

# **Discrimination of extended Higgs sectors by precision measurement of the Higgs boson couplings**

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Paper in preparation

# Introduction

- Higgs boson was discovered !  $\Rightarrow$  SM has been completed.
- But, we don't know the Higgs field and the Higgs sector!
  - Negative mass term
  - Elemental scalar? or Composite scalar?
  - # of scalar multiplets, their representations
  - ...
- Each NP model has a characteristic Higgs sector
  - MSSM  $\Phi + \Phi$
  - B-L extended model  $\Phi + S$
  - Type II seesaw  $\Phi + \Delta$
  - ...
- To clarify the structure of the Higgs sector is one of the most important study of NP

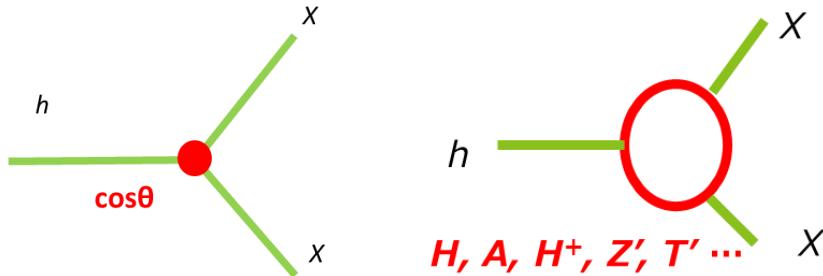
$\Phi$  : Doublet  
 $S$  : Singlet  
 $\Delta$  : Triplet

# How to test extended Higgs sectors

We investigate the possibility of the extended Higgs sectors by using collider experiments.

- Direct Searches of 2<sup>nd</sup> Higgs boson       $H^{++}, H^+, A, H, \dots$
- Indirect Searches  
IS through coupling constants of 125 GeV Higgs boson!

$hZZ, hWW, h\gamma\gamma, hgg, h\gamma Z, hbb, h\tau\tau, htt, hhh, \dots$



In order to compare with future precision data of Higgs boson couplings measurements by O(1) % level,  
we should investigate these couplings with higher order corrections in several extended Higgs sectors

# Our projects

Project Authors:  
S. Kanemura, M. Kikuchi, K.Yagyu

- We calculate a full set of 125 GeV Higgs boson couplings with radiative corrections in the 7 models. (Without QCD corrections)

- **HSM**  
Kanemura, MK, Yagyu, in preparation
- **4 types of 2HDMs**  
Kanemura, MK, Yagyu, NPB 896,80(2015)  
Kanemura, MK, Yagyu, PLB731 (2014)27
- **IDM**  
Kanemura, MK, Sakurai, in preparation
- **HTM**  
Aoki, Kanemura, MK, Yagyu; PRD87,015012(2013),  
Kanemura, MK, Yagyu, in preparation



*hZZ, hWW, hbb, hττ, htt, hcc,  
hγγ, hγZ, hgg, hh*

- We make the program code group of the calculation for the 1-loop corrected Higgs boson couplings.

*hZZ, hWW, hγγ, hgg,  
hγZ, hbb, hττ, htt, hh, ...*



Precision  
measurements



Determination of  
the Higgs sector !!

Radiative corrections

- We had created numerical calculation code for  $h_{125}$  couplings in all 7 models.

# **Calculations of One-loop corrected Higgs boson couplings**

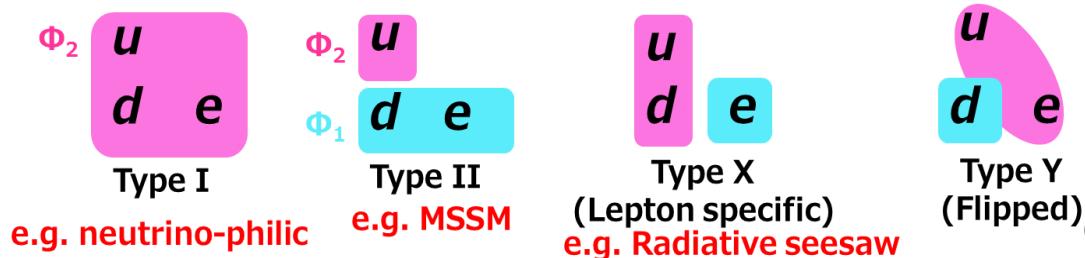
# Model list

S : Singlet,  $\Phi$  : Doublet,  $\Delta$  : Triplet

- Renormalizable theory
- Second simplest Higgs sectors

Theories with second simplest Higgs sectors are effective theories of infinite extended Higgs models.

|   | Scalar fields | Symmetry         |
|---|---------------|------------------|
| ■ Higgs Singlet Model (HSM)                     | $\Phi + S$    |                  |
| ■ 4 types of Two Higgs doublet model<br>(THDMs) | $\Phi + \Phi$ | Softly broken Z2 |

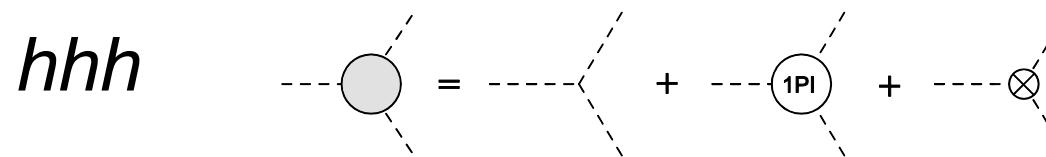
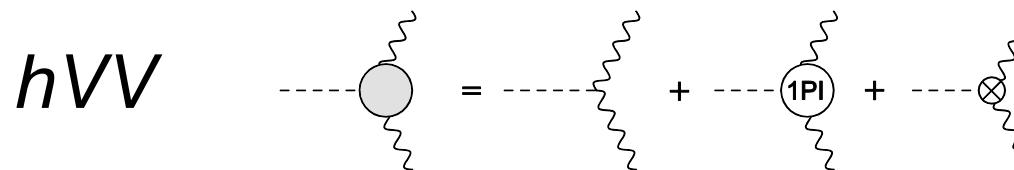
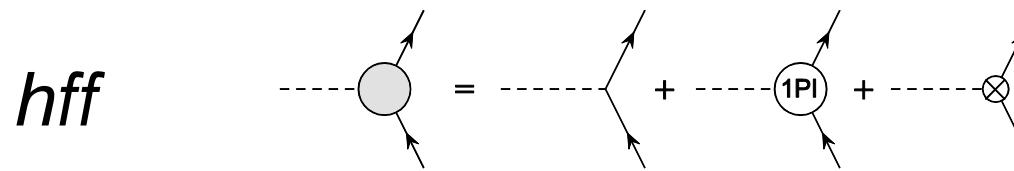


|                             |                 |          |
|-----------------------------|-----------------|----------|
| ■ Inert doublet model (IDM) | $\Phi + \Phi$   | Exact Z2 |
| ■ Higgs triplet model (HTM) | $\Phi + \Delta$ |          |

# $h_{125}$ couplings

- We calculate 1-loop corrected Higgs couplings by on-shell scheme
- QCD corrections are still not included in our calculations.

$hZZ, hWW, hbb, h\tau\tau, htt, hcc, h\gamma\gamma, h\gamma Z, hgg, hhh$



- Most of them will be measured by typically  $O(1)$  % at HL-LHC and future lepton colliders such as ILC.

# Constraints

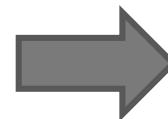
- We incorporate theoretical constraints to our program.
  - Perturbative unitarity
  - Vacuum stability
  - The condition to avoid wrong vacuum (only HSM)
- We will add constraints from experiments
  - Constraints from EW precision data
    - $m_W$
    - $S, T, U$
  - ...

# **Discriminating models by comparing one-loop corrected couplings and future precision measurements**

- We can investigate how large  $h$  couplings deviate from the SM predictions at one-loop level.

**Inner parameters**

$m_\phi$ , mixing parameters, ...



$h_{125}$  couplings,  
 $\kappa_x, \Delta\kappa_x$

**Ex.>>** The pattern of deviations in Yukawa couplings in 4 types of 2HDMs

Deviations in scaling factor

$$\Delta\kappa_X \equiv \frac{\hat{\Gamma}_{hXX}[p_1^2, p_2^2, q^2]}{\hat{\Gamma}_{hXX,SM}[p_1^2, p_2^2, q^2]} - 1$$

### Parameter range in 2HDM

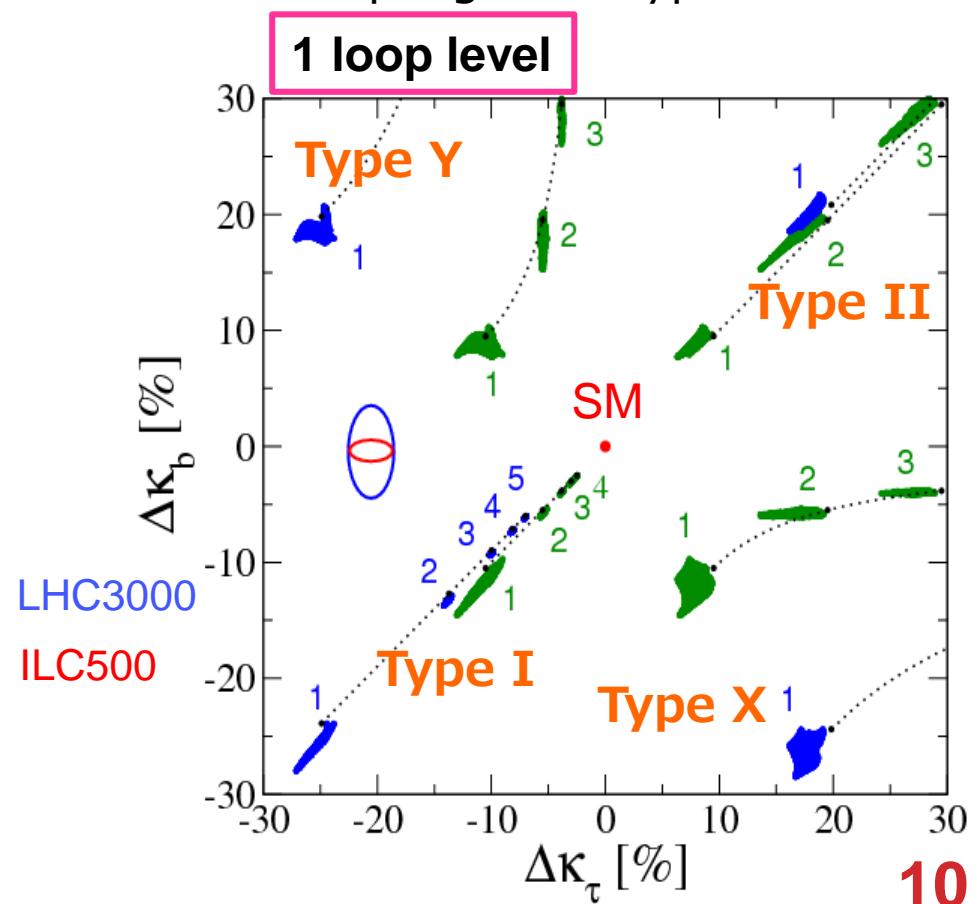
$300\text{GeV} < m_\phi < 1000\text{GeV}$ ,

