H_{125} coupling measurement:

what to expect and what can we do with it

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This talk

1. Introduction
2. Extended Higgs Sectors
3. Radiative corrections to decays of h_{125}
4. Radiative corrections to the Higgs to Higgs decays
5. Summary

1 Introduction

EWSB in the standard model

- The SM is composed of two pillars
  - Gauge principle (interactions)
  - EWSB (mass)

- But there is no theoretical principle for EWSB
  - In SM, a Higgs field is tentatively introduced for EWSB
  - This is just an assumption

Higgs and New Physics

- A Higgs boson was found at LHC
  - The coupling constants seem to be SM-like.
  - No new particle has been found up to now.

- However, SM is not enough
  - There are BSM phenomena which SM cannot explain
    Neutrino, Baryon Asymmetry, Dark Matter, Dark Energy, …
  - Theoretical issues, Gravity, GUT, Flavor, Hierarchy, …

- New theory beyond the SM is necessary.

Higgs sector is key

- **SM Higgs is just an assumption.**
  - **Nature of the Higgs boson is unknown**
  - **Nature of EWSB (Higgs potential) is unknown.**
  - **Nature of EW Phase Transition is unknown.**

- **Possibility of non-minimal Higgs sectors.**
  - **Required in many new physics models such as SUSY etc**
  - **BSM phenomena may be explained**
  - **Testable at experiments including ILC, CEPC, CLIC,…**

Higgs is the most important probe of new physics

All SM particles have been discovered

Next target is new physics!

- Importance of **accurate calculations**
- Future **precision measurements**
  - S, T, U (Giga Z, Mega W)
  - Top (e.g. ttZ) couplings
  - Couplings of the discovered Higgs (Higgs factory)

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

At future lepton colliders, we may be able to distinguish models by detecting a pattern of deviations in the h_{125} couplings from the SM predictions!

Fingerprinting new physics models

2 Extended Higgs sectors

Extended Higgs sectors?

Multiplet Structure (with additional scalars)

- Φ_{SM} + Isospin Singlet,
- Φ_{SM} + Doublet (2HDM),
- Φ_{SM} + Triplet,
- …

Additional Symmetry

- Discrete or Continuous?
- Exact or Approximate or Softly broken?

Interaction

- Weakly coupled or Strongly Coupled?

} Hint for BSM models

Rho parameter	➡	Multi-doublet (and singlet) structures
FCNC Suppression	➡	Strong constraint on the Yukawa sector

2HDM with a softly-broken Z_2

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

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

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

↑ CPeven ↑ CPodd ↑charged

Mass eigenstates

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

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

masses

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

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

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

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

M_{soft}: soft breaking scale

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

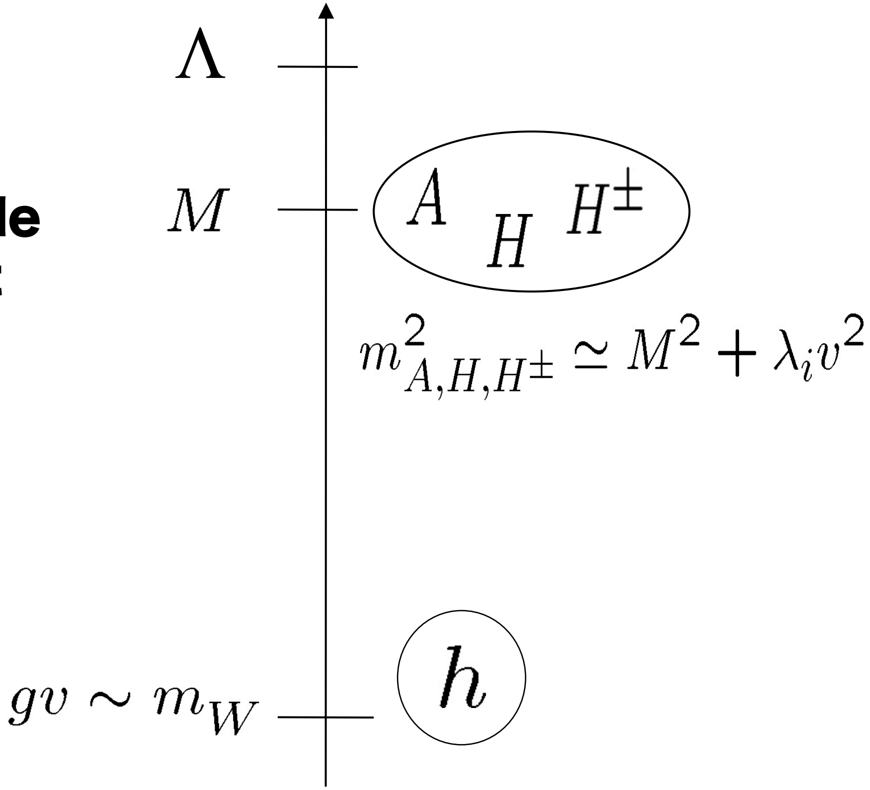
$M_{\text{soft}} \quad \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

soft-breaking scale of the discrete symm.

Two possibilities satisfying current data

Λ : **Cutoff**

M : **Mass scale irrelevant to VEV**



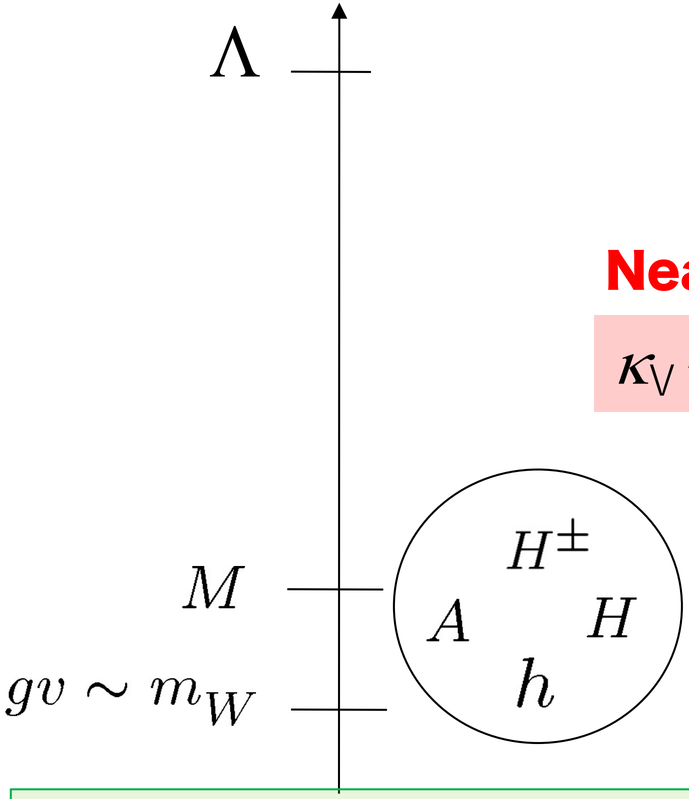
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM

Decoupling

Near Alignment

$\kappa_V \sim 1$ $\cos(\beta-\alpha) \sim 0$



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

Effective Theory is an extended Higgs sector

Alignment without decoupling

Deviation = New Scale

No Lose Theorem

Lee, Quigg, Thacker 1977

Unitarity: Higgs boson must appear below 1 TeV,
Otherwise, new physics must appear below 1TeV

Motivation to build SSC, LHC
Lead to Higgs discovery at LHC!

