

# H-COUP

Kei Yagyū (Osaka U.)



Based on

Kanemura, Kikuchi, Sakurai, KY, 1710.04603 (H-COUP v1)

Kanemura, Kikuchi, Sakurai, Mawatari, KY, 1910.12769 (H-COUP v2)

Aiko, Kanemura, Kikuchi, Sakurai, KY, 2311.15892 (H-COUP v3)

and

Kanemura, Kikuchi, KY (Ongoing)

KUTS2024

June 27<sup>th</sup>, DESY

# Content

## I. What is H-COUP?

## II. Details and recent developments of H-COUP

- 2 Higgs doublet models
- Renormalization (KOSY scheme)
- New renormalization scheme
- Results

## III. Summary

# What is H-COUP?



ChatGPT

What is H-COUP in particle physics



In particle physics, H-COUP refers to a computational tool designed to calculate Higgs boson couplings. It is used to analyze the properties of the Higgs boson within the context of the Standard Model and beyond. The main purpose of H-COUP is to provide precise theoretical predictions for Higgs boson production and decay processes, which are essential for understanding experimental results from particle colliders like the Large Hadron Collider (LHC).

Key aspects of H-COUP in particle physics include:

1. **Higgs Boson Couplings:** H-COUP computes the couplings of the Higgs boson to other particles, such as fermions and gauge bosons. These couplings are critical for predicting how often the Higgs boson is produced and how it decays.
2. **Precision Calculations:** It incorporates higher-order corrections and precision calculations, which are necessary for making accurate comparisons between theoretical predictions and experimental data.
3. **Standard Model and Beyond:** While H-COUP is primarily used within the framework of the Standard Model of particle physics, it can also be adapted to study extensions of the Standard Model, including various Higgs sector models.
4. **Collider Physics:** The tool is particularly useful for interpreting results from high-energy physics experiments, such as those conducted at the LHC, where precise measurements of the Higgs boson properties are performed.

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What is H-COUP

???

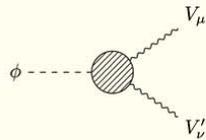
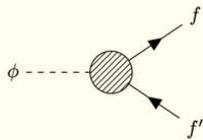


H-COUP (Hierarchical Clustering On the Unit Hypersphere) is a clustering algorithm designed for high-dimensional data analysis. Unlike traditional clustering methods like k-means or hierarchical clustering, H-COUP is specifically adapted to work on the unit hypersphere, making it particularly useful for directional data, such as text data represented as TF-IDF vectors in natural language processing or any data where the magnitude is not as important as the direction.

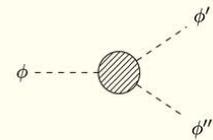
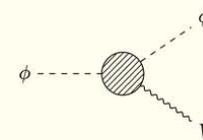
# What is H-COUP?

Q HCOUP

G HCOUP — Google で検索



## H-COUP



[Home](#) [Publications](#) [Release History](#) [Old Versions](#) [Contact](#)

**NEW!!** H-COUP version 3.0 was released (28th Nov. 2023)

**H-COUP is a package of Fortran codes for computing observables of Higgs bosons including radiative corrections in extended Higgs models.** H-COUP version 3 (28th Nov. 2023) calculates various Higgs effective vertices, decay rates and branching ratios of any Higgs bosons including radiative corrections (one-loop Electroweak and higher-order QCD corrections). The current version includes the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model.

The manual for H-COUP version 3 can be taken on [arXiv:2311.15892 \[hep-ph\]](https://arxiv.org/abs/2311.15892).

Authors: Masashi Aiko, Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

### Downloads

- H-COUP version 3.0 : [[HCOUP-3.0.zip](#)] [The manual for H-COUP ver. 3 is [here](#)]
- H-COUP needs a Fortran compiler (gfortran is recommended) and LoopTools ([www.feynarts.de/looptools/](http://www.feynarts.de/looptools/)).

Models: 2HDMs (Type-I, II, X and Y), Higgs (real) singlet model, Inert doublet model

Quantities: Effective vertices, decay rates, branching ratio at one-loop level (EW)