$0 < M^2 < (1000\text{GeV})^2$

$$(m_H = m_A = m_{H^\pm})$$

### Constraints

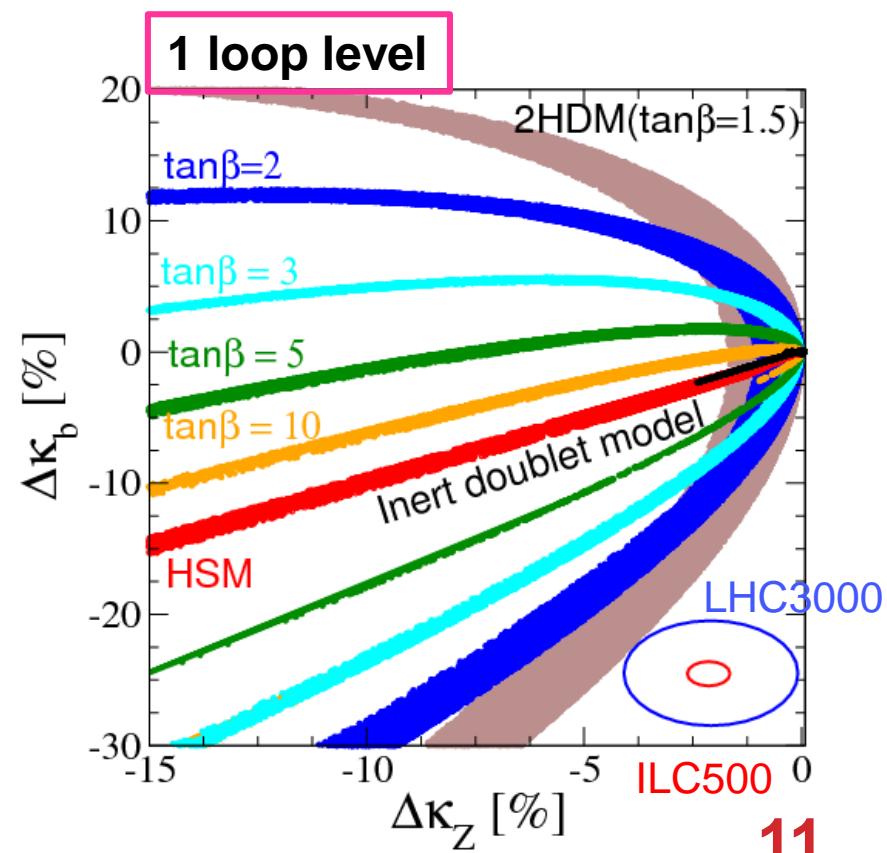
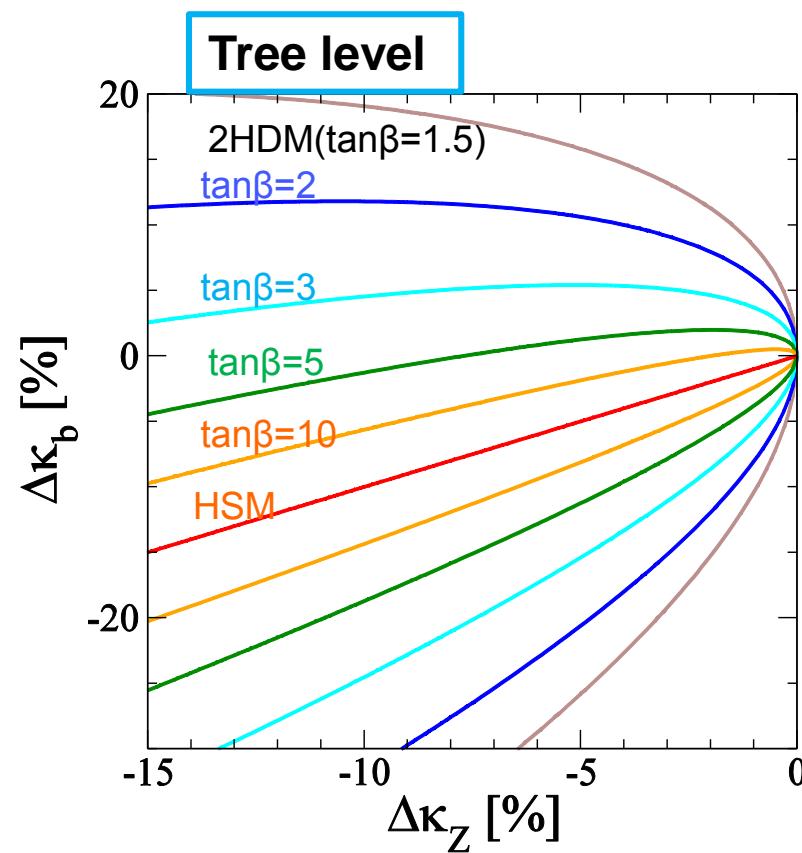
- Perturbative unitarity
- Vacuum stability



- We can investigate how large h couplings deviate from the SM predictions at one-loop level.

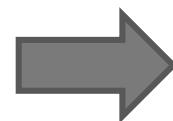
**Inner parameters**  $m_\phi$ , mixing parameters, ... →  **$h_{125}$  couplings,**  
 $\kappa_x, \Delta\kappa_x$

Ex.>>  $\Delta\kappa_z$  VS  $\Delta\kappa_b$  in **HSM** **2HDM(Type I)** **IDM**



- We can investigate how large h couplings deviate from the SM predictions at one-loop level.

**Inner parameters**  
 $m_\phi$ , mixing parameters, ...



**$h_{125}$  couplings,**  
 $\kappa_x, \Delta\kappa_x$

**Ex.>>  $\Delta\kappa_z$  VS  $\Delta\kappa_b$  in HSM 2HDM(Type I) IDM**

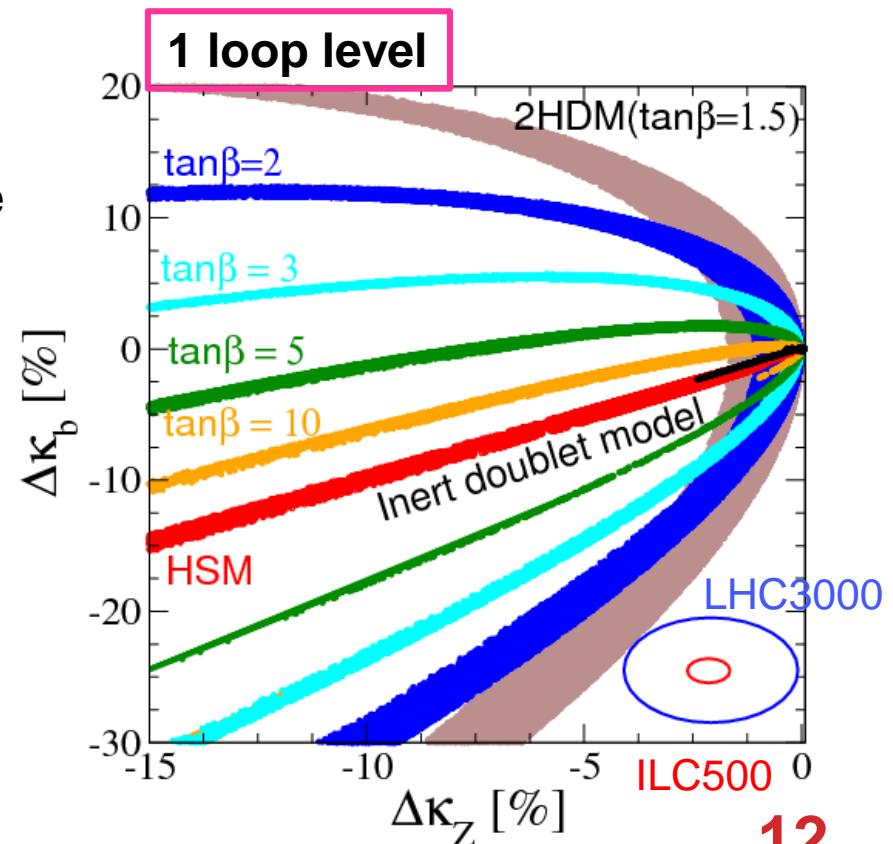
## HSM

- $\Delta\kappa_z$  and  $\Delta\kappa_b$  take a common form at the tree level.

$$\Delta\kappa_z = \Delta\kappa_b = (\cos\alpha - 1)$$



$hZZ$  and  $hbb$  deviate to the directions with the rate 1 : 1 by the mixing effect.  
The small width of the line of 1 : 1 is made by the one-loop contributions.



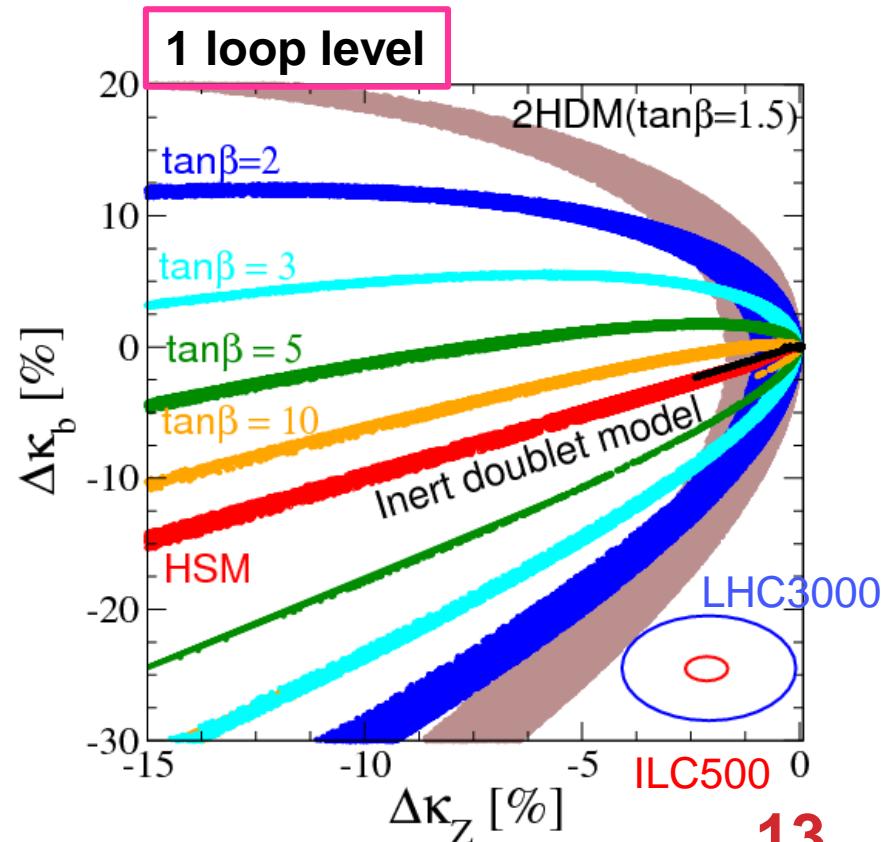
- We can investigate how large  $h$  couplings deviate from the SM predictions at one-loop level.