m_h=125 GeV

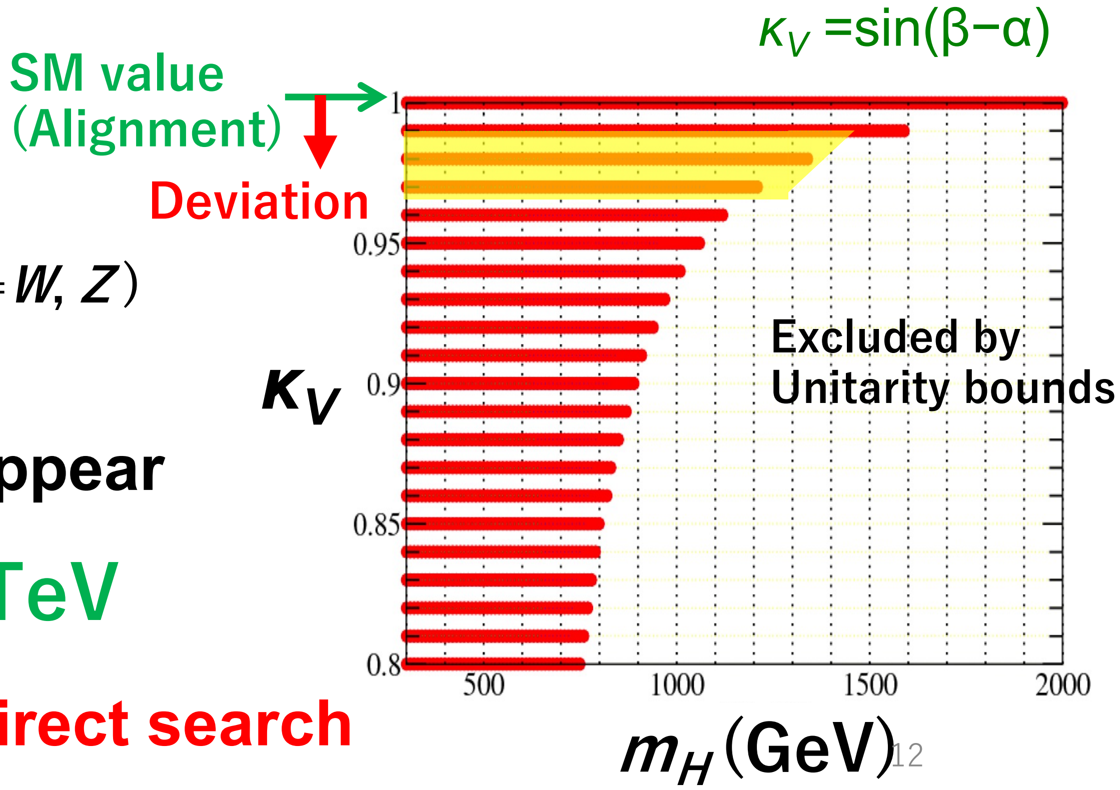
New No Lose Theorem

hVV coupling ($V=W, Z$)

Unitarity: If deviations in Higgs couplings,
the second Higgs *H* or new physics must appear

Ex) $\Delta\,\kappa_V = 2\,\%$ ⇄ $m_H < 1.4$ TeV

Higgs precision test has the same power as direct search



Yukawa Couplings

Multi-doublet models: FCNC appears via the Higgs mediation

In two Higgs doublet models:

to avoid FCNC, give different charges to Φ_1 and Φ_2

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

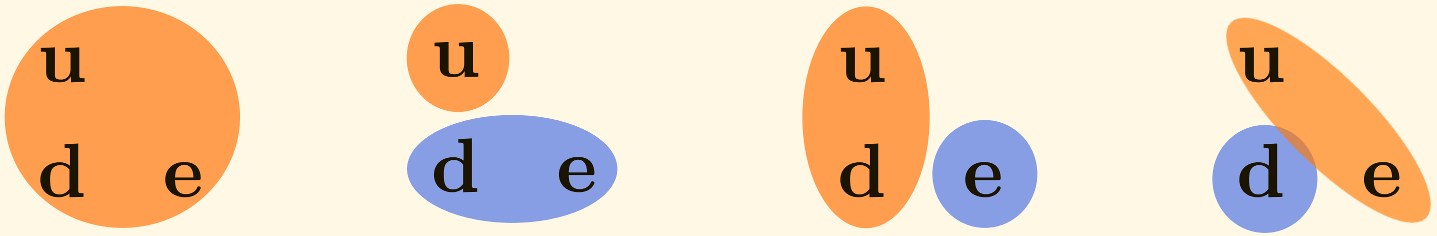
Each quark or lepton couples only one Higgs doublet

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
Neutrinophilic Inert	SUSY	Radiative Seesaw Lepton specific	

Pattern of Deviations

Gauge couplings: *hVV*

Yukawa couplings: $h\tau\tau$, *hbb*, *hcc*

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

	κ_V	κ_τ	κ_b	κ_c
Type-I	↓	↓	↓	↓
Type-II	↓	↑	↑	↓
Type-X	↓	↑	↓	↓
Type-Y	↓	↓	↑	↓

Direction of deviation in each coupling

We can fingerprint extended Higgs models from the pattern of deviation in Higgs couplings

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014

Fingerprinting the 2HDM (tree)

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

SM-like: |x| <<1

x = cos(β−α)