# History of H-COUP

*Kanemura, Senaha, Okada, Yuan (2004)*

On-shell scheme in the 2HDM

Higgs discovery

I got Ph.D

*Kanemura, Kikuchi,  
Sakurai, KY (1710.04603)*

*Kanemura, Kikuchi, Sakurai,  
Mawatari, KY (1910.12769)*

*Kanemura, Kikuchi, Sakurai,  
KY (2311.15892)*

H-COUP v1

H-COUP v2

H-COUP v3

Year

2004

2012

2017

2019

2023

*Kanemura, Kikuchi, KY (1401.0515, 1502.07716)*

$h_{125}$  coup. in 4 types of the 2HDMs @1-loop

*Kanemura, Kikuchi, KY (1511.06211, 1608.01582)*

$h_{125}$  coup. in the HSM @1-loop

*Kanemura, Kikuchi, Sakurai (1605.08520)*

$h_{125}$  coup. in the IDM @1-loop

*Kanemura, Kikuchi, Sakurai, KY (1705.05399)*

Improved OS-scheme

*Kanemura, Kikuchi, Mawatari,  
Sakurai, KY*

*(1803.01456, 1906.10070)*

$h_{125}$  decays @NLO

*Kanemura, Kikuchi, KY (2207.01032)*

H decays @NLO

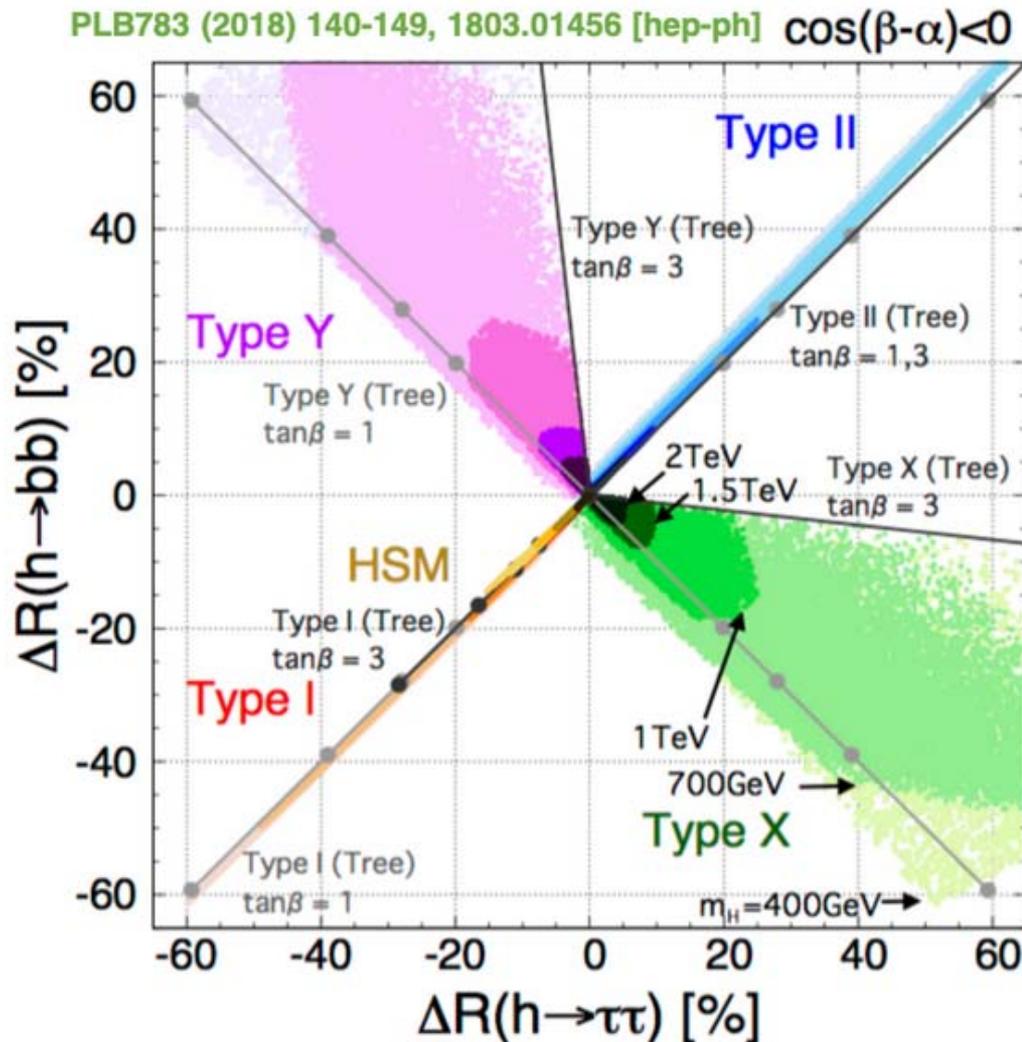
*Aiko, Kanemura, Sakurai (2207.01032)*

A decays @NLO

*Aiko, Kanemura, Sakurai (2108.11868)*

$H^\pm$  decays @NLO

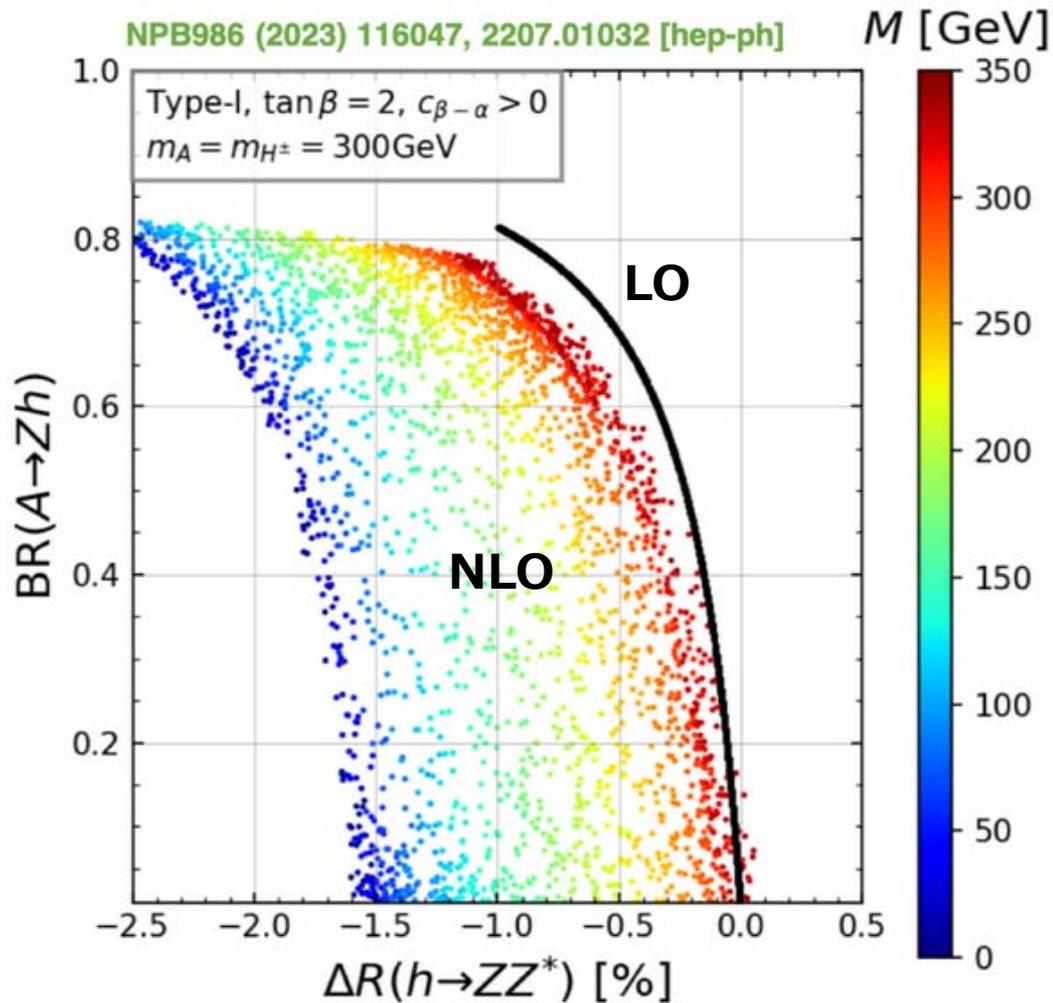
# Application: SM-like Higgs decays



$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$

- “Fingerprinting” the Higgs sector
- New no-loose theorem

# Application: Heavy Higgs decays



$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$

- Synergy between direct searches and precise measurements.

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# Quick review on 2HDMs

- Symmetry: SM gauge symmetry +  $Z_2$  (softly-broken)

$$(\Phi_1, \Phi_2) \rightarrow (\Phi_1, -\Phi_2) \quad (\text{to avoid tree level FCNCs})$$

We assume CP-conservation in the Higgs sector.

- Higgs basis *Davidson, Haber PRD71 (2005)*

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi' \end{pmatrix} \quad \tan \beta = v_2/v_1$$

NG boson

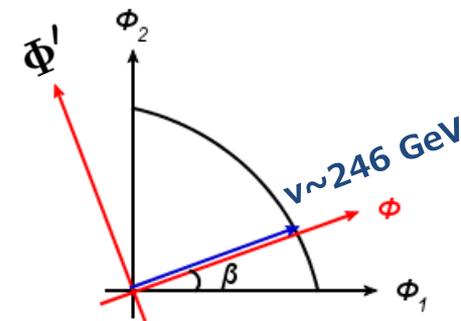
$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h'_1 + v + iG^0) \end{bmatrix}$$

CP-even Higgs

Charged Higgs

$$\Phi' = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA) \end{bmatrix}$$

CP-odd Higgs



- Higgs mixing  $\begin{pmatrix} h'_1 \\ h'_2 \end{pmatrix} = \begin{bmatrix} \cos(\beta - \alpha) & \sin(\beta - \alpha) \\ -\sin(\beta - \alpha) & \cos(\beta - \alpha) \end{bmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$  **125 GeV Higgs**

# Higgs potential

- Higgs potential with a softly-broken  $Z_2$  symmetry ( $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2$ ).

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

- Higgs masses

( $h_1', h_2'$ ) basis

$$m_{H^\pm}^2 = M^2 - \frac{v^2}{2} (\lambda_4 + \lambda_5), \quad m_A^2 = M^2 - v^2 \lambda_5, \quad \mathcal{M}_{\text{even}} = v^2 \begin{pmatrix} \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \frac{\lambda_{345}}{2} s_{2\beta}^2 & \frac{1}{2} (\lambda_2 s_\beta^2 - \lambda_1 c_\beta^2 + \lambda_{345} c_{2\beta}) s_{2\beta} \\ \frac{M^2}{v^2} + \frac{1}{4} (\lambda_1 + \lambda_2 - 2\lambda_{345}) s_{2\beta}^2 & \end{pmatrix} \\ M^2 = m_3^2 / (\sin \beta \cos \beta) \quad R^T(\alpha - \beta) \mathcal{M}_{\text{even}} R(\alpha - \beta) = \text{diag}(m_H^2, m_h^2)$$