Ex.>> Δκ<sub>Z</sub> VS Δκ<sub>b</sub> in **HSM** **2HDM(Type I)** **IDM**

## 2HDM(Type I)

- Δκ<sub>Z</sub> and Δκ<sub>b</sub> are substantially modified by radiative corrections in the case for low tan  $\beta$  values.
- As the value of tan  $\beta$  become large, the Δκ<sub>Z</sub> and Δκ<sub>b</sub> plane prediction approximates the line of 1 : 1.
- Parameter regions for tan $\beta \geq 10$ , cos( $\beta - \alpha$ ) < 0, m<sub>φ</sub> > 300 GeV are excluded by the perturbative unitarity and vacuum stability.



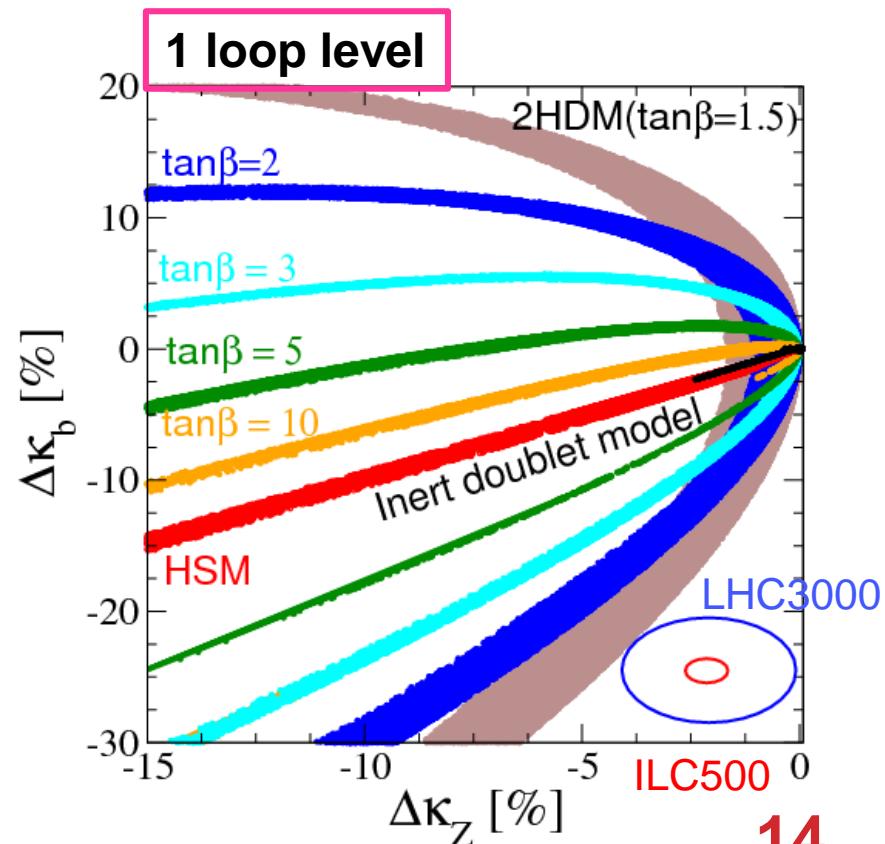
- We can investigate how large h couplings deviate from the SM predictions at one-loop level.



Ex.>>  $\Delta\kappa_z$  VS  $\Delta\kappa_b$  in **HSM** **2HDM(Type I)** **IDM**

## IDM

- $\Delta\kappa_z$  and  $\Delta\kappa_b$  move with same ratio.
- The deviations in the couplings product via pure one loop corrections
- Because of constraints from perturbative unitarity, the deviations can not be larger than about 2 %.



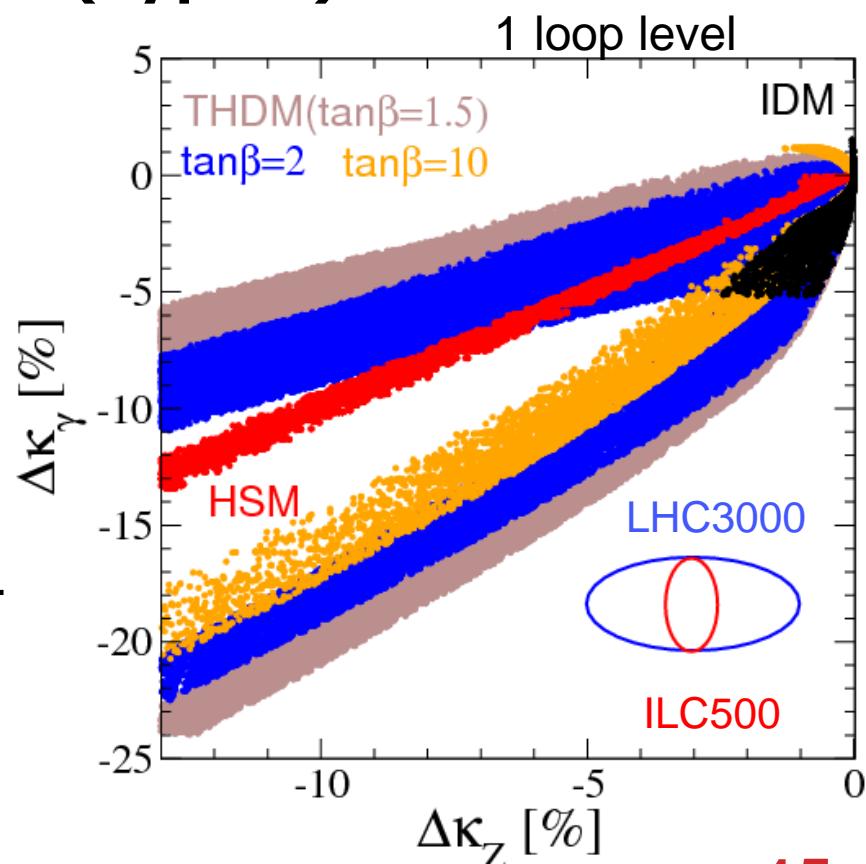
- We can investigate how large h couplings deviate from the SM predictions at one-loop level.

**Inner parameters**  $m_\phi$ , mixing parameters, ... →  **$h_{125}$  couplings,**  
 **$\kappa_x, \Delta\kappa_x$**

Ex.>>  $\Delta\kappa_Z$  VS  $\Delta\kappa_\gamma$  in **HSM** **2HDM(Type I)** **IDM**

## HSM

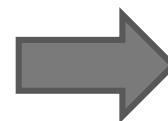
- There is no charged new particle.  
→ Deviations in  $h\gamma\gamma$  are made by mixing effects.
- $hZZ$  and  $h\gamma\gamma$  deviate to the directions with the rate 1 : 1 by the mixing effect.



- We can investigate how large h couplings deviate from the SM predictions at one-loop level.

**Inner parameters**

$m_\phi$ , mixing parameters, ...

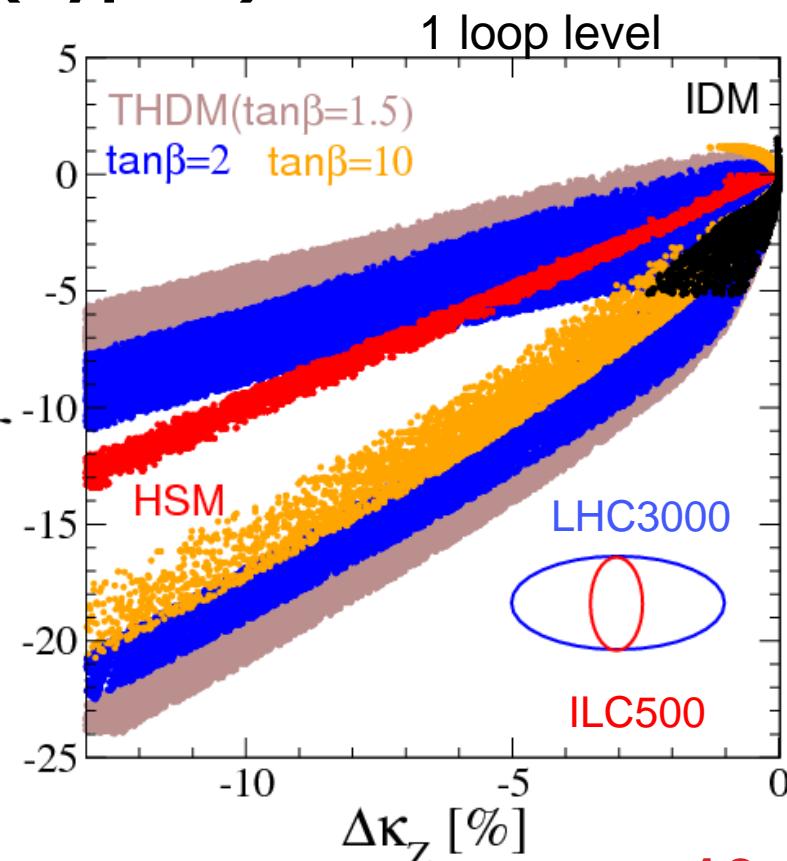
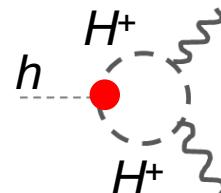


