

Non-decoupling!

Scale Factors (1-loop level)

SM-like ($x \ll 1$) $\sin(\beta - \alpha) = 1 - \frac{1}{2}x^2$ ($\cos(\beta - \alpha) = x$)

$$\Delta \hat{\kappa}_V \simeq -\frac{1}{2}x^2 - \underbrace{A(m_\Phi^2, M^2)}_{\text{Loop effect}}$$

Yukawa couplings

$$\Delta \hat{\kappa}_\tau - \Delta \hat{\kappa}_V \simeq \xi_\ell x$$

$$\Delta \hat{\kappa}_c - \Delta \hat{\kappa}_V \simeq \xi_u x$$

$$\Delta \hat{\kappa}_b - \Delta \hat{\kappa}_V \simeq \xi_d x - \xi_u \xi_d F_b(m_{H^\pm}, M)$$

$$\Delta \hat{\kappa}_t - \Delta \hat{\kappa}_V \simeq \xi_u x - \xi_u^2 F_t(m_\Phi)$$

| | ξ_u | ξ_d | ξ_ℓ |
|---------|--------------|---------------|---------------|
| 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 | $\cot \beta$ | $-\tan \beta$ | $\cot \beta$ |

Loop Effect

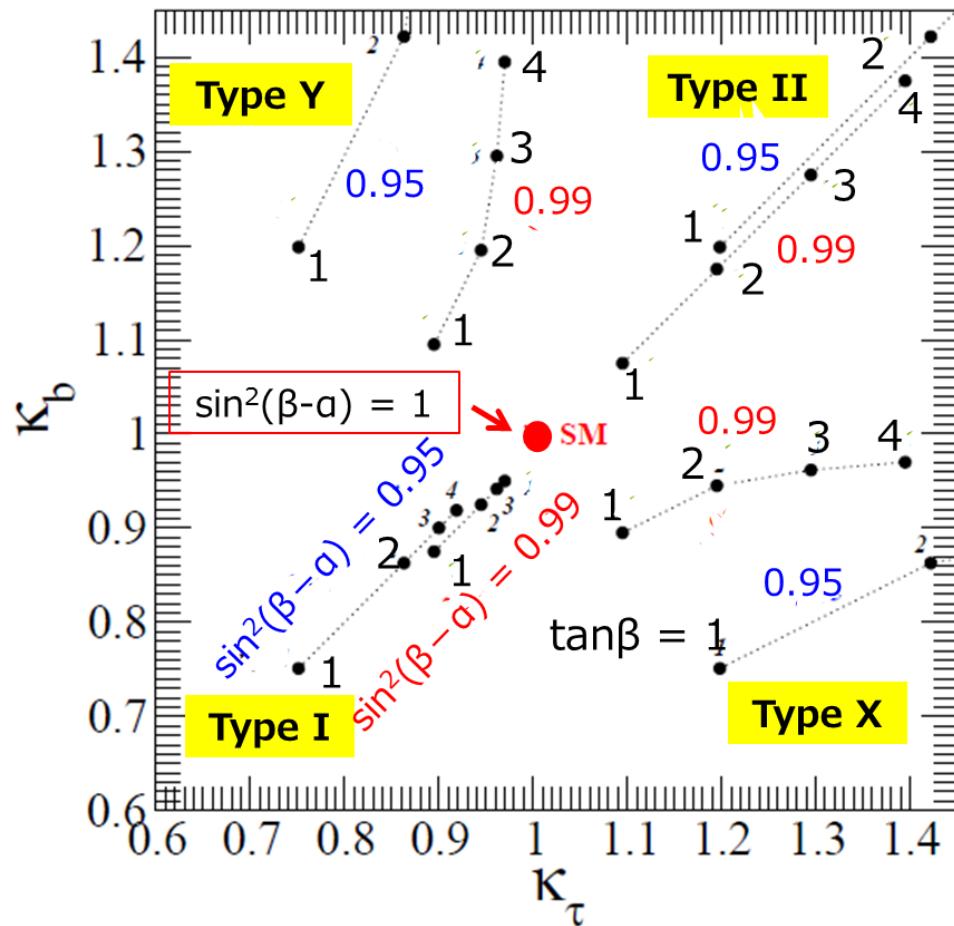
Questions in mind

- Shape SM? 2HDM? Type of Yukawa? Singlet? Triplet?
- Mass scale of the 2nd Higgs boson
- Decoupling property of extra Higgs bosons
Decoupling? or Non-decoupling?