- Decoupling limit

$$M^2 \rightarrow \infty \quad (s_{\beta-\alpha} \rightarrow 1)$$

We can take  $s_{\beta-\alpha} \rightarrow 1$  without  $M^2 \rightarrow \infty$

→ Alignment without decoupling

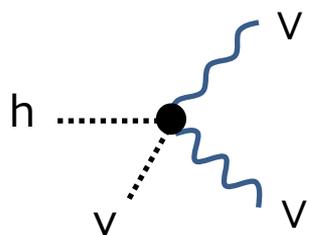
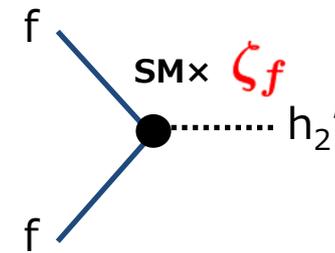
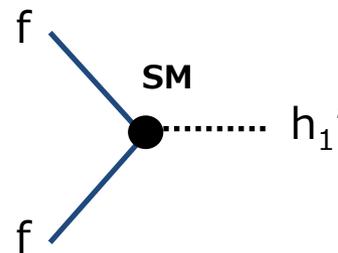
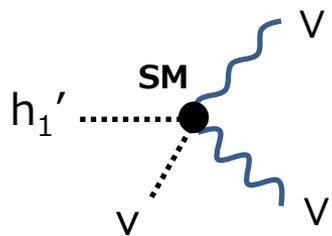
- 8 parameters

$$m_h^2, m_H^2, m_A^2, m_{H^\pm}^2, \sin(\beta-\alpha), \tan\beta, v \text{ and } M^2$$

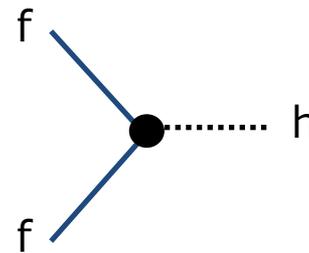
# Gauge & Yukawa sector in the Higgs basis

$$\mathcal{L}_{2\text{HDM}} \supset |D_\mu \Phi|^2 + |D_\mu \Phi'|^2 - \frac{\sqrt{2}M_f}{v} (\bar{f}_L \Phi f_R + \zeta_f \bar{f}_L \Phi' f_R) + \text{h.c.}$$

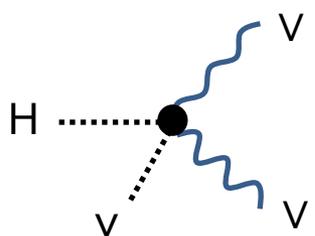
	$\zeta_u$	$\zeta_d$	$\zeta_e$
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$



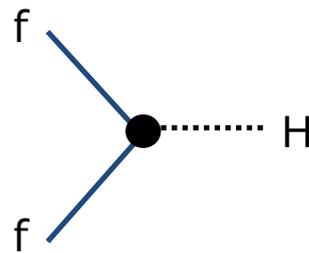
$$= (\text{SM}) \times s_{\beta-\alpha}$$



$$= (\text{SM}) \times \frac{(s_{\beta-\alpha} + \zeta_f c_{\beta-\alpha})}{= \kappa_f^h}$$



$$= (\text{SM}) \times c_{\beta-\alpha}$$

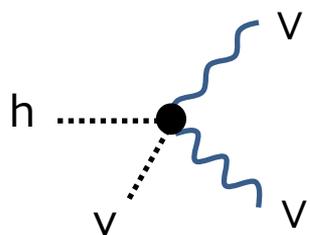
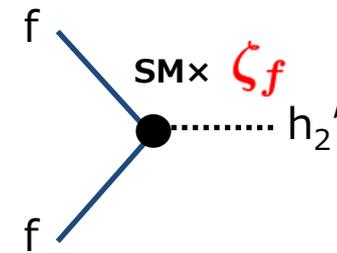
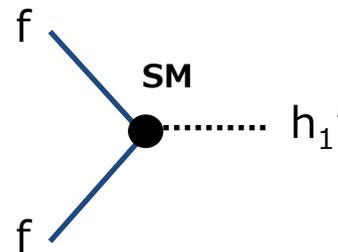
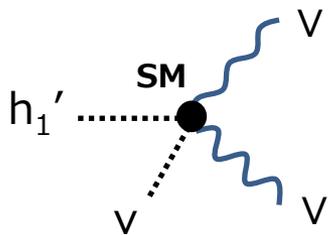


$$= (\text{SM}) \times \frac{(c_{\beta-\alpha} - \zeta_f s_{\beta-\alpha})}{= \kappa_f^H}$$

# Gauge & Yukawa sector in the Higgs basis

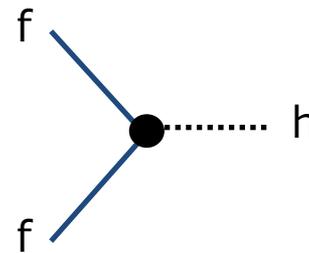
□ Alignment limit:  $\sin(\beta - \alpha) \rightarrow 1$

	$\zeta_u$	$\zeta_d$	$\zeta_e$
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$



$$= (\text{SM}) \times s_{\beta-\alpha}$$

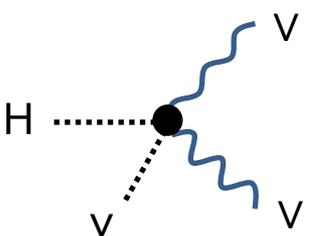
$\rightarrow \text{SM}$



$$= (\text{SM}) \times \frac{(s_{\beta-\alpha} + \zeta_f c_{\beta-\alpha})}{s_{\beta-\alpha}}$$

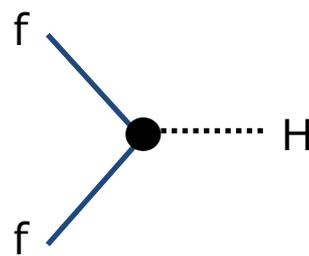
$$= \kappa_f^h$$

$\rightarrow \text{SM}$



$$= (\text{SM}) \times c_{\beta-\alpha}$$

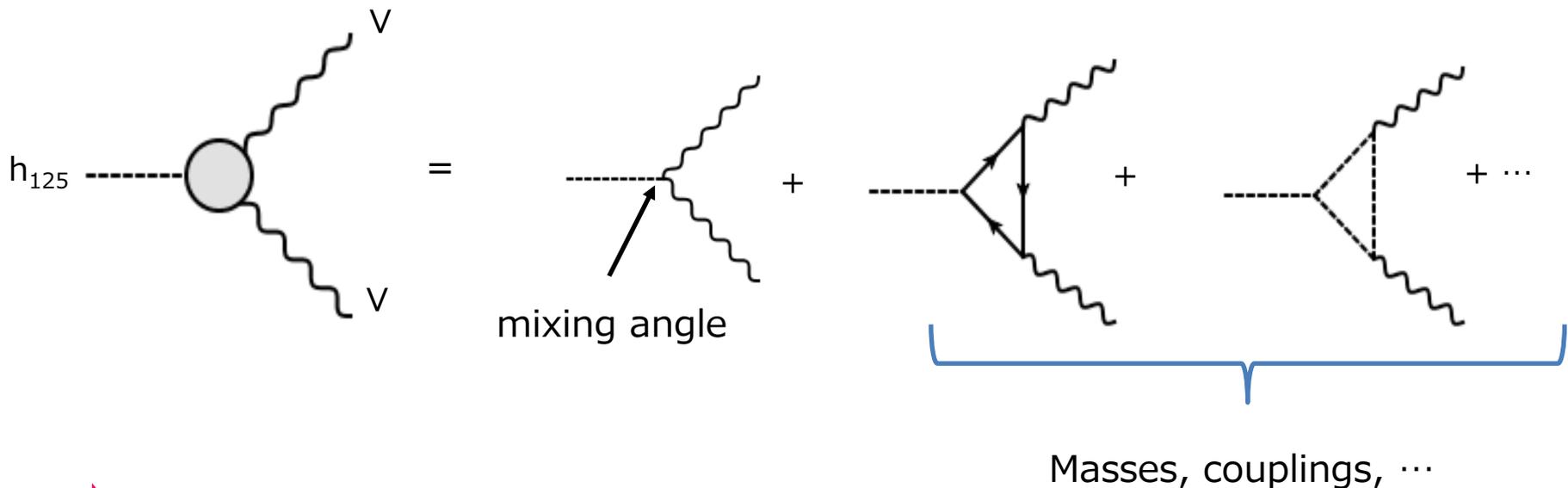
$\rightarrow 0$



$$= (\text{SM}) \times \frac{(c_{\beta-\alpha} - \zeta_f s_{\beta-\alpha})}{c_{\beta-\alpha}} = \kappa_f^H$$

$\rightarrow -\zeta_f (\text{SM})$

# Higgs alignment at quantum levels?



Mixing angle no longer describes the "alignmentness".