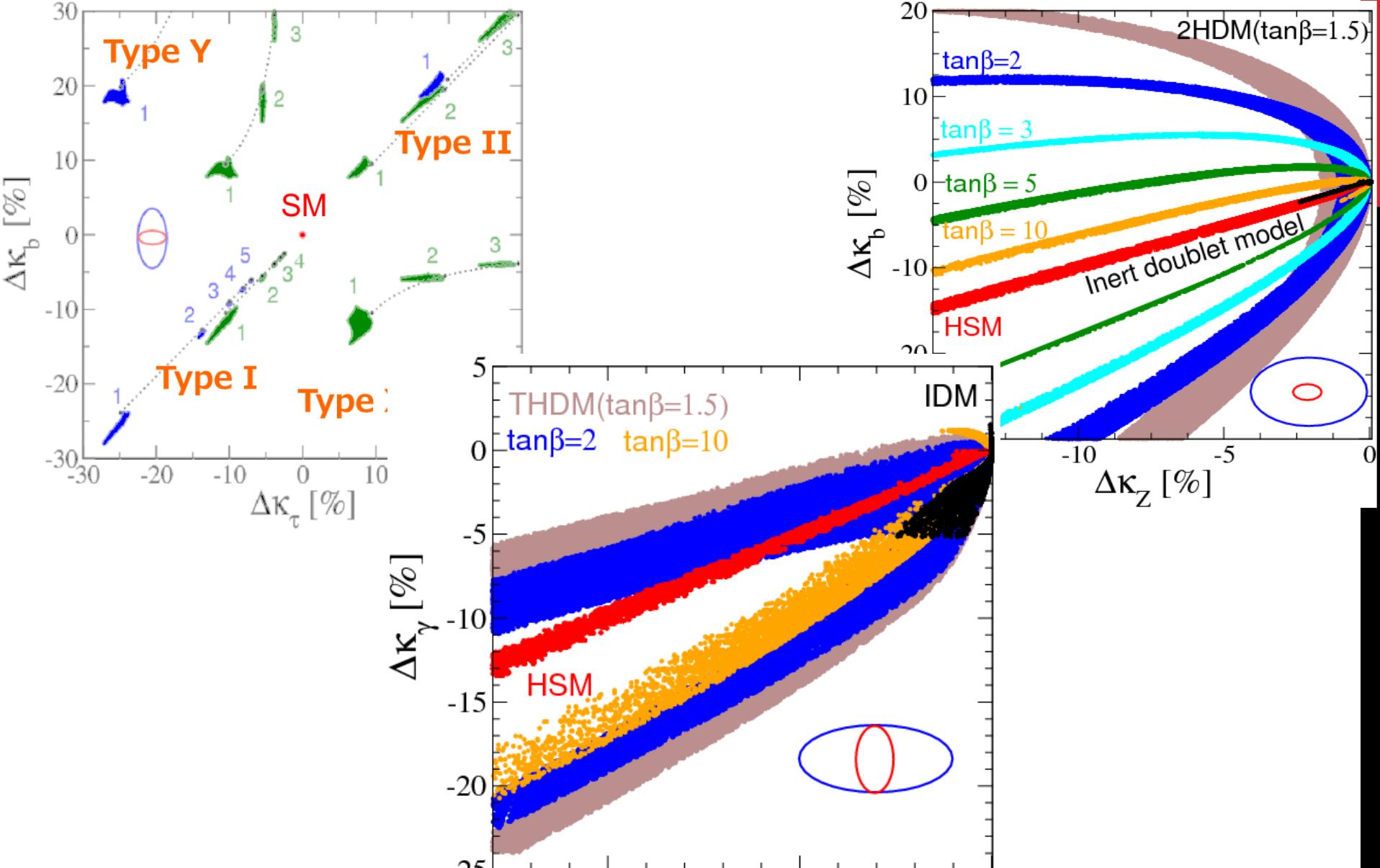
**$h_{125}$  couplings,**  
 $\kappa_x, \Delta\kappa_x$

**Ex.>>  $\Delta\kappa_z$  VS  $\Delta\kappa_\gamma$  in HSM 2HDM(Type I) IDM**

## 2HDM(Type I)

- Mixing effects and singly charged Higgs bosons loop contributions modify the value of  $\Delta\kappa_\gamma$ .
- $\Delta\kappa_\gamma$  depends on the sign of  $\cos(\beta - \alpha)$
- There are allowed regions with  $\Delta\kappa_\gamma > 0$ , which are caused by inverting the sign of the  $hH^+H^-$  coupling.





In most of parameter regions except the decoupling limit, we can discriminate models by using the pattern of deviations in various Higgs couplings, even if there is no discovery of new particles.

# Summary

- A full set of fortran code for Higgs couplings in extended Higgs sectors had been completed.

- HSM
- 4 types of 2HDMs
- IDM
- HTM



$hZZ, hWW, hbb, h\tau\tau, htt, hcc,$   
 $h\gamma\gamma, h\gamma Z, hgg, hh$

$hZZ, hWW, h\tau\tau, hgg,$   
 $h\gamma Z, hbb, h\tau\tau, htt, hh$ , ...



Precision  
measurements



Determination of  
the Higgs sector !!

Radiative corrections

- Future work

- Other renormalization scheme (MS scheme)
- Calculation of  $\sigma$ , Br, ...
- Incorporating QCD corrections
- Calculation of extra Higgs boson couplings “ $hhH$ ,  $hAA$ ,  $HVV$ ,  $Hff$ ,  $hAH+$ , ...”
- Other models



# Higgs singlet model

$$V(\Phi, S) = m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \lambda_{\Phi S} |\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4,$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(\phi + v + iG^0) \end{pmatrix}, \quad S = s + v_S.$$

- Mass eigenstates

$$\begin{pmatrix} s \\ \phi \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

SM-like Higgs boson      ***h***,      ***H***  
Extra Higgs boson

$$m_h^2 = 2\lambda v^2 + \mathcal{O}\left(\frac{v^4}{\tilde{M}^2}\right) \quad (\tilde{M}^2 \gg v^2)$$

$$m_H^2 = \tilde{M}^2 + \lambda_{\Phi S} v^2 + \mathcal{O}\left(\frac{v^4}{\tilde{M}^2}\right) \quad \tilde{M}^2 = 2m_S^2 + 12\lambda_S v_S^2 + 6v_S \mu_S$$

- Parameters(8)

$$v \approx 246 \text{ GeV} \quad m_h \approx 126 \text{ GeV}$$

$$\underline{m_H \quad a \quad \mu_S \quad \lambda_{\Phi S} \quad \lambda_S \quad v_S}$$

- Scaling factors of ***h***<sub>125</sub> couplings at tree level

$$\kappa_V = \kappa_f = \cos \alpha,$$

$$\kappa_h = c_\alpha^3 + \frac{2v}{m_h^2} s_\alpha^2 (\lambda_{\Phi S} v c_\alpha - \mu_S s_\alpha - 4s_\alpha \lambda_S v_S).$$

## < Parameter range in HSM >

$300\text{GeV} < m_H < 1000\text{GeV},$

$-15 < \lambda_{\Phi S} < 15,$

$-15 < \lambda_S < 15,$

$0.80 < \cos \alpha < 1,$

$-2000\text{GeV} < \mu_S < 2000\text{GeV}.$

## < Parameter range in 2HDM >

$300\text{GeV} < m_H (= m_A = m_{H^\pm}) < 1000\text{GeV},$

$0 < M^2 < (1000\text{GeV})^2,$

$0.80 < \sin(\beta - \alpha) < 1.$

## < Parameter range in IDM >

$300\text{GeV} < m_H (= m_A = m_{H^\pm}) < 1000\text{GeV},$

$0 < \mu_2^2 < (1000\text{GeV})^2$

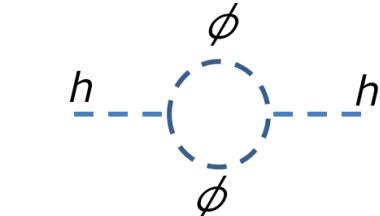
# One-loop contributions

Approximate formulae (SM like limit)  $x \ll 1$

$$\Delta\kappa_X = \kappa_X - 1 \quad (\text{1-loop level}) \quad (\Phi = H^\pm, A, H)$$

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

mixing Loop



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

Loop effects

$$m_\Phi^2 \left(1 - \frac{M^2}{m_\Phi^2}\right)^2 \begin{cases} \infty \frac{1}{m_\Phi^2} & (M \gg v) \quad \text{Decoupling!} \quad (\eta \rightarrow 0) \\ \infty m_\Phi^2 & (M \sim v) \quad \text{Non-decoupling!} \quad (\eta \rightarrow 1) \end{cases}$$

$$\text{Decoupling property : } \eta = 1 - \frac{M^2}{m_\Phi^2}$$

$$\Delta\hat{\kappa}_b \simeq \Delta\hat{\kappa}_V + \xi_d x - \frac{1}{16\pi^2} \xi_u \xi_d \frac{2m_t^2}{v^2} \left(1 - \frac{m_t^2}{m_{H^\pm}^2} - \frac{M^2}{m_{H^\pm}^2}\right) - \frac{1}{16\pi^2} \frac{1}{6} \xi_d^2 \sum_{\Phi=A,H,H^\pm} \frac{m_b^4}{v^2 m_\Phi^2},$$

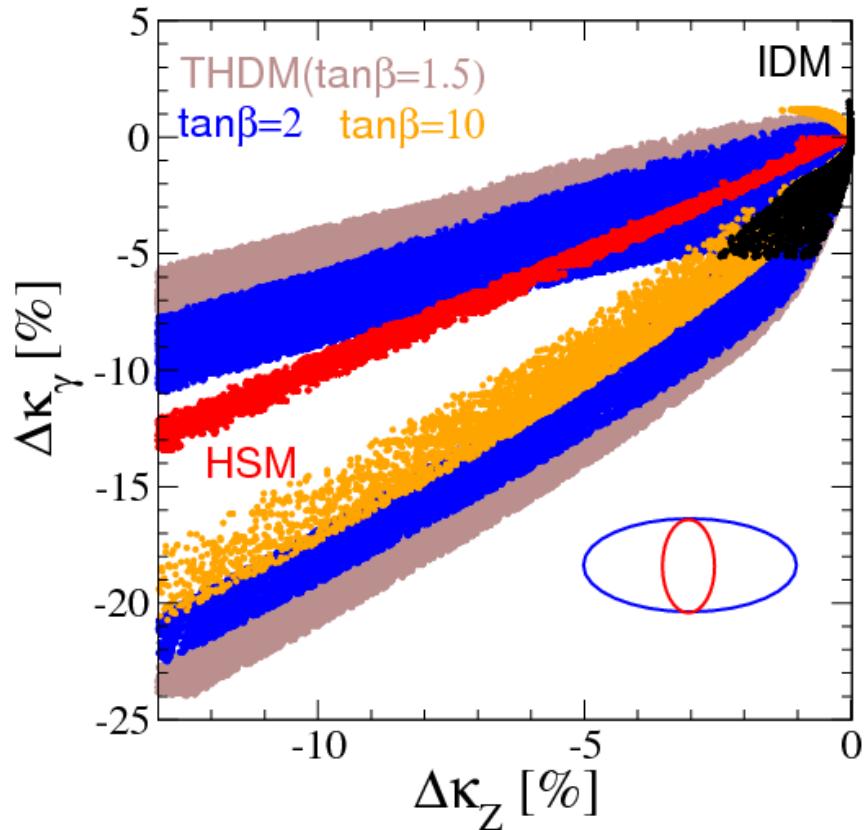
$$\Delta\hat{\kappa}_\tau \simeq \Delta\hat{\kappa}_V + \xi_e x,$$