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

When a Fermion couples to Φ_1

$$\kappa_f = 1 + \cot\beta \; x + \cdots$$

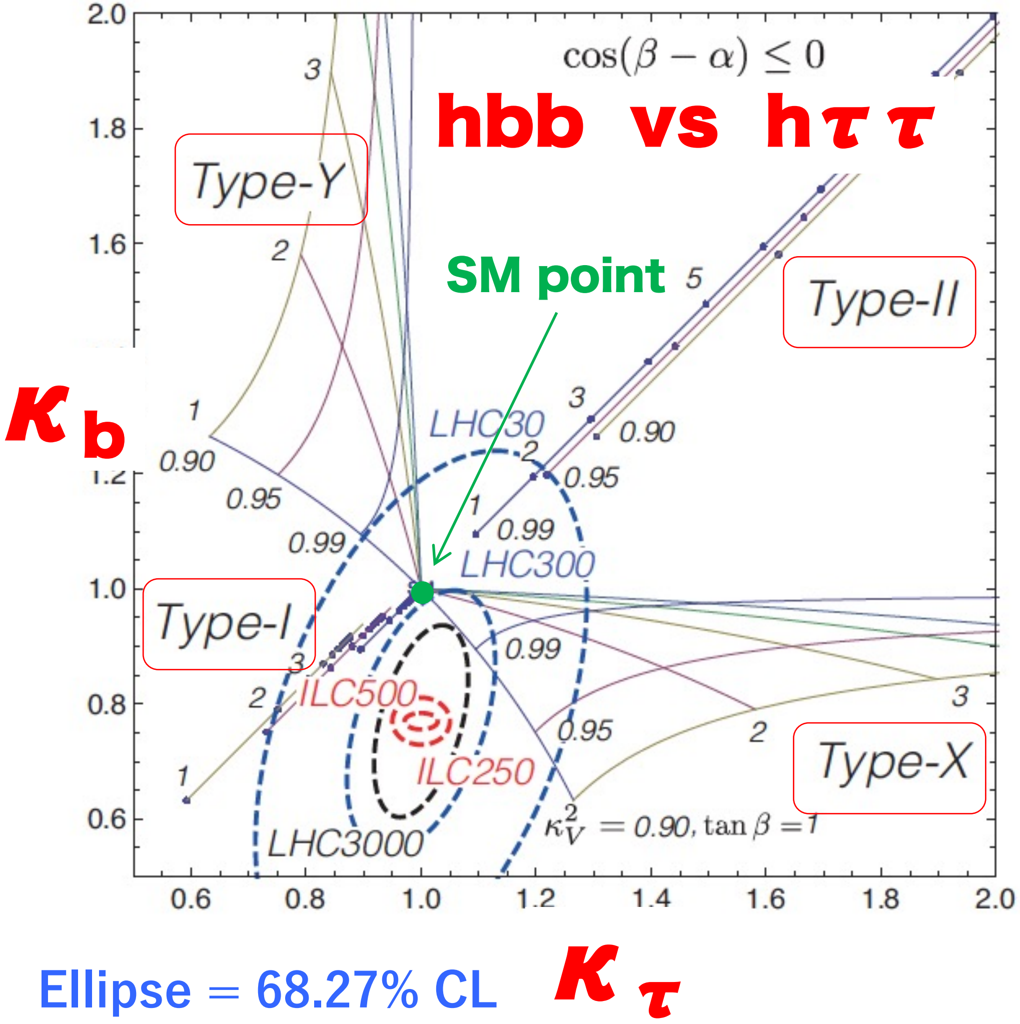
and if it couples to Φ_2

$$\kappa_f = 1 - \tan\beta \; x + \cdots$$

If deviation in κ^2_V is large enough to be detected at future collider

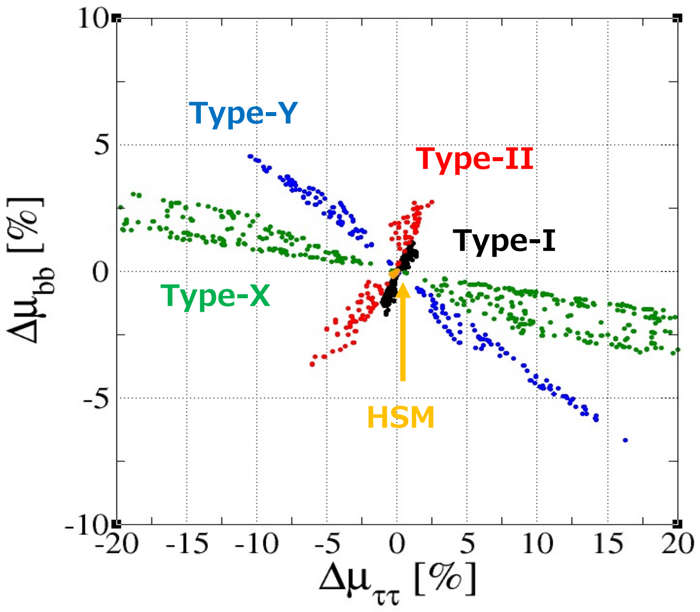
4-models can be separated by looking at deviations in Yukawa couplings κ_τ, κ_b, κ_c, …

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014



Ellipse = 68.27% CL

3　Radiative corrections for Fingerprinting



H-COUP ver.2

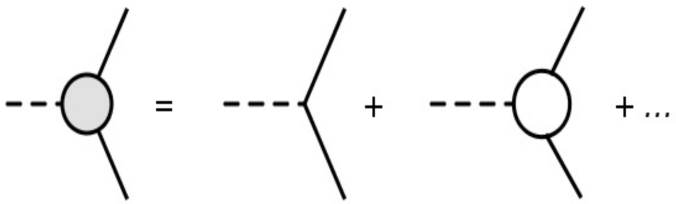
Importance of Radiative Corrections

Higgs couplings *$h\gamma\gamma$, hgg, hWW, hZZ, $h\tau\tau$, hbb, htt, …* will be measured thoroughly in the future lepton colliders such as ILC, CEPC, FCCee

Accurate Theory Predictions × **Future Precision Measurements**

1% or better level measurement

New Physics!



H-COUP Project

SK, Kikuchi, Yagyu, Sakurai, Mawatari, Aiko

Full set of programs to systematically perform NLO calculations to Higgs couplings and decays in a set of extended Higgs models

H-COUP ver. 1 released in 2017

H-COUP ver. 2 released in 2020

Models:
- Additional Singlet
- 2HDM (I)
- 2HDM (II)
- 2HDM (X)
- 2HDM (Y)
- Inert doublet/singlet
- Triplet model

H-COUP Project

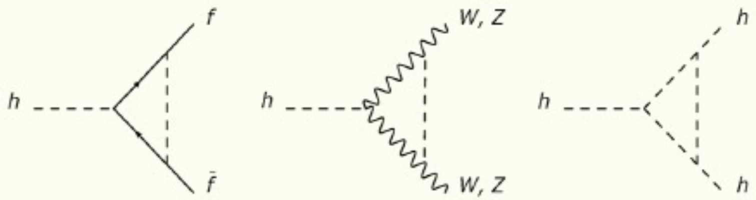
Ver. 2 h(125) decays

Ver. 3 β (to appear)
Production cross sections of h_{125}
Heavy Higgs decays

Full set of Fortran Codes for the NLO calculation of H125 couplings and decays in various extended Higgs models

Four types of 2HDM
Higgs Singlet Model
Inert doublet/singlet model
Higgs triplet model

H-COUP



NEW!! H-COUP version 2.3 was released (30 Apr. 2020)

H-COUP version 2 (1 Sep. 2019) is a calculation tool composed of a set of Fortran codes to compute the Higgs boson decay rates and the branching ratios with radiative corrections (NNLO for QCD and NLO for EW) in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. H-COUP ver. 2 contains all the functions in H-COUP ver. 1.

Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu (and Masashi Aiko (for Ver 3))

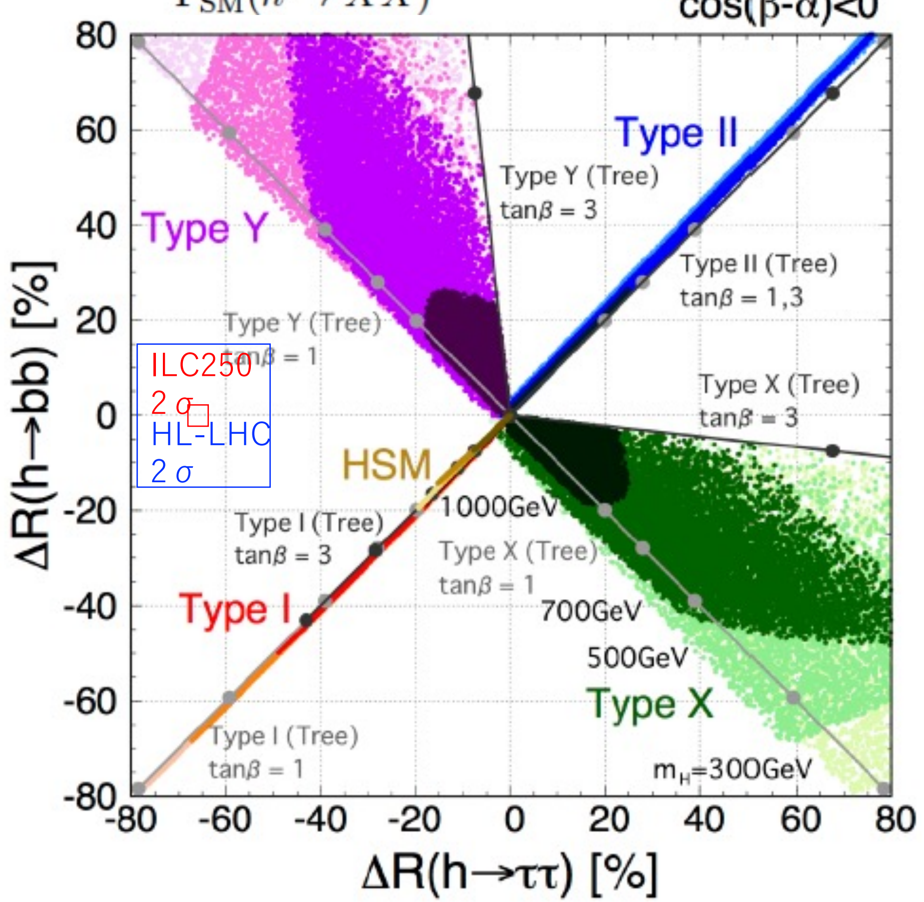
The manual for H-COUP version 2 can be taken on arXiv:1910.12769 [hep-ph].