Can we explore these questions by the study of radiative correction to the Higgs-couplings with future precision data?

Which Yukawa Type ? (tree)

| Model | μ | τ | b | c | t | g_V |
|--------------------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Singlet mixing | \downarrow | \downarrow | \downarrow | \downarrow | \downarrow | \downarrow |
| 2HDM-I | \downarrow | \downarrow | \downarrow | \downarrow | \downarrow | \downarrow |
| 2HDM-II (SUSY) | \uparrow | \uparrow | \uparrow | \downarrow | \downarrow | \downarrow |
| 2HDM-X (Lepton-specific) | \uparrow | \uparrow | \downarrow | \downarrow | \downarrow | \downarrow |
| 2HDM-Y (Flipped) | \downarrow | \downarrow | \uparrow | \downarrow | \downarrow | \downarrow |



What is going on with radiative correction?

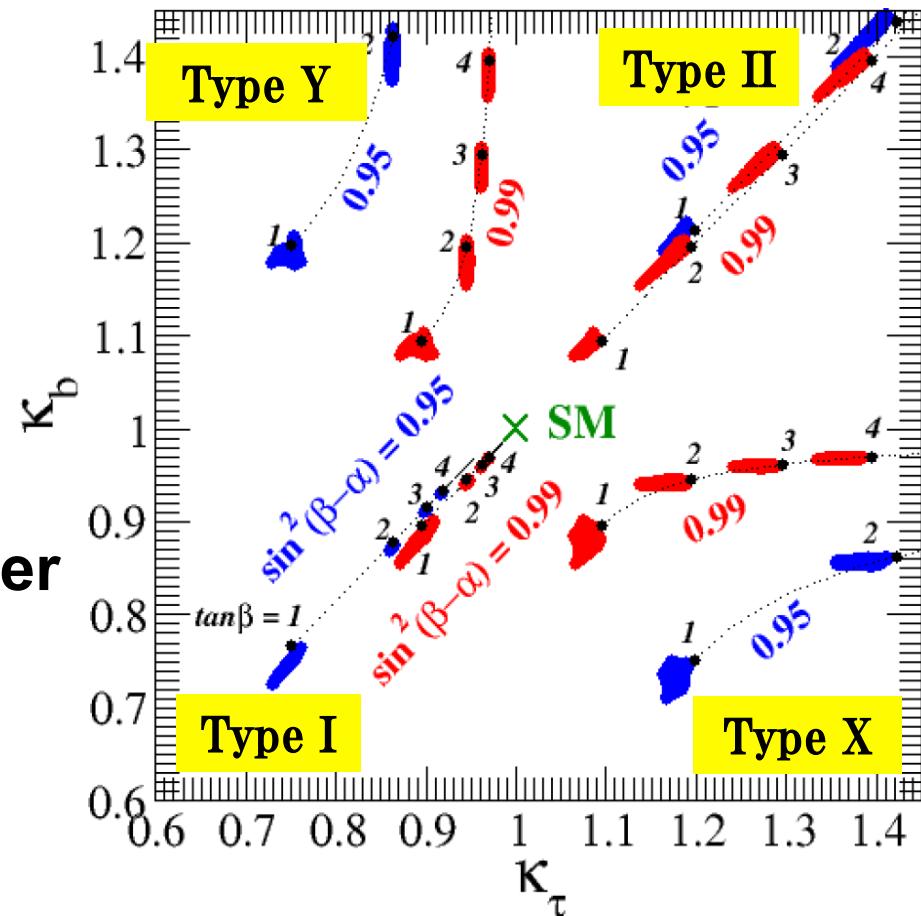
Which Yukawa Type ? (loop)

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| 2HDM-X (Lepton-specific) | ↑ | ↑ | ↓ | ↓ | ↓ | ↓ |
| 2HDM-Y (Flipped) | ↓ | ↓ | ↑ | ↓ | ↓ | ↓ |

Evaluation at one-loop

Scan of inner parameters under theoretical and experimental constraints (for each $\tan\beta$)

The separation of type can also be done at loop level !