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

$$\Delta\hat{\kappa}_t \simeq \Delta\hat{\kappa}_V + \xi_u x - \frac{1}{16\pi^2} \frac{1}{6} \left[ \xi_u^2 \sum_{\Phi=A,H,H^\pm} \frac{m_t^4}{v^2 m_\Phi^2} + \xi_d^2 \frac{m_b^2 m_t^2}{v^2 m_{H^\pm}^2} \right],$$

## 2HDM(Type I)

$$\Gamma(h \rightarrow \gamma\gamma) \cong \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3} \left| -\frac{1}{3} \left( 1 - \frac{M^2}{m_{H+}^2} \right) + Q_t N_c^t (\sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)) I_t + \sin(\beta - \alpha) I_W \right|$$



## IDM

$$\Gamma(h \rightarrow \gamma\gamma) \cong \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3} \left| -\frac{1}{3} \left( 1 - \frac{\mu_2^2}{m_{H+}^2} \right) + Q_t N_c^t I_t + I_W \right|$$

# PARAMETRIC UNCERTAINTIES

|                             |                  |                        |                 | Parametric Uncertainties<br>of $hXX$ couplings |      |      |
|-----------------------------|------------------|------------------------|-----------------|--|------|------|
|                             | $\delta m_b(10)$ | $\delta \alpha_s(m_Z)$ | $\delta m_c(3)$ | $hbb$ ,<br>$hcc$ ,<br>$hgg$                    | [%]  |      |
| current errors [10]         | 0.70             | 0.63                   | 0.61            | 0.77   | 0.89 | 0.78 |
| + PT                        | 0.69             | 0.40                   | 0.34            | 0.74   | 0.57 | 0.49 |
| + LS                        | 0.30             | 0.53                   | 0.53            | 0.38   | 0.74 | 0.65 |
| + LS <sup>2</sup>           | 0.14             | 0.35                   | 0.53            | 0.20   | 0.65 | 0.43 |
| + PT + LS                   | 0.28             | 0.17                   | 0.21            | 0.30   | 0.27 | 0.21 |
| + PT + LS <sup>2</sup>      | 0.12             | 0.14                   | 0.20            | 0.13   | 0.24 | 0.17 |
| + PT + LS <sup>2</sup> + ST | 0.09             | 0.08                   | 0.20            | 0.10   | 0.22 | 0.09 |
| ILC goal                    |                  |                        |                 | 0.30   | 0.70 | 0.60 |

PT ; 4<sup>th</sup> order QCD perturbative theory

LS, LS<sup>2</sup>; reduction of lattice spacing

ST; increasing the statistics of simulation

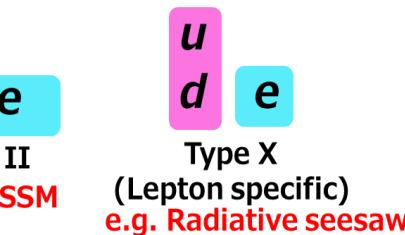
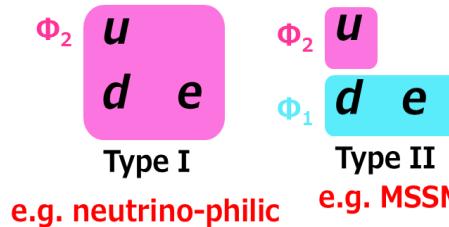
Lepage, Mackenzie,  
Peskin [1401.0319]

# 2HDM, IDM

## 2HDMs

- Softly break Z2 sym.

$$\begin{aligned}\Phi_1 &\rightarrow +\Phi_1 \\ \Phi_2 &\rightarrow -\Phi_2\end{aligned}$$



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

Soft breaking  
scale of Z2 sym.

- Mass eigenstates

$h, H A H^\pm$

- $h(125)$  coupling constants (tree level)

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

If  $f$  couples to  $\Phi_2$

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

If  $f$  couples to  $\Phi_1$

$$\kappa_f = \sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha)$$

## IDM

- Additional scalar field  $\Phi_2$  is  $Z_2$ -odd

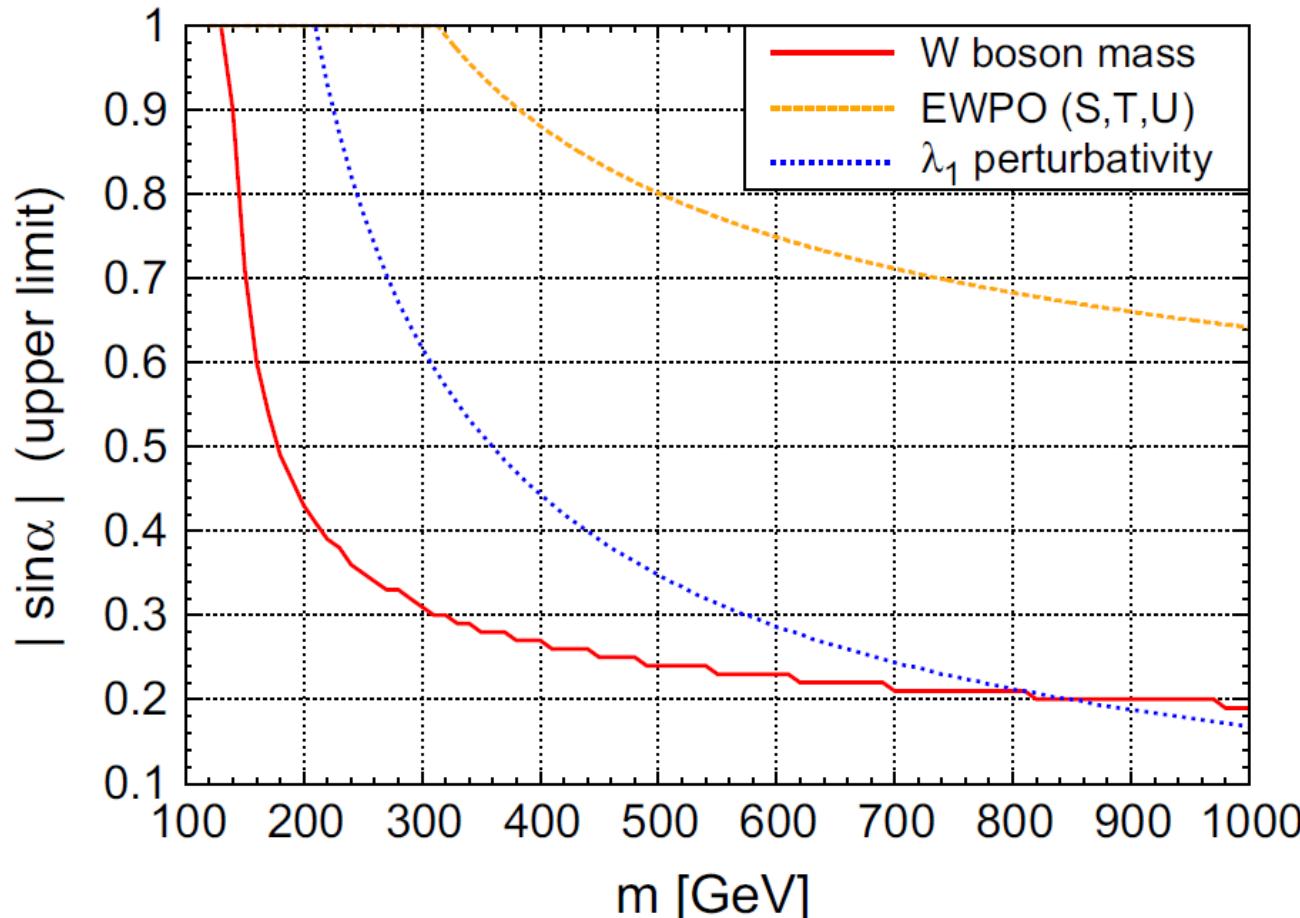
$$\text{Eigenstates } h, H A H^\pm \quad m_\Phi^2 \cong \lambda' v^2 + \mu^2$$

- $h(125)$  coupling constants  
(tree level)  $\kappa_X = 1$

# ELECTROWEAK PRECISION DATA

Higgs Singlet Model with a spontaneously broken Z<sub>2</sub> sym

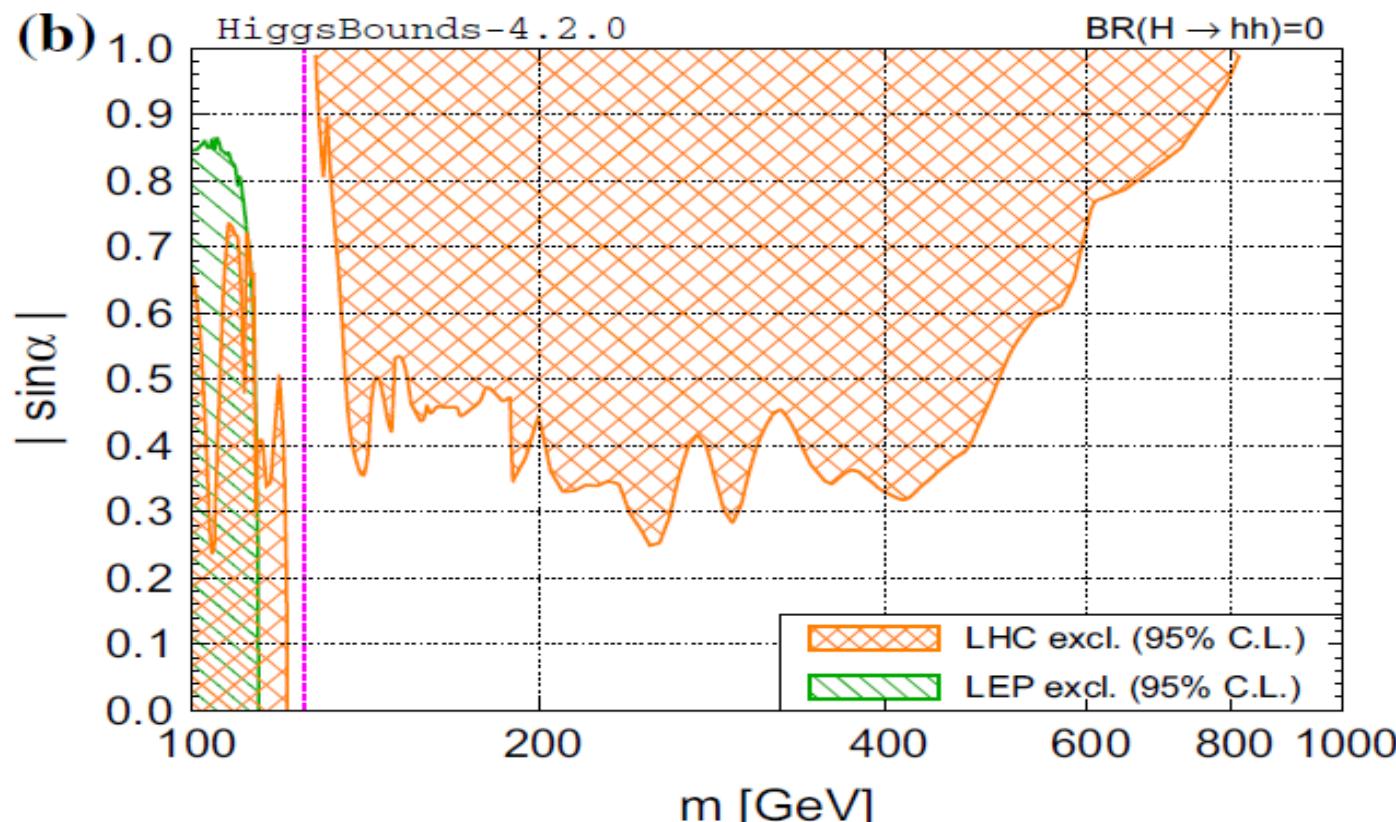
T. Robens and T. Stefaniak, Eur. Phys. J. C75, 104,(2015)