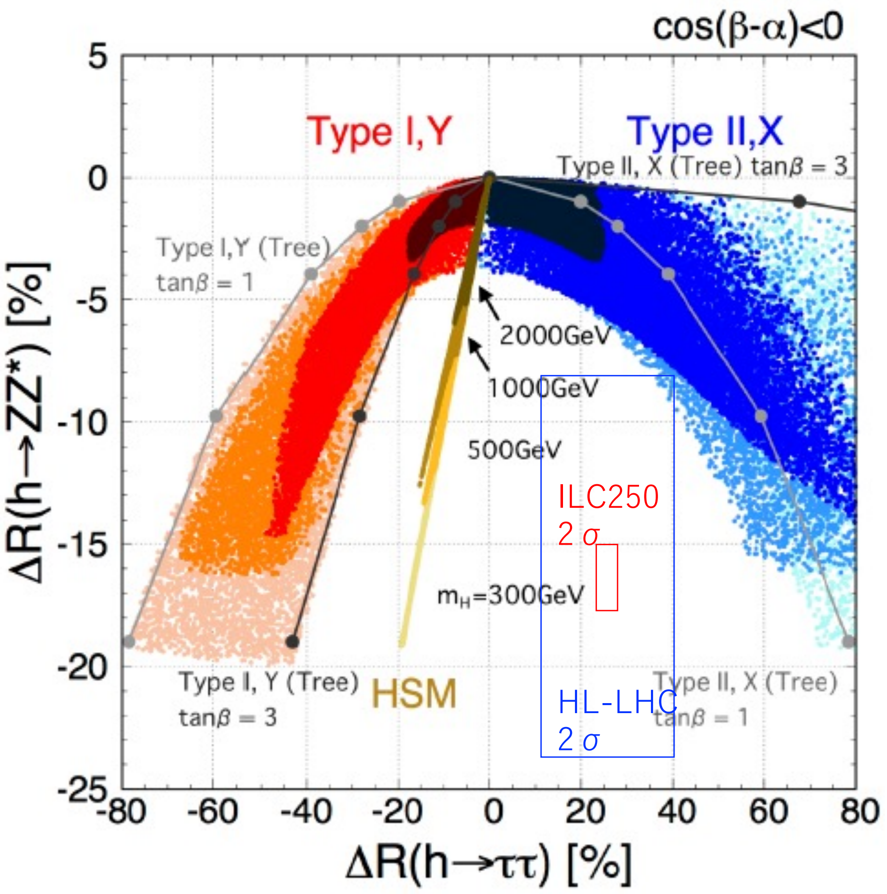
Fingerprinting the new physics

H-COUP Project

SK, Kikuchi, Mawatari, Sakurai, Yagyu 2018

$$\Delta R(h \to XX) = \frac{\Gamma_{NP}(h \to XX)}{\Gamma_{SM}(h \to XX)} - 1$$





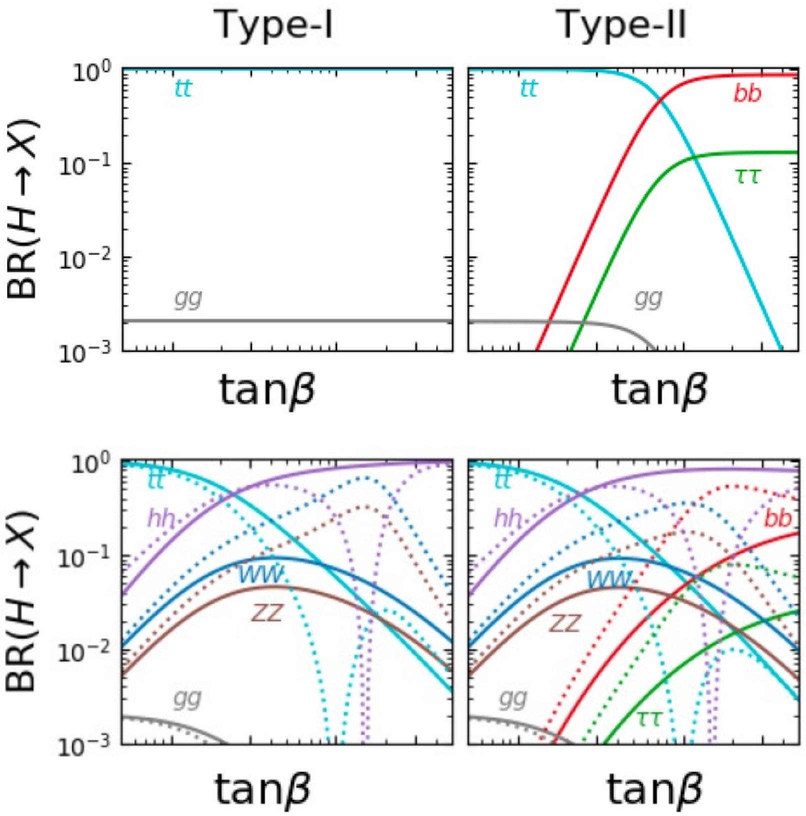
Full set of 1-loop corrections (EW + QCD + Higgs) to the decay rates in various Higgs sectors and future precision measurements at Higgs factories make us possible to fingerprint models and also to get information of inner parameters such as mass of the second Higgs boson

4 Radiative correction to the Higgs-to-Higgs decays

HL-LHC and the Higgs Factory (ILC, CEPC, etc) can explore cases of $\kappa \neq 1$ but not the case of $\kappa = 1$

Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

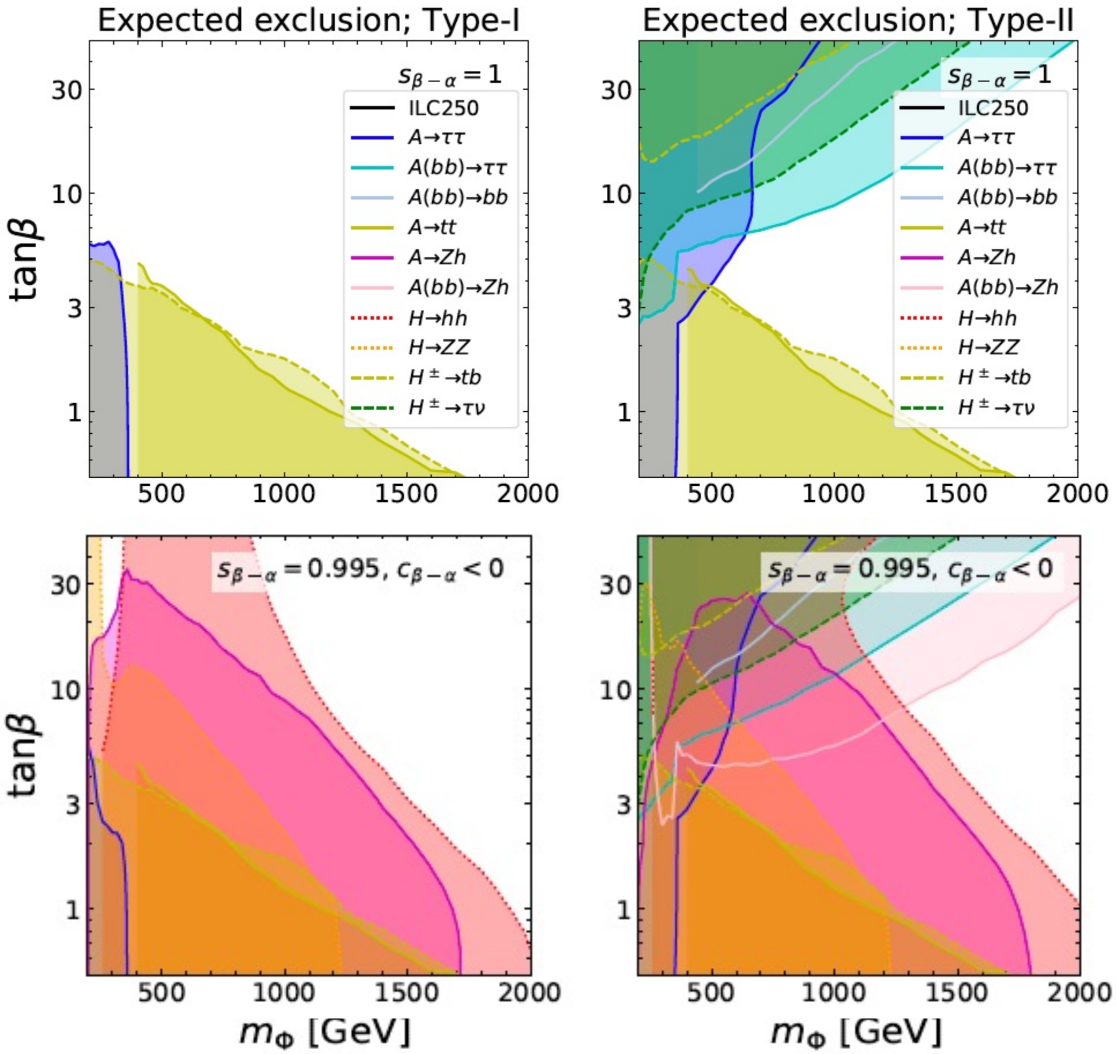
Near and exact are drastically different