Extraction of inner parameters

- For the determination of the Type of Yukawa, Tree-level study is enough.
- We here numerically study how accurately inner parameters can be determined
- Example: suppose that κ_i are measured like

$$\Delta \hat{\kappa}_V = -2.0 \pm 0.4\%$$

$$\Delta \hat{\kappa}_\tau = +18 \pm 1.9\%$$

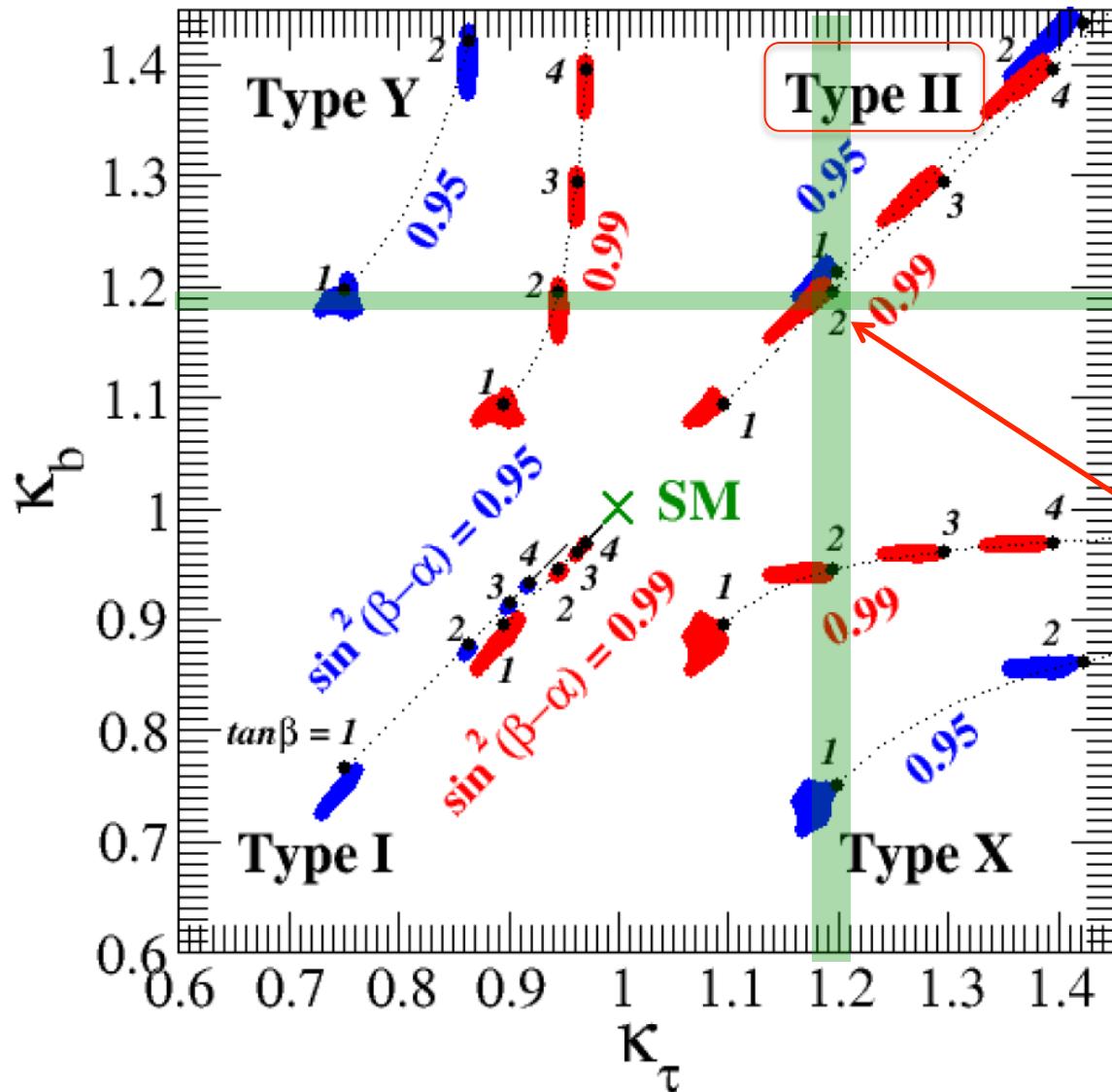
$$\Delta \hat{\kappa}_b = +18 \pm 0.9\%$$

These data indicate that it is **Type-II** in 2HDM

Errors are from ILC(500)
in *Snowmass 2014 Rep.*

How we can know the inner parameters?