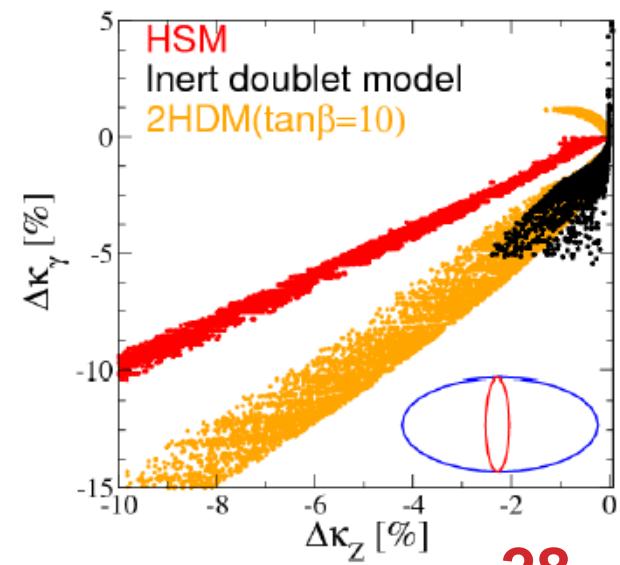
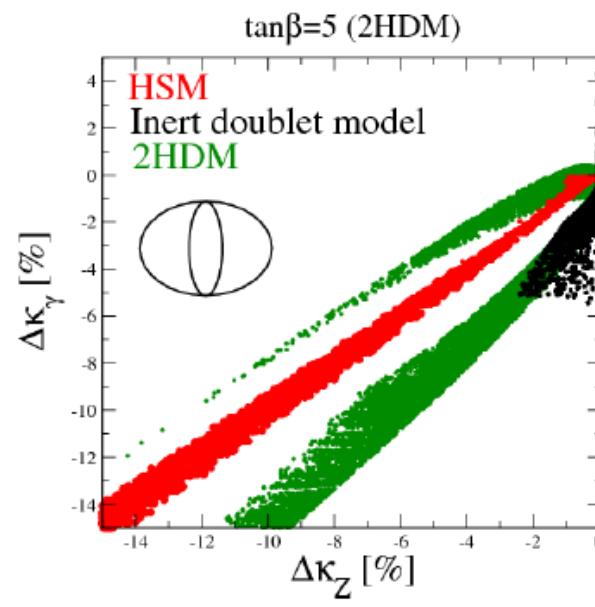
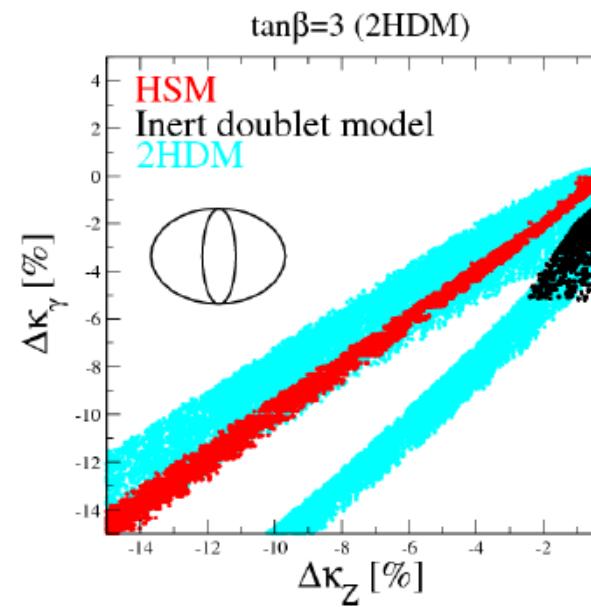
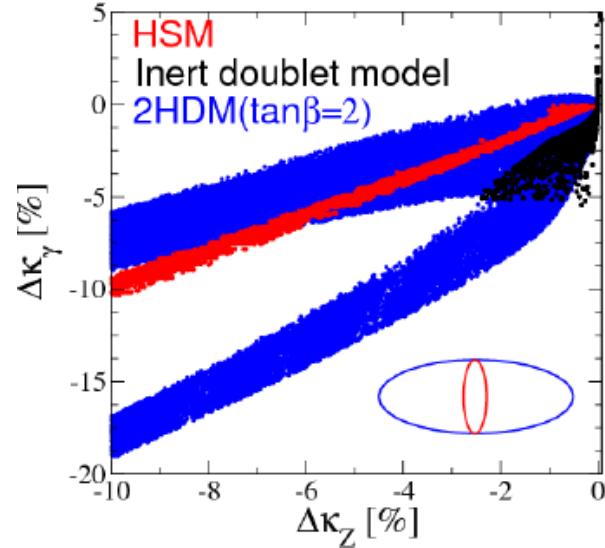
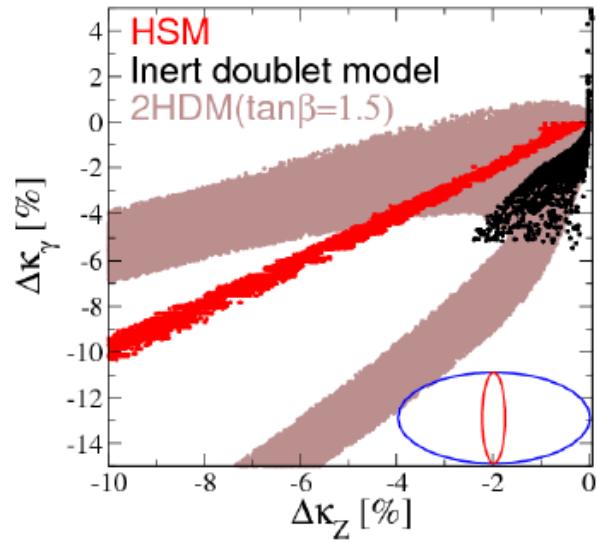
# CONSTRAINTS BY HIGGS SEARCH

Higgs Singlet Model with a spontaneously broken Z<sub>2</sub> sym

T. Robens and T. Stefaniak, Eur. Phys. J. C75, 104,(2015)



$$\Gamma(h \rightarrow \gamma\gamma) \cong \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3} \left| -\frac{1}{3} \left( 1 - \frac{M^2}{m_{H+}^2} \right) + Q_t N_c^t (\sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)) I_t + \sin(\beta - \alpha) I_W \right|$$



# THDMs

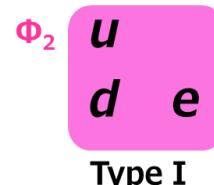
$\Phi_1, \Phi_2$

In general, multi-doublet structures cause FCNCs.

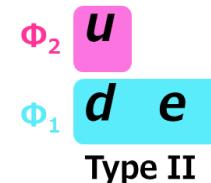
To avoid FCNCs,  $\Phi_1$  and  $\Phi_2$  should have different quantum numbers each other.

Discrete  $Z_2$  symmetry

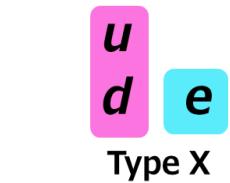
$$\begin{aligned}\Phi_1 &\rightarrow +\Phi_1 \\ \Phi_2 &\rightarrow -\Phi_2\end{aligned}$$



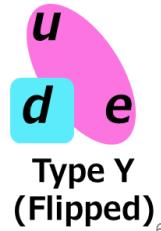
e.g. neutrino-philic



e.g. MSSM



e.g. Radiative seesaw



4 types of Yukawa interactions

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

- Softly broken  $Z_2$  & CP invariance

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

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

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

Mass eigenstates :  $h, H, A, H^\pm$

$$m_\Phi^2 \simeq \lambda' v^2 + M^2$$

$$\tan\beta = \frac{v_2}{v_1} \quad v^2 = v_1^2 + v_2^2 \sim (246 \text{GeV})^2$$

Soft breaking scale of  $Z_2$  sym.