We can define the alignmentness by the deviation of the coupling or decay rate, but it cannot simply be expressed by model parameters ...

We propose a new reno. scheme such that the mixing describes the alignmentness.

# Renormalization

## □ Parameter shift

$$m_\varphi^2 \rightarrow m_\varphi^2 + \delta m_\varphi^2 \quad (\varphi = h, H, A, H^\pm),$$

$$M^2 \rightarrow M^2 + \delta M^2, \quad v \rightarrow v + \delta v,$$

$$\alpha \rightarrow \delta\alpha, \quad \beta \rightarrow \delta\beta,$$

## □ Field shift

$$\begin{pmatrix} H \\ h \end{pmatrix} \rightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_H & \delta Z_{Hh} \\ \delta Z_{hH} & 1 + \frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \quad \begin{pmatrix} G^0 \\ A \end{pmatrix} \rightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_G & \delta Z_{GA} \\ \delta Z_{AG} & 1 + \frac{1}{2}\delta Z_A \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \rightarrow \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{G^\pm} & \delta Z_{G^\pm H^\mp} \\ \delta Z_{H^\pm G^\mp} & 1 + \frac{1}{2}\delta Z_A \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

We have **20** counterterms.

# Treatment of tadpoles

## Standard tadpole scheme

$$T_{h/H} \rightarrow 0 + \delta T_{h/H}$$

Renormalization condition

$$\text{Diagram} = \text{1PI Diagram} + \text{X Diagram} = 0 \quad \delta T_{h/H} = -\Gamma_{h/H}^{1\text{PI}}$$

## Alternative tadpole scheme

*Fleischer, Jegerlehner (1981)*

*Krause, Lorenz, Muhlleitner, Santos, Ziesche (2016)*

No tadpole counterterms are introduced, but Higgs fields are shifted as

$$h \rightarrow h + \Delta v_h, \quad H \rightarrow H + \Delta v_H \quad \langle h \rangle = \langle H \rangle = 0 \quad \text{E.g., 2p func.}$$

$$\Delta v_{h/H} = \frac{-i}{m_{h/H}^2} \times \left[ \text{1PI Tadpole} \right] \quad \text{1PI Self-Energy} \rightarrow \text{1PI Self-Energy} + \text{1PI Tadpole}$$

# Renormalization in the Higgs sector

$$\text{---} \bigcirc \text{---} = \text{---} \text{---} + \text{---} \bigcirc \text{---} + \text{---} \otimes \text{---}$$

OS condition I:

$$\varphi \text{---} \bigcirc \text{---} \varphi = 0$$

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



$$\delta m_\varphi^2 \quad (4)$$

( $\varphi = h, H, A, H^\pm$ )

OS condition II:

$$\frac{d}{dp^2} \left[ \text{---} \bigcirc \text{---} \right] = 1$$

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



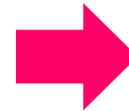
$$\delta Z_\varphi \quad (6)$$

( $\varphi = h, H, A, H^\pm, G^0, G^\pm$ )

OS condition III:

$$\varphi \text{---} \bigcirc \text{---} \varphi' = 0$$

( $\varphi \neq \varphi'$ )  
@  $p^2 = m_\varphi^2$  and  $p^2 = m_{\varphi'}^2$



$$\delta Z_{Hh}, \delta Z_{hH}, \delta Z_{GA},$$

$$\delta Z_{AG}, \delta Z_{H+G^-}, \delta Z_{G+H^-} \quad (6)$$

*Hollik (1990),...*

$\delta v$  : Ren. in the EW sector

*Kanemura, Okada, Senaha, Yuan (2004)*

$\delta M^2$  : MS-bar in the hhh vertex

We need 2 more conditions to determine

$\delta\alpha$  and  $\delta\beta$ .

# Previous scheme (KOSY scheme)

*Kanemura, Okada, Senaha, Yuan (2004)*

Field shifts are performed as follows (e.g. CP-even part):

$$\begin{pmatrix} H_B \\ h_B \end{pmatrix} = \underline{R(-\alpha_B)} \underline{\begin{pmatrix} h_{1B} \\ h_{2B} \end{pmatrix}} = \underline{R(-\delta\alpha)R(-\alpha_R)} \underline{\tilde{Z} \begin{pmatrix} h_{1R} \\ h_{2R} \end{pmatrix}} = R(-\delta\alpha) \underline{R(-\alpha_R)\tilde{Z}R(\alpha_R)} \begin{pmatrix} H_R \\ h_R \end{pmatrix} = Z$$

$$Z = \begin{pmatrix} 1 + \frac{\delta Z_H}{2} & \delta C_{Hh} \\ \delta C_{hH} & 1 + \frac{\delta Z_h}{2} \end{pmatrix} \quad \rightarrow \quad R(-\delta\alpha)Z = \begin{pmatrix} 1 + \frac{\delta Z_H}{2} & \delta C_{Hh} + \delta\alpha \\ \delta C_{hH} - \delta\alpha & 1 + \frac{\delta Z_h}{2} \end{pmatrix} \quad @ \text{ 1-loop level}$$

We then identify the W.F. renormalization factors as

$$\delta Z_{Hh} = \delta C_{Hh} + \delta\alpha$$

$$\delta Z_{hH} = \delta C_{hH} - \delta\alpha$$

CP-even

$$\delta Z_{GA} = \delta C_{GA} + \delta\beta$$

$$\delta Z_{AG} = \delta C_{AG} - \delta\beta$$

CP-odd

$$\delta Z_{G^\pm H^\mp} = \delta C_{G^\pm H^\mp} + \delta\beta$$

$$\delta Z_{H^\pm G^\mp} = \delta C_{H^\pm G^\mp} - \delta\beta$$

Charged

Assumptions:  $\delta C_{Hh} = \delta C_{hH}$

$$\delta C_{GA} = \delta C_{AG}$$

$$\delta C_{G^\pm H^\mp} = \delta C_{H^\mp G^\pm}$$

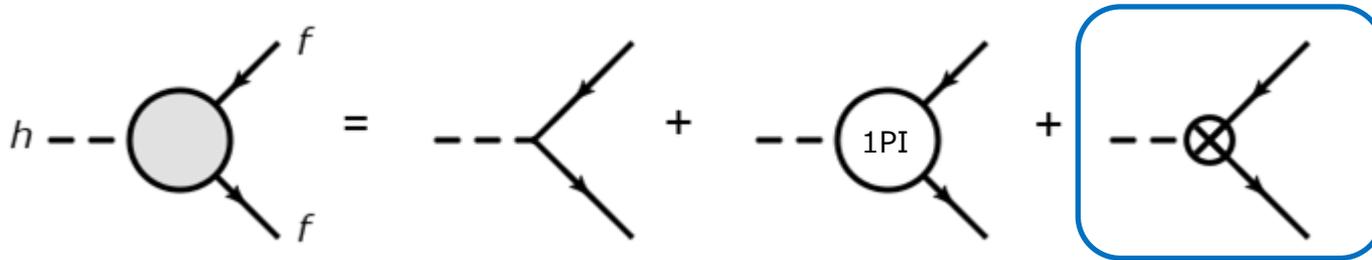
In total, we have 21 conditions.