***Kv* =1**
Alignment

***Kv* =0.995**
Near alignment

H to H decays become important



Color regions: exclusion at HL-LHC

HL-LHC and the Higgs Factory (ILC, CEPC, etc) can explore cases of $\kappa \neq 1$ but not the case of $\kappa = 1$

Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

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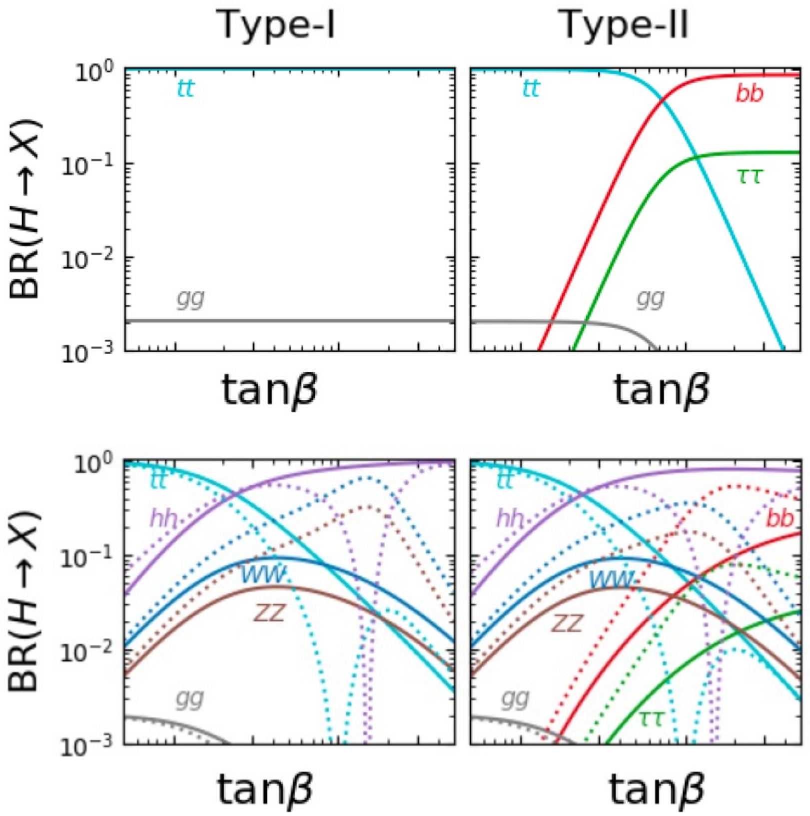
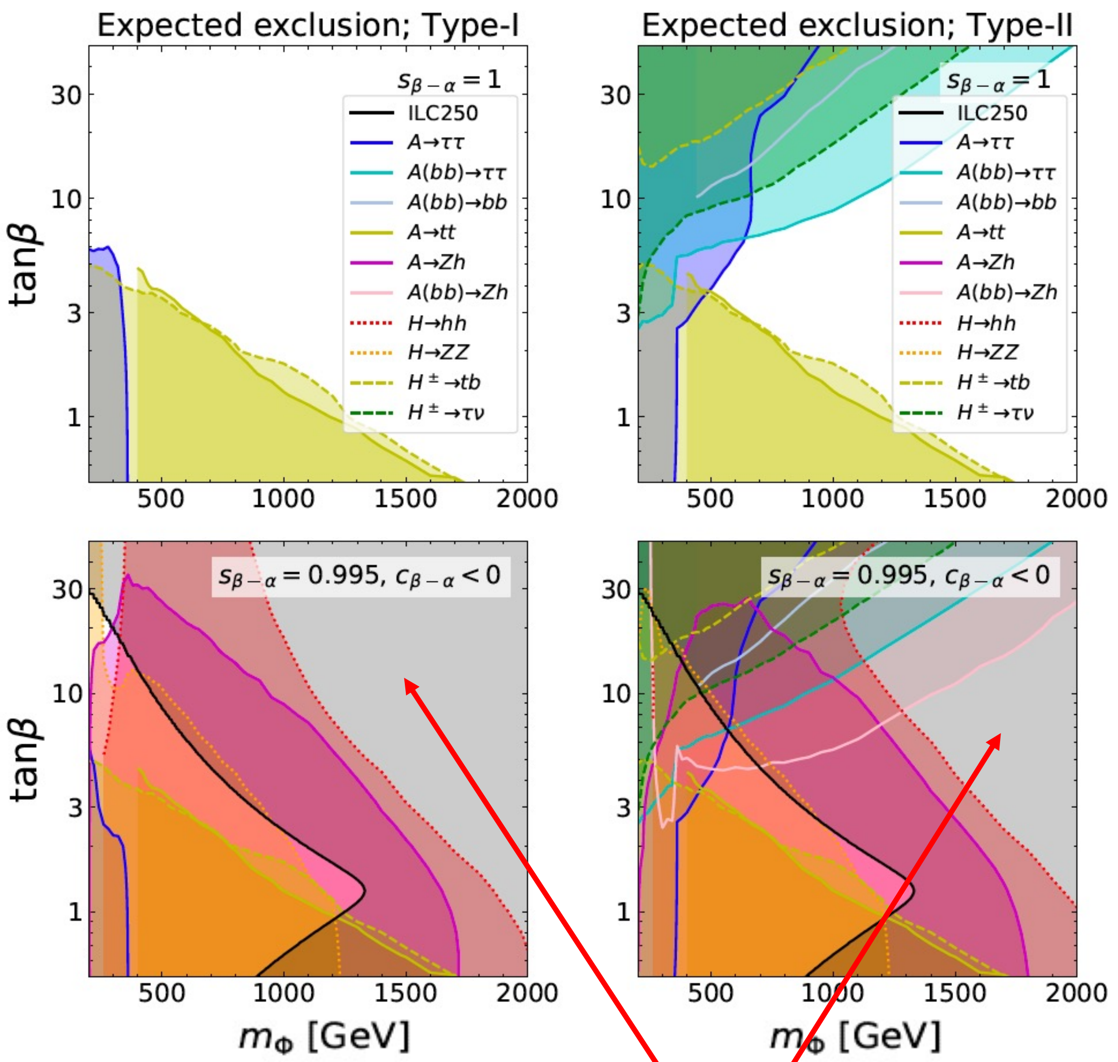