$x, m_\phi, \tan\beta, M$



If measured values are

$$\Delta \hat{\kappa}_V = -2.0 \pm 0.4\%$$

$$\Delta \hat{\kappa}_\tau = +18 \pm 1.9\%$$

$$\Delta \hat{\kappa}_b = +18 \pm 0.9\%$$

Errors are from ILC(500)
in Snowmass 2014 Rep.

This point!

$$x = \cos(\beta - \alpha)$$

$$\Delta\hat{\kappa}_\tau - \Delta\hat{\kappa}_V \simeq -\tan\beta x$$

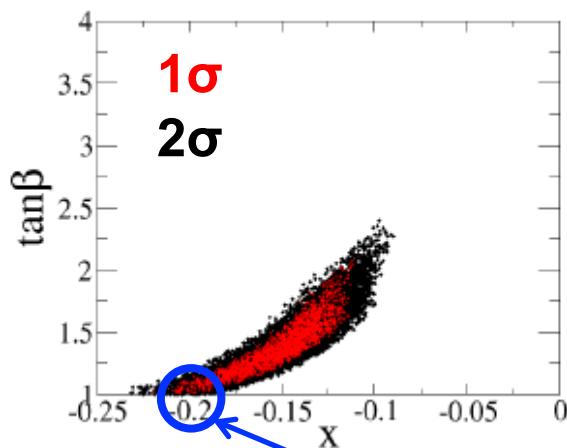
Example

Inputs

Errors are from ILC(500)
in Snowmass 2014 Rep.

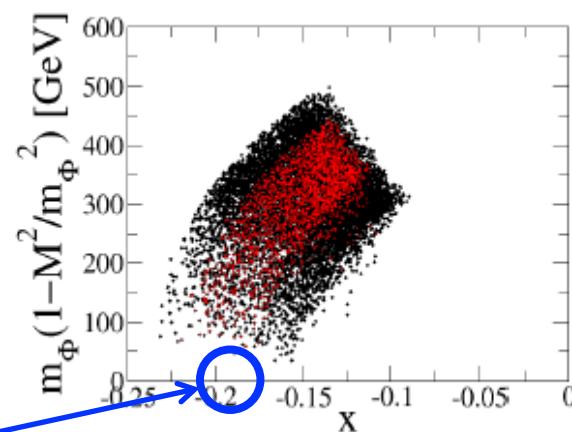
$$\begin{aligned}\Delta\hat{\kappa}_V &= -2.0 \pm 0.4\% \\ \Delta\hat{\kappa}_\tau &= +18 \pm 1.9\% \\ \Delta\hat{\kappa}_b &= +18 \pm 0.9\%\end{aligned}$$

Type-II



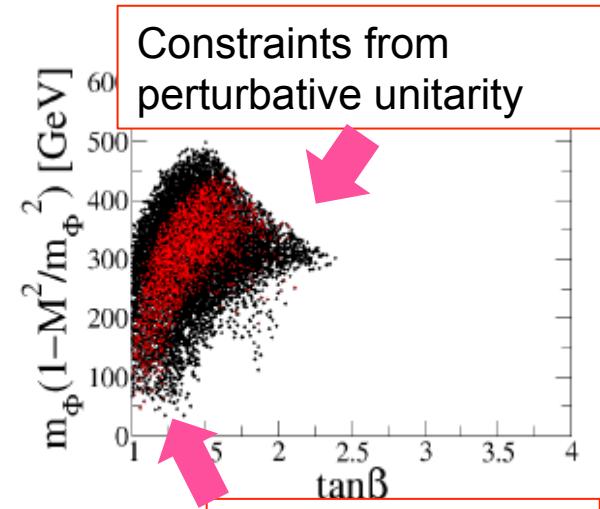
Point by tree-level
analysis

$$\begin{aligned}\Delta\hat{\kappa}_V &\simeq -\frac{1}{2}x^2 - A(m_\Phi^2, M^2) \\ A(m_\Phi, M) &= \frac{1}{16\pi^2} \frac{1}{6} \sum_{\Phi} c_{\Phi} \frac{1}{v^2} \left\{ m_{\Phi} \left(1 - \frac{M^2}{m_{\Phi}^2} \right) \right\}^2 \\ (\Phi &= H^\pm, A, H)\end{aligned}$$



New mass scale
can be extracted!