→ Relaxing one of the OS cond. III,  
all the CTs are determined.

In the new scheme, we take  $\delta C_{ij}$  &  $\delta C_{ji}$  or  $\delta Z_{ij}$  &  $\delta Z_{ji}$  ( $i \neq j$ ) independently.

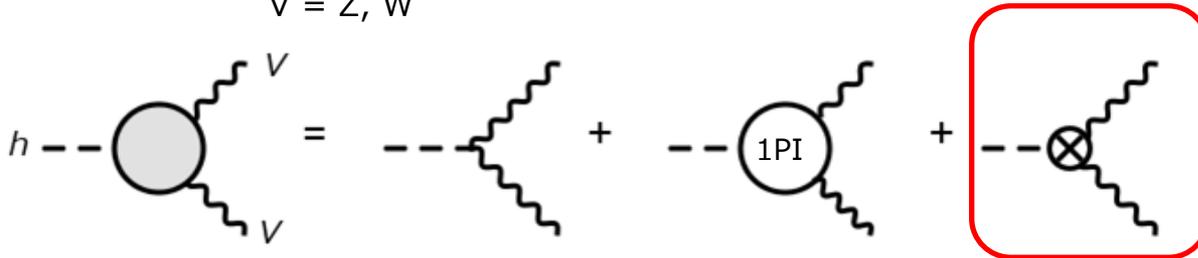
# 3-point functions

We exhausted all the 2-point functions. Let us consider 3-point functions.



$$-\frac{m_f}{v} \kappa_f^h \left[ \frac{\delta m_f}{m_f} + \delta Z_V^f + \frac{\delta Z_h}{2} - \frac{\delta v}{v} + \frac{\kappa_f^H}{\kappa_f^h} [\delta(\beta - \alpha) + \delta Z_{Hh}] - \frac{(1 + \zeta_f^2) c_{\beta - \alpha}}{\kappa_f^h} \delta\beta \right]$$

$V = Z, W$



$$\frac{2m_V^2}{v} \left[ s_{\beta - \alpha} \left( \frac{\delta m_V^2}{m_V^2} - \frac{\delta v}{v} + \delta Z_V + \frac{1}{2} \delta Z_h \right) + c_{\beta - \alpha} (\delta(\beta - \alpha) + \delta Z_{Hh}) \right]$$

# New renormalization scheme

Decay rate at NLO

$$\Gamma_{\text{NLO}}(h \rightarrow \tau\tau) = \Gamma_{\text{LO}}(h \rightarrow \tau\tau)(1 + \Delta_{\text{EW}}^\tau)$$

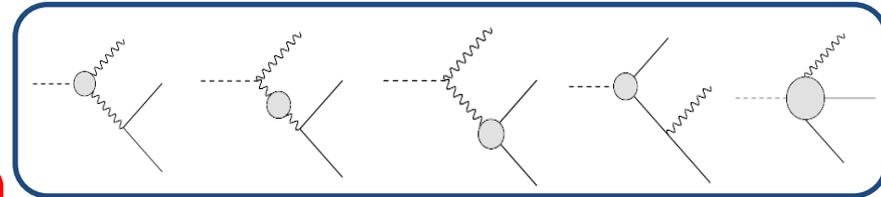
$$\Gamma_{\text{NLO}}(h \rightarrow Z\ell\ell) = \Gamma_{\text{LO}}(h \rightarrow Z\ell\ell)(1 + \Delta_{\text{EW}}^{Z\ell\ell})$$

where

$$\Delta_{\text{EW}}^f = 2 \frac{\delta\Gamma_{hff}^{\text{S}} + \Gamma_{hff}^{\text{S,1PI}} \Big|_{\text{div}}}{\Gamma_{hff}^{\text{S,tree}}} + \Delta_{\text{rem}}^f \quad \Delta_{\text{EW}}^{Vff} = 2 \frac{\delta\Gamma_{hVV}^1 + \Gamma_{hVV}^{1,1PI} \Big|_{\text{div}}}{\Gamma_{hVV}^{1,tree}} + \Delta_{\text{rem}}^{Vff}$$

Renormalization conditions

$$\Delta_{\text{EW}}^\tau = \Delta_{\text{EW}}^\tau|_{\text{SM}} \quad \Delta_{\text{EW}}^{Z\ell\ell} = \Delta_{\text{EW}}^{Z\ell\ell}|_{\text{SM}}$$



$$\Gamma_{\text{NLO}}(h \rightarrow \tau\tau) = (\kappa_\tau^h)^2 \Gamma_{\text{NLO}}(h \rightarrow \tau\tau)_{\text{SM}}$$

$$\Gamma_{\text{NLO}}(h \rightarrow Z\ell\ell) = \sin^2(\beta - \alpha) \Gamma_{\text{NLO}}(h \rightarrow Z\ell\ell)_{\text{SM}}$$



The mixing angles describe the alignmentness at quantum levels.

# Prediction?

- The mixing counterterms are determined by

$$\delta(\beta - \alpha) = -\delta Z_{Hh} - t_{\beta-\alpha} \left[ \delta_{\text{SM}}^Z + \frac{\Gamma_{hZZ}^{1,1\text{PI}}|_{\text{div}}}{\Gamma_{hZZ}^{1,\text{tree}}} + \frac{\Delta_{\text{rem}}^{Z\ell\ell} - \Delta_{\text{EW}}^{Z\ell\ell}|_{\text{SM}}}{2} \right]$$

$$\delta_{\text{SM}}^Z = \frac{\delta Z_h}{2} - \frac{\delta v}{v} + \frac{\delta m_Z^2}{m_Z^2} + \delta Z_Z$$

$$\delta_{\text{SM}}^\tau = \frac{\delta Z_h}{2} - \frac{\delta v}{v} + \frac{\delta m_\tau}{m_\tau} + \delta Z_V^\tau$$

$$\delta\beta = \frac{\kappa_\tau^h}{(1 + \zeta_\tau^2)c_{\beta-\alpha}} \left[ \delta_{\text{SM}}^\tau + \frac{\Gamma_{h\tau\tau}^{S,1\text{PI}}|_{\text{div}}}{\Gamma_{h\tau\tau}^{S,\text{tree}}} + \frac{\Delta_{\text{rem}}^\tau - \Delta_{\text{EW}}^\tau|_{\text{SM}}}{2} + \frac{\kappa_\tau^H}{\kappa_\tau^h} [\delta(\beta - \alpha) + \delta Z_{Hh}] \right]$$

- The other h decays ( $h \rightarrow WW^*, bb, cc, \text{etc.}$ ) are the predictions.

$$\Delta_{\text{EW}}^{Wff} = 2 \left( \frac{\delta m_W^2}{m_W^2} - \frac{\delta m_Z^2}{m_Z^2} + \delta Z_W - \delta Z_Z \right)_{\text{fin}} + \Delta_{\text{rem}}^{Wff} - \Delta_{\text{rem}}^{Z\ell\ell} + \Delta_{\text{EW}}^{Z\ell\ell}|_{\text{SM}}$$

The dominant contribution  $\delta Z_h$  vanishes in the new scheme.