***Kv* =1**
Alignment

***Kv* =0.995**
Near alignment

H to H decays become important



These analyses are at tree level for Higgs-to-Higgs decays

Clearly radiative corrections should be considered

For near alignment cases, all the parameter regions are excluded by 95%CL

By the New No-Lose Theorem

Radiative Corrections to Heavy Higgs bosons

H-COUP ver.3β

Nearly alignment

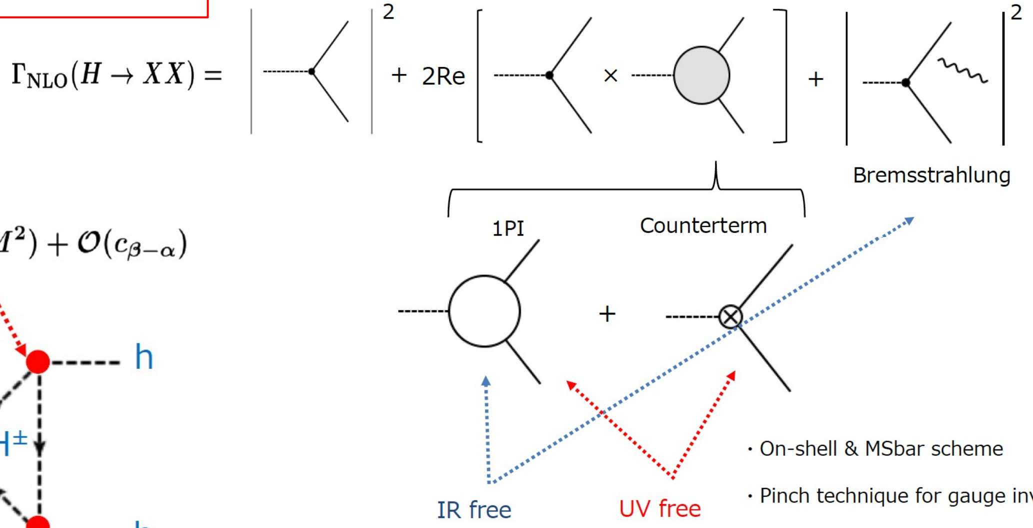
$\cos(\beta-\alpha)\sim 0$

Heavy CP even Higgs boson H

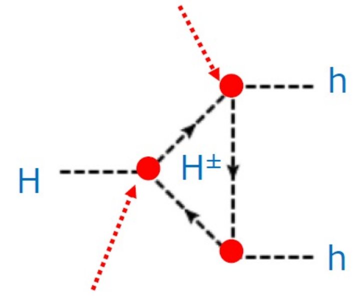
LO Calculation

$$\lambda_{Hhh} = -\frac{c_{\beta-\alpha}}{2vs_{2\beta}}\{(2m_h^2+m_H^2-3M^2)s_{2\alpha}+M^2 s_{2\beta}\}$$

NLO Calculation



$\frac{2}{v}(m_{H^\pm}^2 - M^2) + \mathcal{O}(c_{\beta-\alpha})$



$\frac{2}{v}(m_H^2 - M^2)\cot 2\beta + \mathcal{O}(c_{\beta-\alpha})$

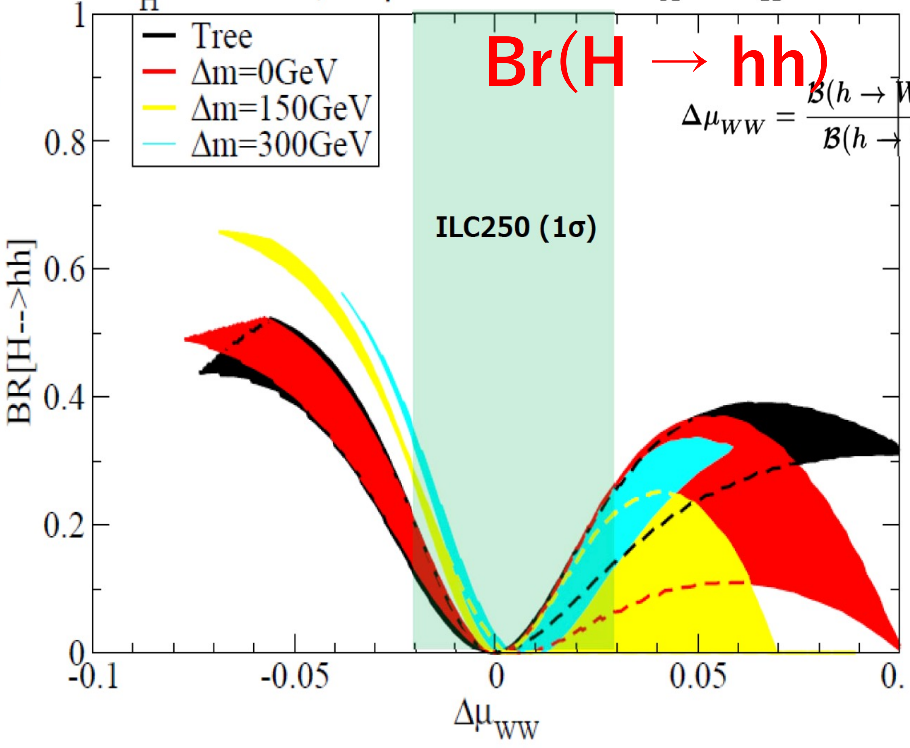
- On-shell & MSbar scheme
- Pinch technique for gauge inv.

1 loop amplitude not suppressed by cos(β-α).

Can change BR drastically in nearly alignment case.

$m_{H^\pm} = m_A$ [sin(β-α) and M are scanned]

$\Delta m = m_A - m_H$



$\Delta\mu_{WW} = \frac{\mathcal{B}(h\to WW^*)_{\rm 2HDM}}{\mathcal{B}(h\to WW^*)_{\rm SM}} - 1$

SK, M. Kikuchi, K. Yagyu

in preparation

Radiative Corrections to Heavy Higgs bosons

LO Calculation

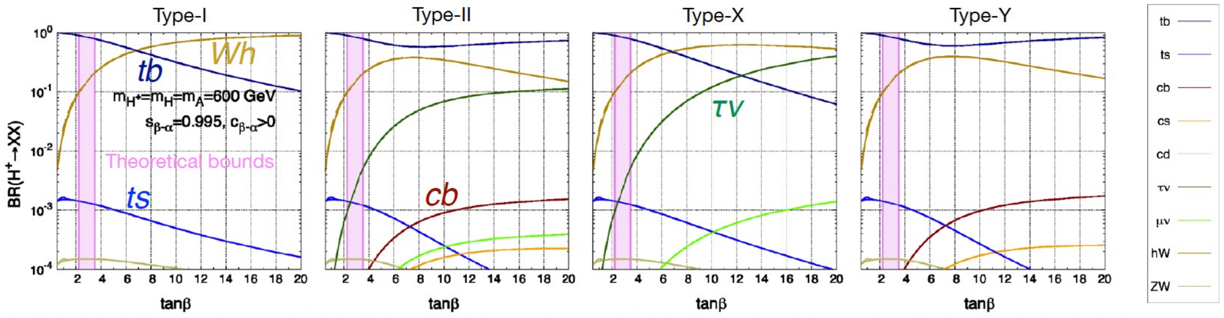
$$\Gamma_{\rm LO}(H^\pm \to f\bar{f}') \simeq \frac{G_f m_{H^\pm}}{4\sqrt{2}\pi} C_f (m_f^2 \xi_f^2 + m_{f'}^2 \xi_{f'}^2)$$

$$\Gamma_{\rm LO}(H^\pm \to Wh) \simeq \frac{G_f m_{H^\pm}^3}{8\sqrt{2}\pi} \cos^2(\beta-\alpha)$$