In addition to the type, parameters x and $\tan\beta$ can be extracted !!



Constraints from
vacuum stability

Summary

- We have calculated a full set of **one-loop corrected Higgs-couplings** in the (modified) on-shell scheme in the 2HDM
- We have discussed how extended Higgs can be indirectly explored by precisely measuring the Higgs-couplings
 - Shape, Mass, Mixing Parameters, Decoupling Property**
- If κ_V turns out to be slightly less than unity, the inner parameters $x, \tan\beta, m_\phi, M, \text{etc}$ can be determined to the considerable extent from the study of h -couplings
- In conclusion, **Higgs-couplings will be definitely a good probe of Higgs sector**

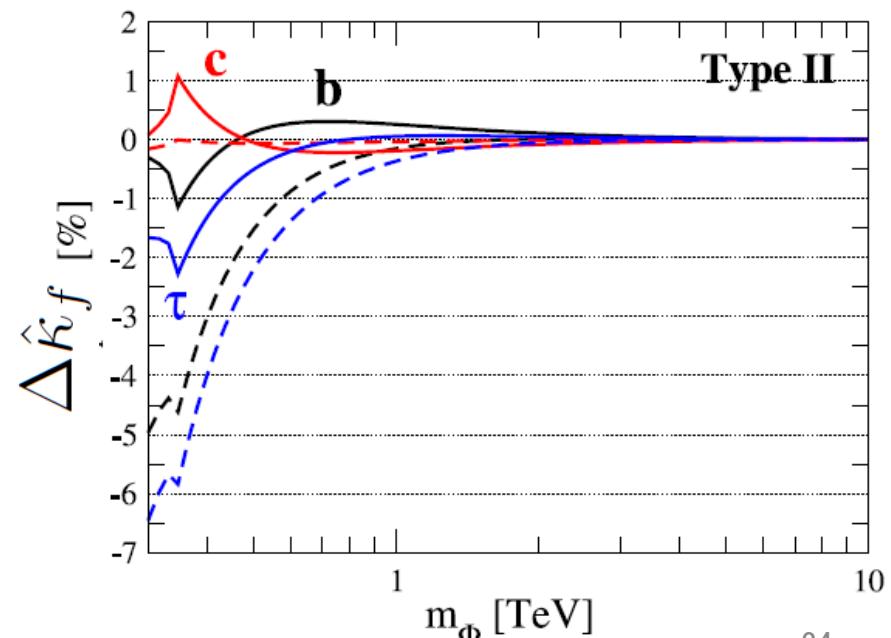
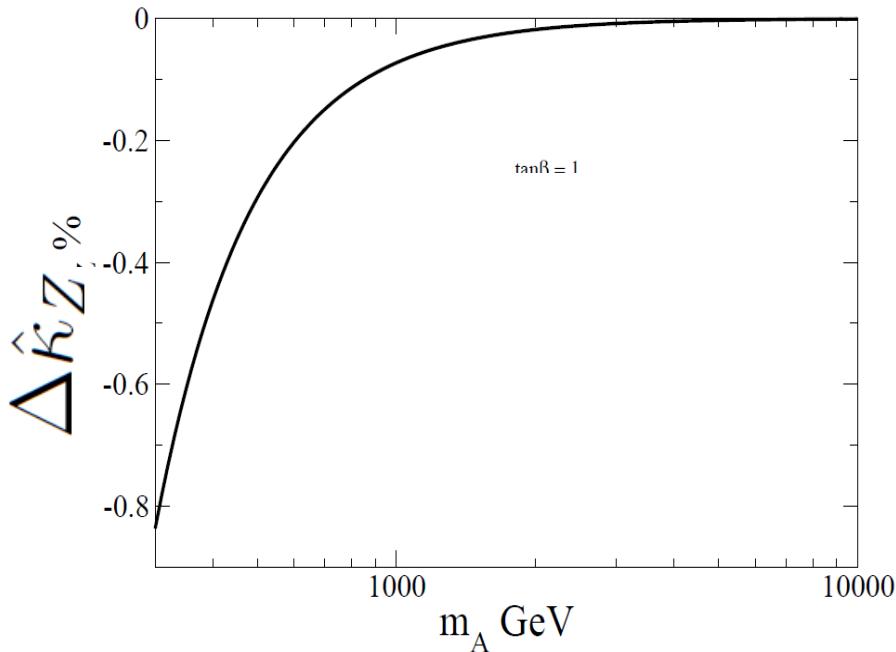
Back up slides