$$\delta Z_h = - \frac{d}{dp^2} \left( \left[ \begin{array}{c} \text{Diagram: } h \text{ (dashed line) enters from the left, } h \text{ (dashed line) exits to the right. A loop of } \Phi \text{ (dashed line) is formed. A red arrow labeled } \lambda_{h\Phi\Phi} \text{ points to the loop vertex.} \end{array} \right]_{p^2 = mh^2} + \dots \right) \propto - \frac{1}{16\pi^2} \frac{\lambda_{h\Phi\Phi}^2}{m_\Phi^2} \sim - \frac{1}{16\pi^2} \frac{m_\Phi^2}{v^2} \left( 1 - \frac{M^2}{m_\Phi^2} \right)^2$$



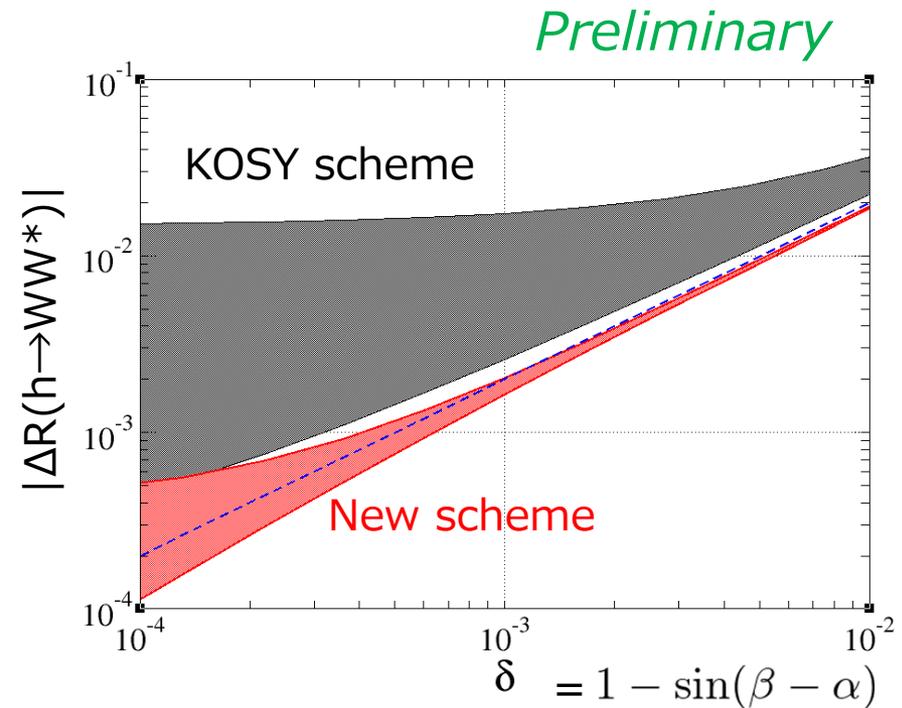
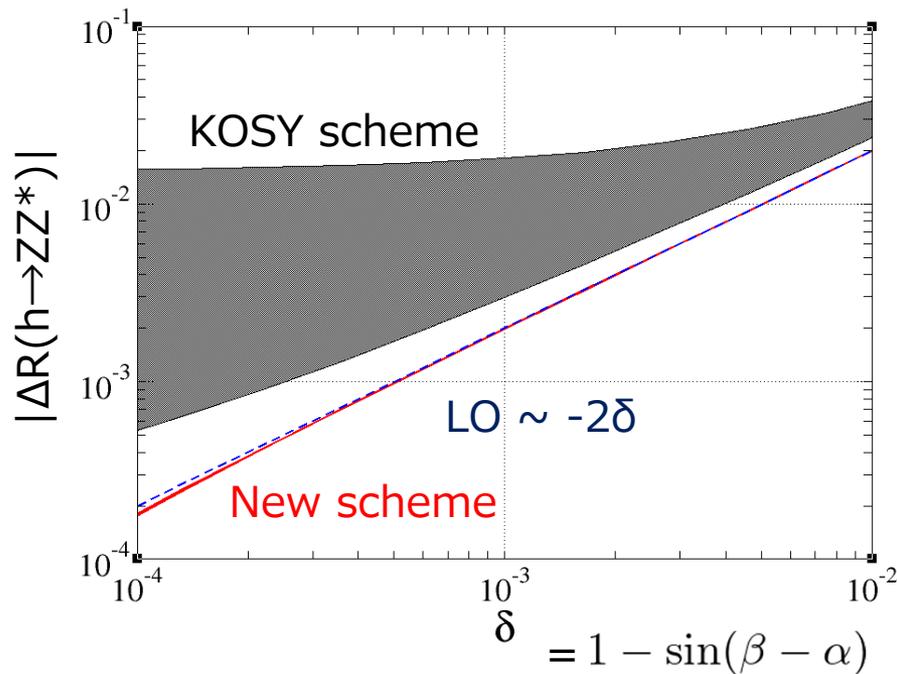
$O(1)\%$  for  $M/m_\Phi \ll 1$

# Deviation in the $h \rightarrow VV^*$ decays

Using H-COUP v3 with modifications

Type-I 2HDM,  $m_{H^+} = m_H = m_A = 300$  GeV,  
 $\tan\beta = 2$ ,  $0 < M^2 < (300 \text{ GeV})^2$

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$



# EW corrections to $h \rightarrow ff$

For  $\zeta_f = \zeta_\tau$

$$\Delta_{\text{EW}}^f = 2 \left( \frac{\delta m_f}{m_f} - \frac{\delta m_\tau}{m_\tau} + \delta Z_V^f - \delta Z_V^\tau \right)_{\text{fin}} + \Delta_{\text{rem}}^f - \Delta_{\text{rem}}^\tau + \Delta_{\text{EW}}^\tau |_{\text{SM}}$$

Again, the  $\delta Z_h$  term vanishes.

For  $\zeta_f = -\frac{1}{\zeta_\tau}$

$$x = \pi/2 - (\beta - \alpha)$$

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

$$\begin{aligned} \Delta_{\text{EW}}^f = & 2 \left[ \frac{\delta m_f}{m_f} - \zeta_f^2 \frac{\delta m_\tau}{m_\tau} + \delta Z_V^f - \zeta_f^2 \delta Z_V^\tau + \underbrace{2\zeta_f \left( \frac{1}{x} - \zeta_f \right) \left( \frac{\delta Z_h}{2} - \frac{\delta v}{v} \right)}_{\text{enhanced}} \right. \\ & \left. + \left( \frac{2\zeta_f}{x} - 1 - \zeta_f^2 \right) \left( \frac{\delta m_Z^2}{m_Z^2} + \delta Z_Z \right) \right]_{\text{fin}} \\ & + \Delta_{\text{rem}}^f - \zeta_f^2 (\Delta_{\text{rem}}^\tau - \Delta_{\text{EW}}^\tau |_{\text{SM}}) + \left( \frac{2\zeta_f}{x} - 1 - \zeta_f^2 \right) (\Delta_{\text{rem}}^{Z\ell\ell} - \Delta_{\text{EW}}^{Z\ell\ell} |_{\text{SM}}) + \mathcal{O}(x) \end{aligned}$$

The  $\delta Z_h$  term appears and it is enhanced by the factor of  $1/x$ .