# Renormalization

## Kinetic term

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

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

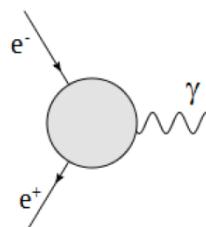
$$\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2},$$

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

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

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

On-shell conditions



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

- Counter term of  $v$

$$v^2 = \frac{m_W^2 \sin^2 \theta_W}{\pi a_{em}} \rightarrow \frac{\delta v}{v} = \frac{1}{2} \left( \frac{\delta m_W^2}{m_W^2} - \frac{\delta \alpha_{em}}{\alpha_{em}} + \frac{\delta s_W^2}{s_W^2} \right)$$

# Counter terms in $V$

---

Parameters ;  $m_h \ \nu \ m_H \ a \ \mu_S \ \lambda_S \ \lambda_S \ \nu_S \quad 8$

Tadpoles ;  $T_\phi \ T_s \quad 2$

Filed mixing ;

Mass eigenstates ;  $h \ H \ G^0 \ G^\pm \quad 4$

$H-h \quad 1$

---

Paramater shift ;  $m \rightarrow m + \delta m$

Field mixing ;

$$\begin{pmatrix} H \\ h \end{pmatrix} \rightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_H & \delta C_{Hh} + \delta \alpha \\ -\delta \alpha + \delta C_{hH} & 1 + \frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$


---

Counter terms;  $\delta m_h \ \delta \nu \ \delta m_H \ \delta a \ \delta \mu_S \ \delta \lambda_S \ \delta \lambda_S \ \delta \nu_S$   
 $\delta T_\phi \ \delta T_s$   
 $\delta Z_h \ \delta Z_H \ \delta Z_{G+} \ \delta Z_{G0}$   
 $\delta C_{hH} \ \delta C_{Hh}$

16

# Counter terms of Higgs couplings

$$\delta\Gamma_{hVV}^1 = \frac{2m_V^2}{v} \cos\alpha \left( \frac{\delta m_V^2}{m_V^2} - \frac{\delta v}{v} + \frac{\sin\alpha}{\cos\alpha} \delta C_h + \delta Z_V + \frac{1}{2} \delta Z_h \right)$$

$$\delta\Gamma_{hff}^S = -\frac{m_f}{v} \cos\alpha \left( \frac{\delta m_f}{m_f} - \frac{\delta v}{v} + \frac{\sin\alpha}{\cos\alpha} \delta C_h + \delta Z_f^V + \frac{1}{2} \delta Z_h \right)$$

$$\delta\Gamma_{hhh} = \delta\lambda_{hhh} + \lambda_{hhH}(\delta C_h + \delta\alpha) + \frac{3}{2}\lambda_{hhh}\delta Z_h.$$

where

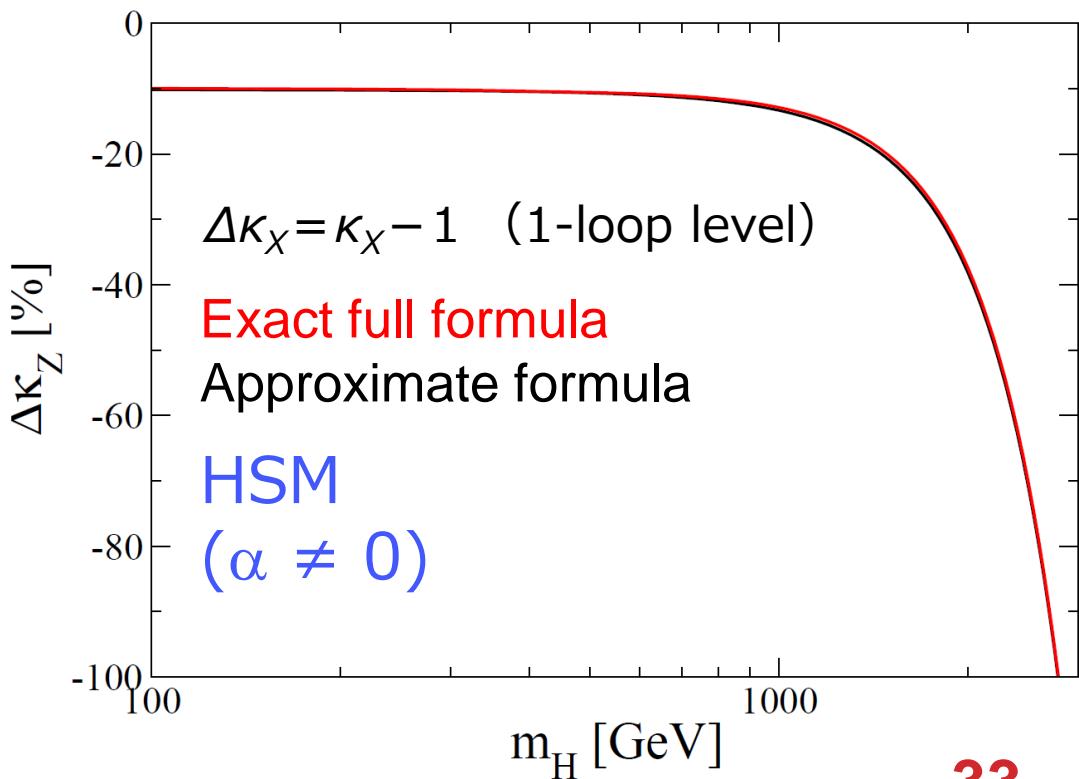
$$\begin{aligned} \delta\lambda_{hhh} = & -\frac{c_\alpha^3}{2v} \delta m_h^2 + \left( \frac{m_h^2 c_\alpha^3}{2v^2} - s_\alpha^2 c_\alpha \lambda_{\Phi S} \right) \delta v \\ & + \left( \frac{3m_h^2}{2v} s_\alpha c_\alpha^2 + \lambda_{\Phi S} v(s_\alpha^3 - 2s_\alpha c_\alpha^2) + 3s_\alpha^2 c_\alpha \mu_S + 12\lambda_S v_S s_\alpha^2 c_\alpha \right) \delta\alpha + s_\alpha^2 \delta\Lambda, \end{aligned}$$

$$\delta\Lambda = -(c_\alpha v \delta\lambda_{\Phi S} - s_\alpha \delta\mu_S - 4s_\alpha v_S \delta\lambda_S). \quad \text{☞ Combine } \delta\mu_S \ \delta\lambda_S \ \delta\lambda_S \text{ into } \delta\Lambda$$

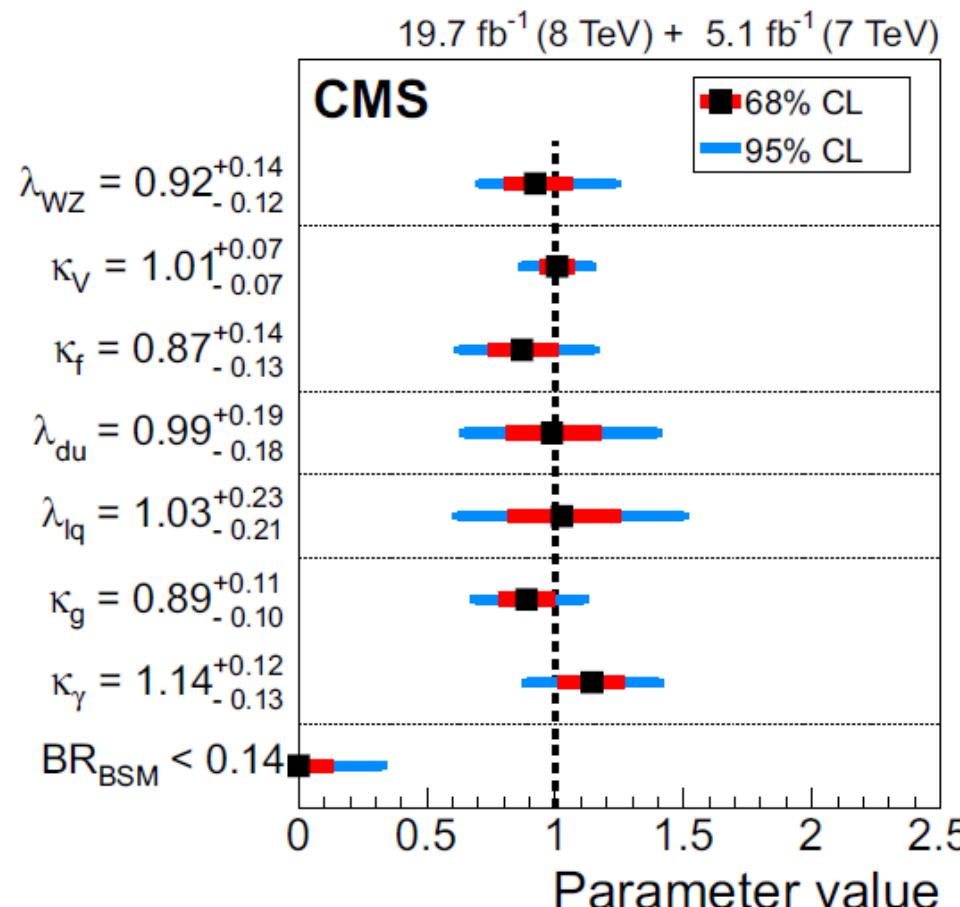
$\delta\Lambda$  is determined by the minimal subtraction condition.

# Check for Code

- We checked our numerical calculation code.
  - Cancellation of divergence
  - Decoupling behavior
  - Comparing numerical values calculated by exact formulae with those by approximate formulae

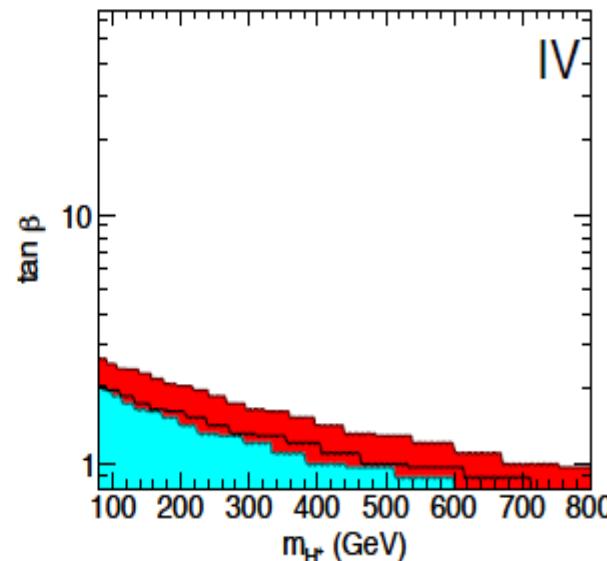
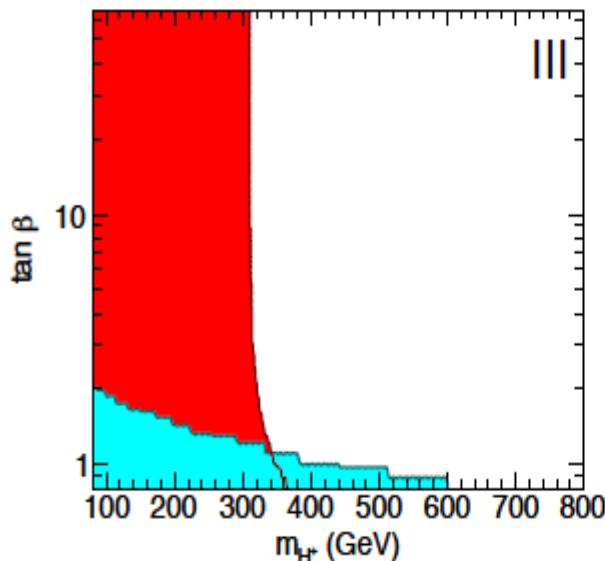
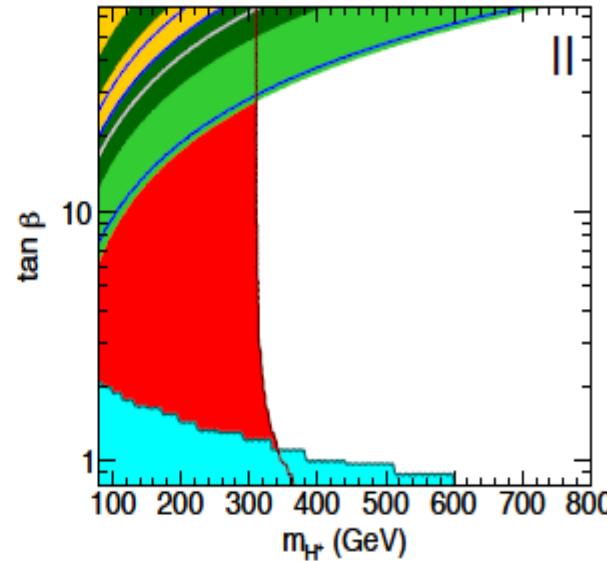
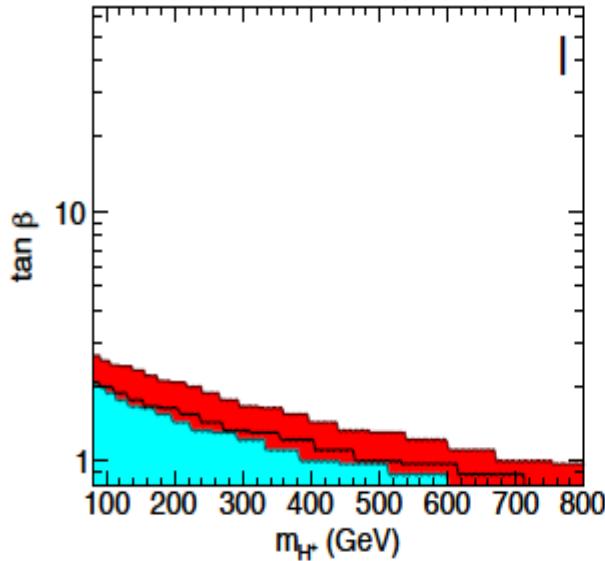