	ξ_u	ξ_d	ξ_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	$\cot\beta$	$-\tan\beta$	$\cot\beta$

$C_f = 3|(V_{\rm CKM})_{qq'}|^2$ (1) for quarks (leptons)

Inputs: $\sin(\beta-\alpha) = 0.995$, $m_{H^\pm} = m_H = m_A = 600$ GeV tree



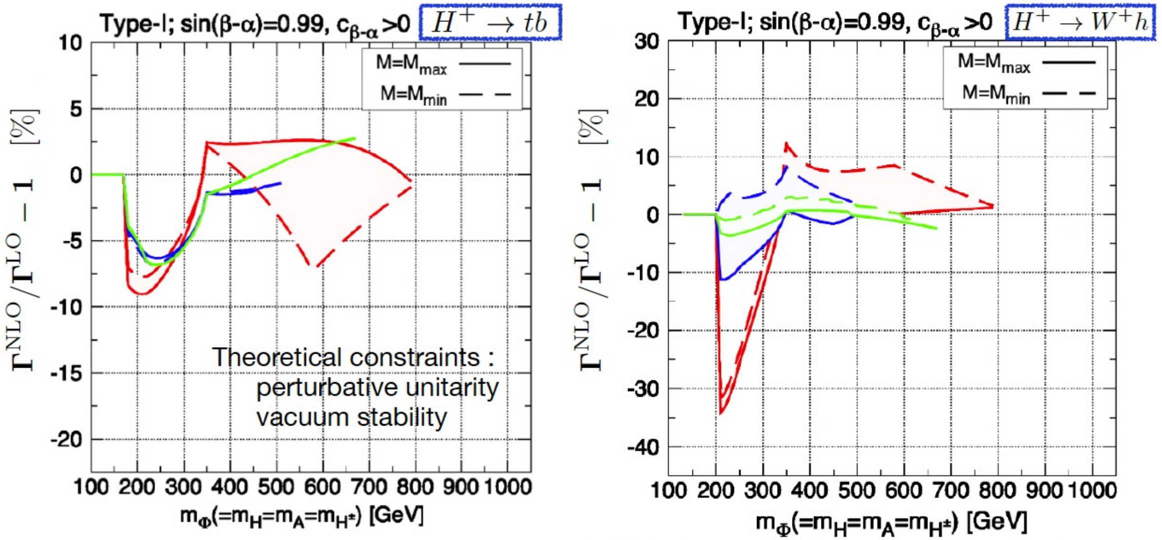
NLO Calculation

$H^\pm \to ff'$, $H^\pm \to W\phi\ (\phi = h, H, A)$, $H^\pm \to WV (V = Z, \gamma)$

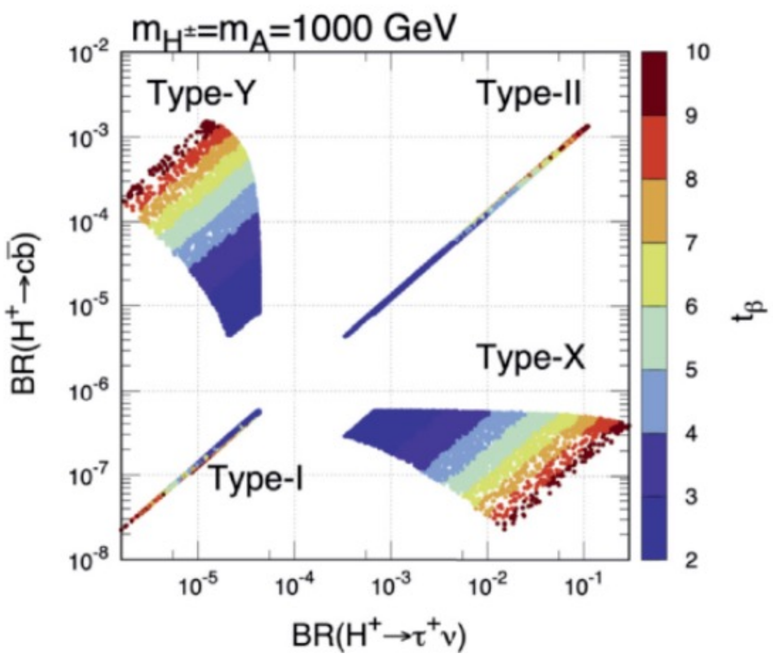
$\tan\beta = 1$

$\tan\beta = 3$

$\tan\beta = 5$



$B_s \to X_s \gamma$, $m_{H^\pm} \gtrsim 800$GeV



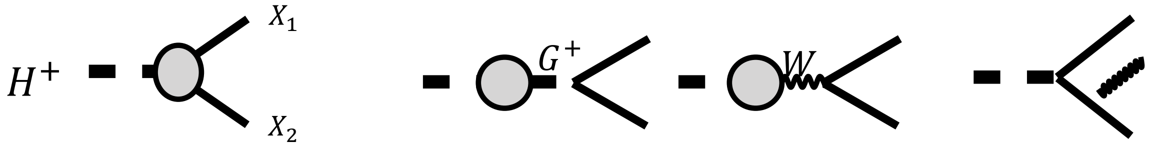
M. Aiko, SK, K. Sakurai, 2021

Radiative Corrections to Heavy Higgs bosons

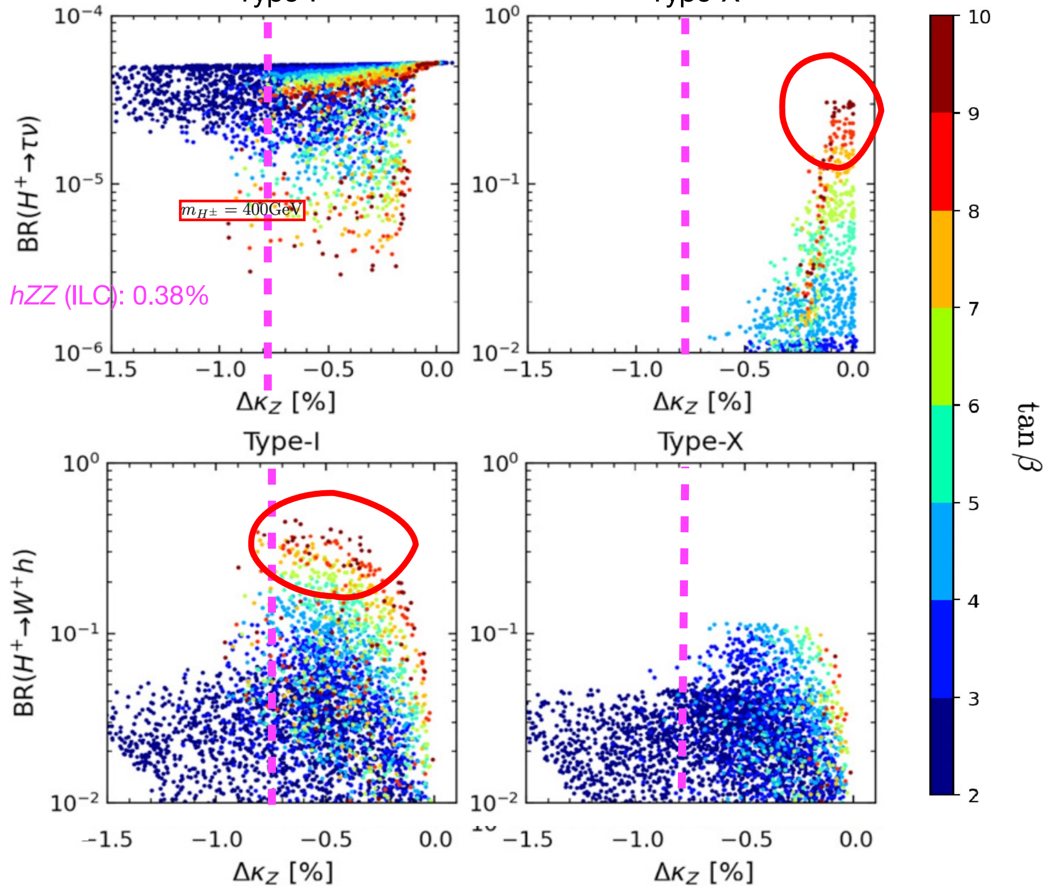
$$(X_1, X_2) = (t,b),\ (\tau,\nu),\ (c,s),\ (\mu,\nu),\ (W^\pm,h),\ (W^\pm,H),\ (W^\pm,A)$$