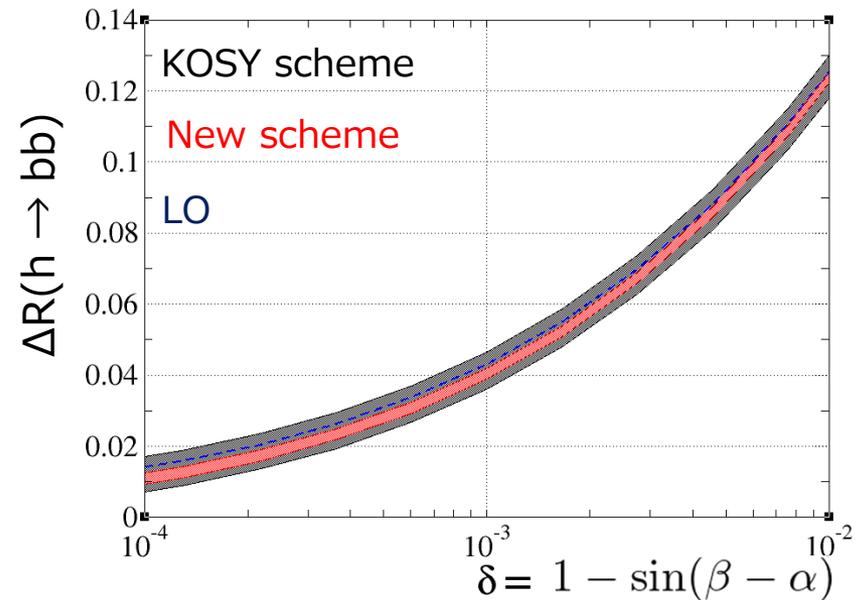
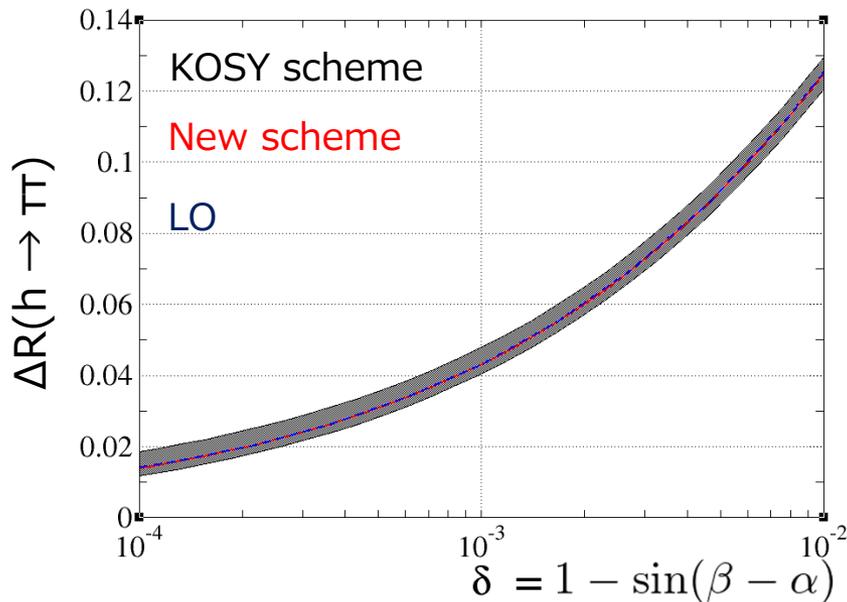
# Deviation in the $h \rightarrow ff$ decays (Type-I)

Using H-COUP v3 with modifications

Type-I 2HDM,  $m_{H^\pm} = m_H = m_A = 300$  GeV,  
 $\tan\beta = 2$ ,  $0 < M^2 < (300 \text{ GeV})^2$

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$

*Preliminary*



$h \rightarrow cc$  is almost the same as  $h \rightarrow \tau\tau$

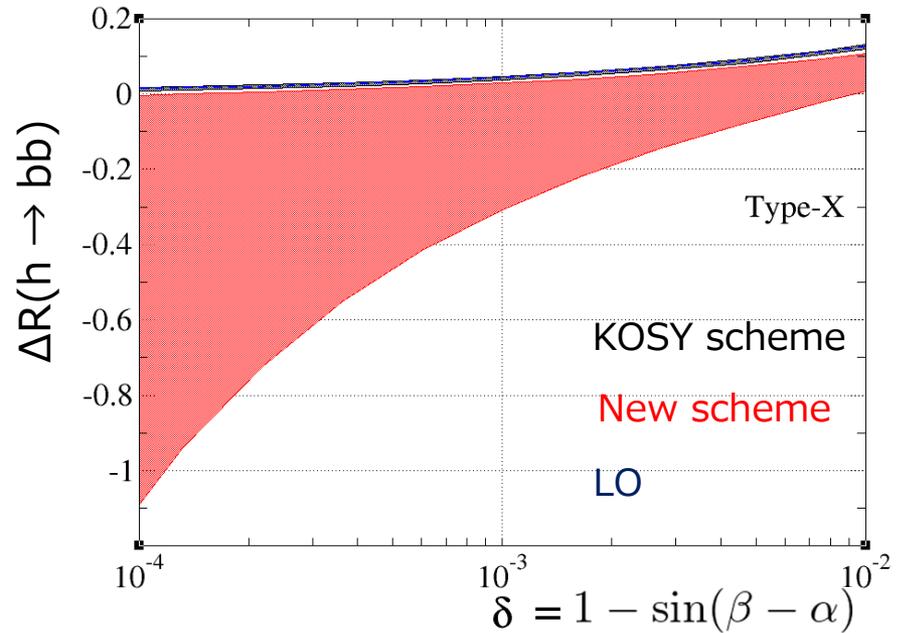
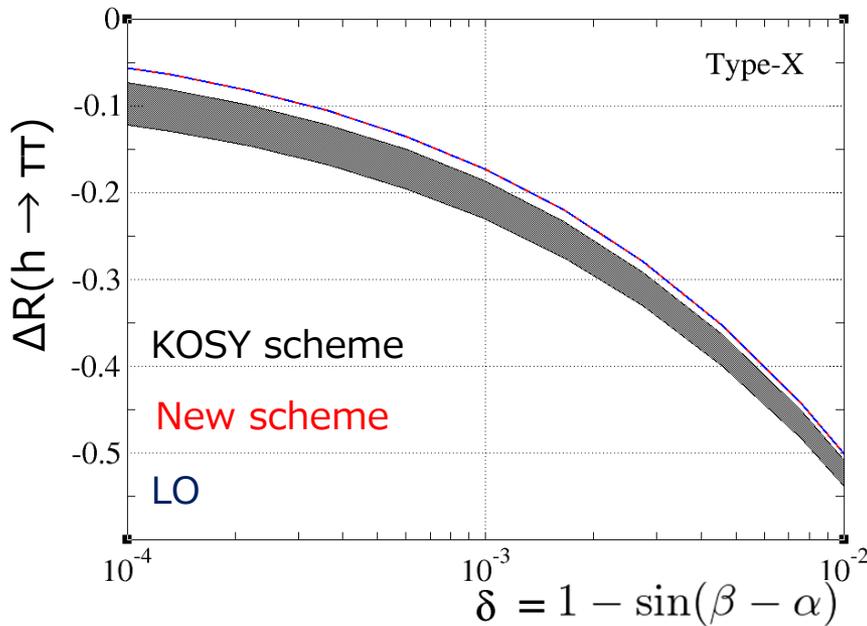
# Deviation in the $h \rightarrow ff$ decays (Type-X)

Using H-COUP v3 with modifications

Type-X 2HDM,  $m_{H^\pm} = m_H = m_A = 300$  GeV,  
 $\tan\beta = 2$ ,  $0 < M^2 < (300 \text{ GeV})^2$

$$\Delta R(h \rightarrow XX) = \frac{\Gamma(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$