Check of our one-loop calculation code

Behavior of large mass limit

$$\Delta \hat{\kappa}_X = \frac{\hat{g}_{hXX}^{\text{2HDM}} - \hat{g}_{hXX}^{\text{SM}}}{\hat{g}_{hXX}^{\text{SM}}}$$

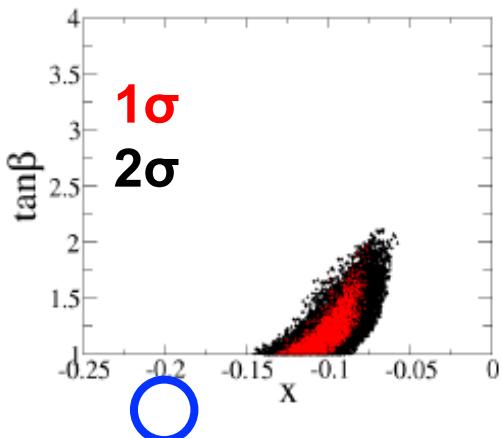
$$m_A^2 = M^2 + (300\text{GeV})^2$$



Example 2

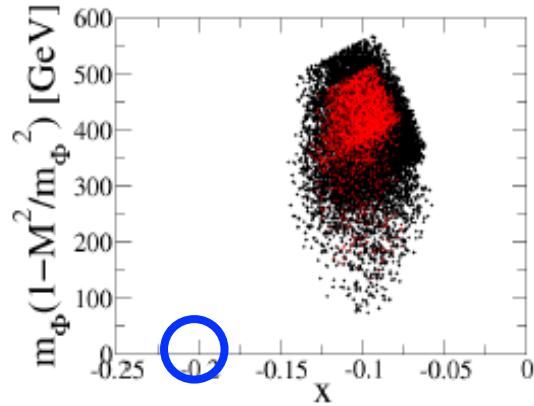
$$\begin{aligned}\Delta \hat{\kappa}_V &= -2.0 \pm 0.4\% \\ \Delta \hat{\kappa}_\tau &= +10 \pm 1.9\% \\ \Delta \hat{\kappa}_b &= +10 \pm 0.9\%\end{aligned}$$

Type-II

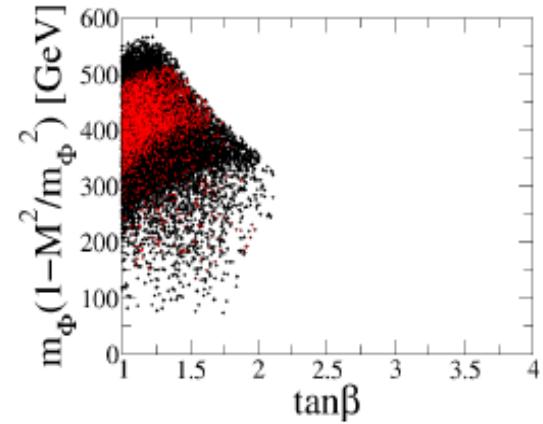


Point by tree-level
analysis

$$\begin{aligned}\Delta \hat{\kappa}_\tau - \Delta \hat{\kappa}_V &\simeq -\tan\beta \times \\ \Delta \hat{\kappa}_V &\simeq -\frac{1}{2}x^2 - A(m_\Phi^2, M^2) \\ A(m_\Phi, M) &= \frac{1}{16\pi^2} \frac{1}{6} \sum_\Phi c_\Phi \frac{1}{v^2} \left\{ m_\Phi \left(1 - \frac{M^2}{m_\Phi^2} \right) \right\}^2 \\ (\Phi &= H^\pm, A, H)\end{aligned}$$



Larger non-decoupling
effect is extracted!



Decoupling/Non-decoupling

Λ : Cutoff

M : Mass scale
irrelevant
to VEV

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2} \mathcal{O}^{(6)}$$

Effective Theory is the SM

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2} \mathcal{O}^{(6)}$$

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

Effective Theory is an extended Higgs sector

Non-decoupling effect