# CURRENT DATA OF SCALING FACTORS



# Flavor experiments

F. Mahmoudi and O. Stal, (2010)



$b \rightarrow s\gamma$

$B_0 - B_0$  mixing

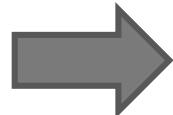
$D_s \rightarrow \tau \bar{\nu}_\tau$

$D_s \rightarrow \mu \bar{\nu}_\mu$

$B \rightarrow D \tau \bar{\nu}_\tau$

■ Determination of inner parameters by using future precision data of  $h_{125}$  couplings

$h_{125}$  couplings,  
 $\kappa_x, \Delta\kappa_x$



Inner parameters

In the future,  
 how much precise can we extract values of inner parameters  
 by using LHC3000 and ILC500 data ?

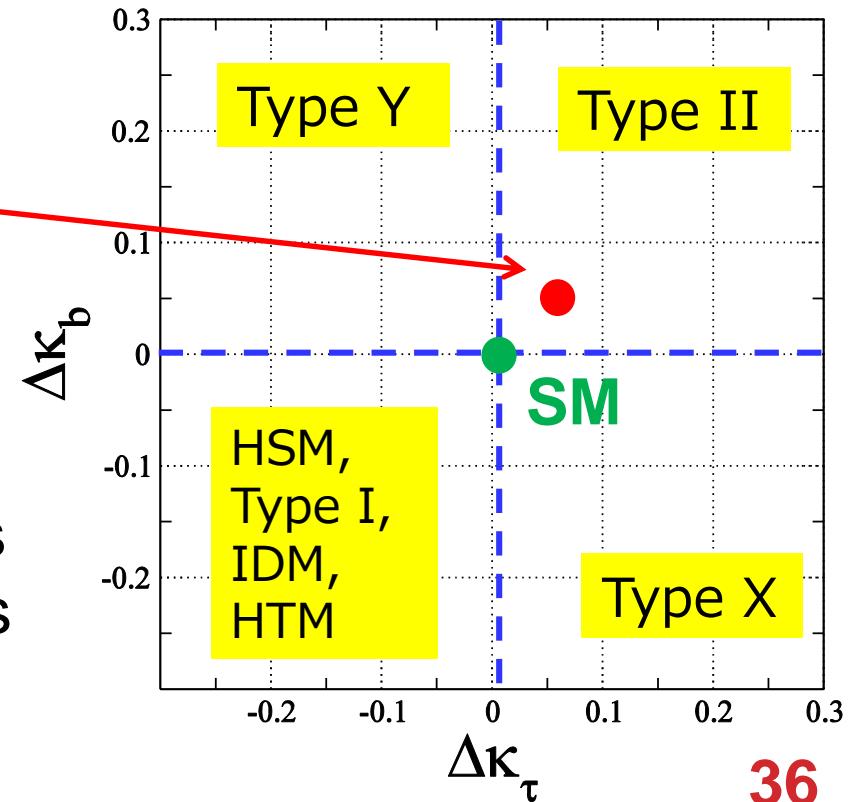
Ex.>>      LHC3000    ILC500     $1\sigma$

|                                 |           |             |
|---------------------------------|-----------|-------------|
| $\Delta\hat{\kappa}_V = -2.0$   | $\pm 2.0$ | $\pm 0.4\%$ |
| $\Delta\hat{\kappa}_\tau = +5$  | $\pm 2.0$ | $\pm 1.9\%$ |
| $\Delta\hat{\kappa}_b = +5$     | $\pm 4.0$ | $\pm 0.9\%$ |
| $\Delta\hat{\kappa}_{t(c)} < 0$ |           |             |



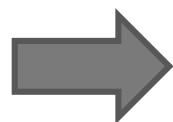
We survey parameter regions  
 by scanning inner parameters

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

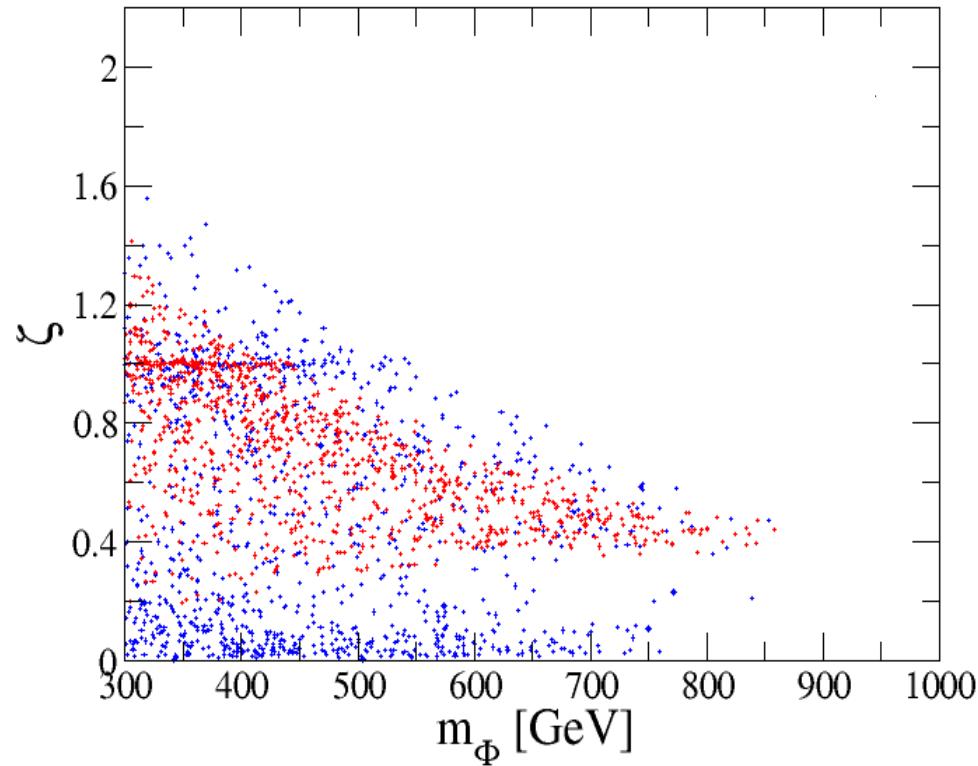
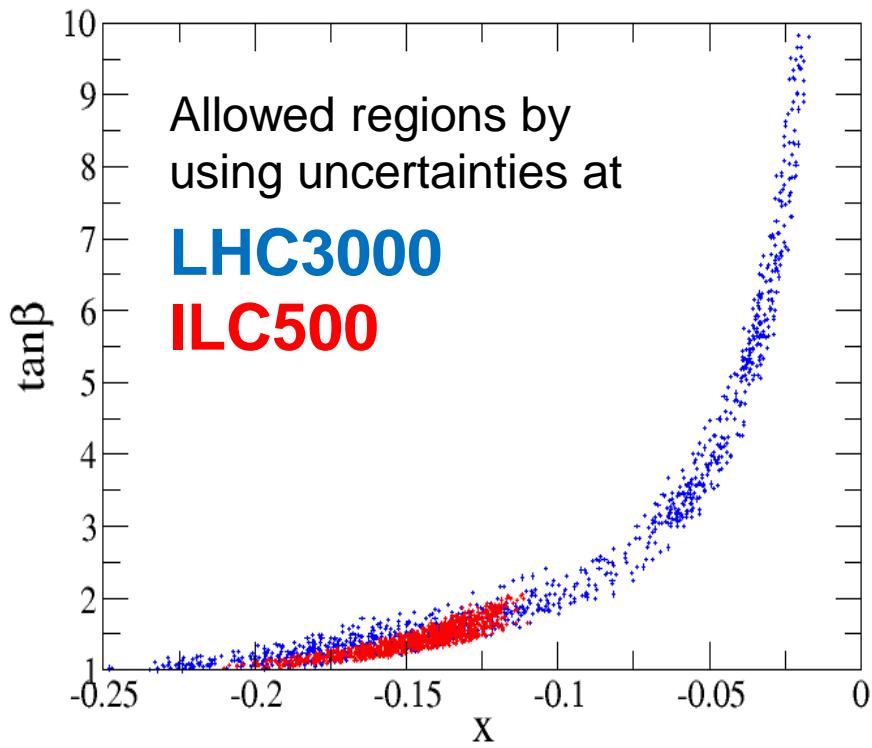


■ Determination of inner parameters by using future precision data of  $h_{125}$  couplings

$h_{125}$  couplings,  
 $\kappa_x, \Delta\kappa_x$



Inner parameters



$x, \tan\beta$  : mixing parameters

$m_\Phi$  : masses of extra Higgs bosons

$\zeta$  : parameter meaning magnitude of loop corrections

$$\zeta = 1 - \frac{M^2}{m_\Phi^2}$$