Preliminary



$h \rightarrow cc$  is almost the same as  $h \rightarrow bb$

$$x \sim \sqrt{2\delta}$$

# Non-decoupling effects on hhh

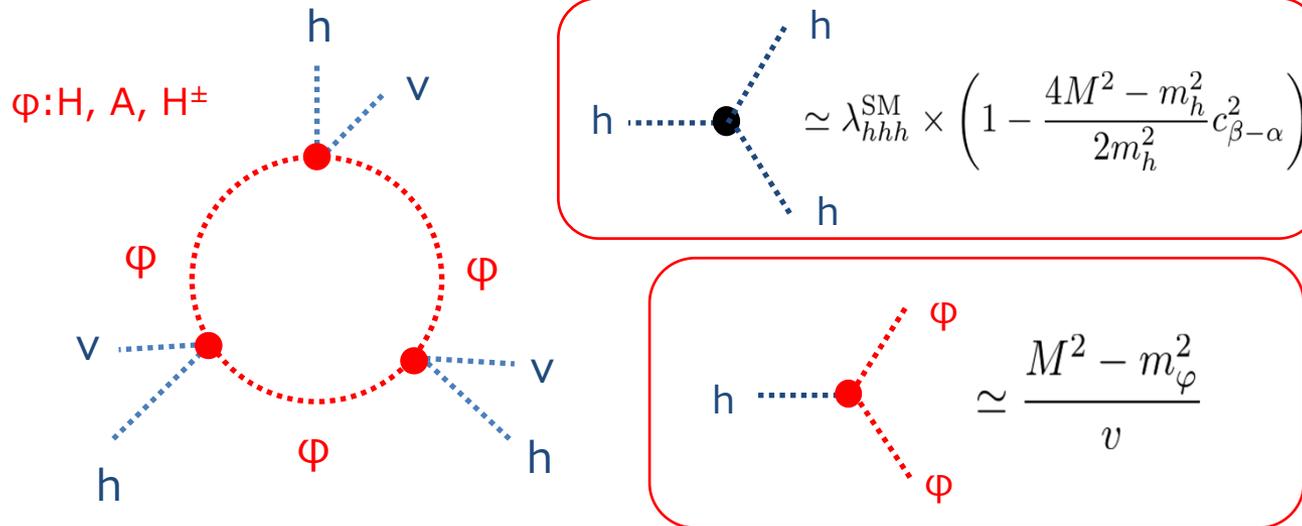
## □ 1-loop correction to hhh

*Kanemura, Okada, Senaha, Yuan (2004)*

*2-loop calculations:*

*Braathen, Kanemura (2019)*

*Bahl, Braathen, Weiglein (2022)*



$$\simeq \frac{1}{32\pi^2} \sum_{\varphi} c_{\varphi} \frac{\lambda_{h\varphi\varphi}^3}{m_{\varphi}^2} \quad c_{\varphi} = 2(1) \text{ for } H^\pm (H, A)$$

$$= -\frac{1}{32\pi^2} \sum_{\varphi} c_{\varphi} \frac{m_{\varphi}^4}{v^3} \left(1 - \frac{M^2}{m_{\varphi}^2}\right)^3 \quad \left\{ \begin{array}{l} \sim \frac{v^3}{M^2} \quad \text{Decoupling case } (M \sim m_{\varphi}) \\ \sim \frac{m_{\varphi}^4}{v^3} \quad \text{Non-dec. case } (M \ll m_{\varphi}) \end{array} \right.$$

This  $m_{\varphi}^4$ -like effect appears in both the KOSY & the new schemes.

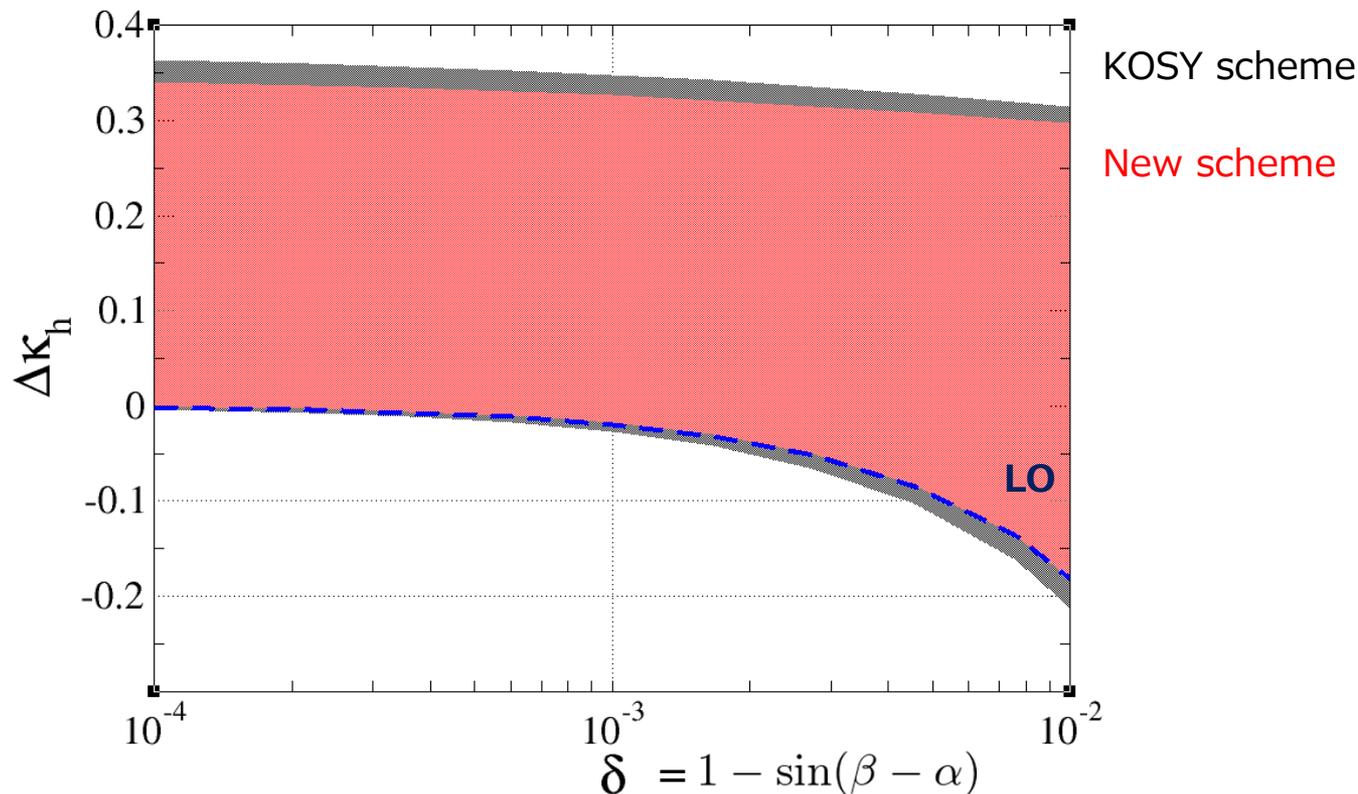
# Renormalized hhh coupling

Using H-COUP v3 with modifications

Type-I 2HDM,  $m_{H^+} = m_H = m_A = 300$  GeV,  
 $\tan\beta = 2$ ,  $0 < M^2 < (300 \text{ GeV})^2$

$$\Delta\kappa_h = \frac{\hat{\Gamma}_{hhh}}{\hat{\Gamma}_{hhh}^{\text{SM}}} - 1$$

*Preliminary*



# Summary

- **H-COUP** is a numerical tool to compute the Higgs decays @ NLOEW.
- We proposed the new renormalization scheme in the 2HDM, where the counterterms  $\delta\alpha$  and  $\delta\beta$  are determined by using the  $h \rightarrow \tau\tau$  and  $h \rightarrow Zll$  decays.
- In the new scheme, the mixing angle  $\sin(\beta-\alpha)$  works to describe the **alignmentness**, and we can compute the other Higgs observables by inputting the deviation in the  $h \rightarrow ZZ^*$  (and/or  $h \rightarrow \tau\tau$ ) decay.
- In the new scheme, the deviation in  $h \rightarrow WW^*$  is almost the same as  $h \rightarrow ZZ^*$ .  
For the  $h \rightarrow ff$  decays, they strongly depend on the Yukawa & fermion types.  
For the  $hhh$  coupling, a large non-decoupling loop effect can appear in both schemes.