H-COUP ver.3β

$$\Gamma(H^\pm \to X_1X_2)_{\rm NLO} = \Gamma_{\rm LO}(1 + \Delta_{\rm vert.} + \Delta_{H^+G^-} + \Delta_{H^+W}) + \Gamma_{\rm real}.$$



Vertex corrections　　Mixing contributions of W/G⁺　　Real corrections



Even if the *hZZ* coupling is not significantly deviated from the SM, characteristic decay patterns of *H*± can be predicted.

$\mathrm{BR}(H^+ \to \tau^+\nu) \sim 30\%$ → Type-X

$\mathrm{BR}(H^+ \to W^+h) \sim 50\%$ → Type-I

M. Aiko, SK, K. Sakurai 2021

5 Summary

Summary

Higgs is a probe of new physics

Non-minimal Higgs models

- **New No-Lose Theorem**
  - **Deviation in Higgs coupling = New Physics Scale**
- **Fingerprinting models via Higgs couplings**
  - **Deviation pattern = model discrimination**
- **Radiative Correction to Higgs couplings**
  - **H-COUP Project**
  - **Decay rates of h_{125} in many Higgs models for ILC, CEPC**
  - **Higgs to Higgs decays for LHC**

Precision study of Higgs couplings is the most promising way to new physics at future Higgs factories!

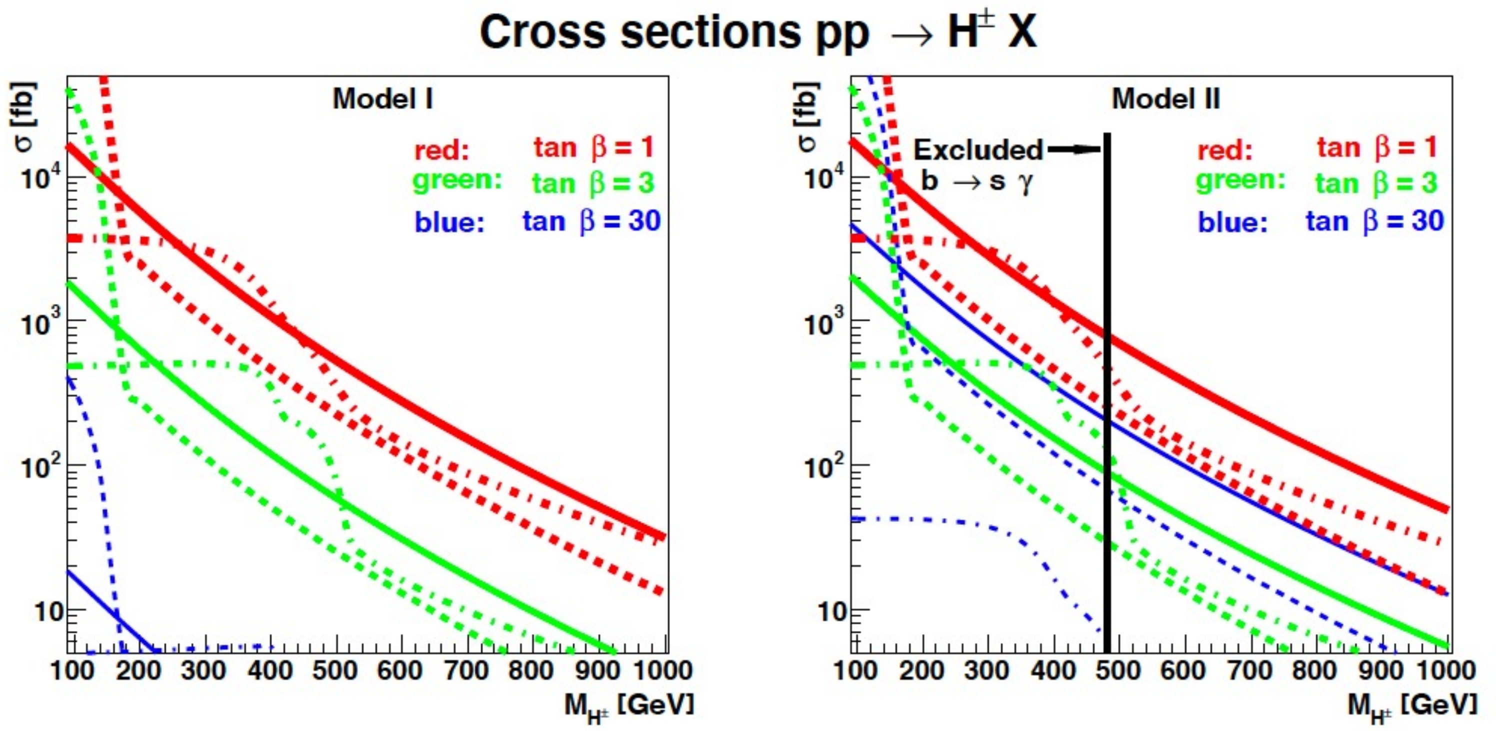


Figure 15: Charged Higgs production cross sections in the 2HDM, at 14 TeV. Left: Model I (or X). Right: Model II (or Y). Solid and dotted curves refer to "fermionic" channels, whereas dash-dotted refer to "bosonic" ones (see text).

1607.01320

Type II 2HDM (MSSM) Higgs couplings

Higgs mixing

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\text{VEV's}: \quad v_1^2 + v_2^2 = v^2 \simeq (246\ \text{GeV})^2$$

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

SM			2HDM Type II	
Gauge coupling:				
$\phi VV \quad (V = Z, W)$			hVV	HVV
	1	$\Rightarrow$	$\sin(\beta-\alpha)$,	$\cos(\beta-\alpha)$
Yukawa coupling:				
$\phi b\bar{b}$			$hb\bar{b}$	$Hb\bar{b}$
	1	$\Rightarrow$	$\frac{\sin\alpha}{\cos\beta}$,	$\frac{\cos\alpha}{\cos\beta}$
$\phi t\bar{t}$			$ht\bar{t}$	$Ht\bar{t}$
	1	$\Rightarrow$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$,

Mixing factors deviate couplings

SM-like regime (aligned regime)

$$\sin(\beta-\alpha)\simeq 1$$

hVV	HVV
$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$

Only the lightest Higgs *h* couples to weak gauge bosons

h **behaves like the SM Higgs**

$$g_{hVV}\to g_{\phi VV}^{\rm SM}$$
$$y_{ht\bar t}\to y_{\phi t\bar t}^{\rm SM}$$
$$y_{hb\bar b}\to y_{\phi b\bar b}^{\rm SM}$$
$$y_{h\tau\tau}\to y_{\phi\tau\tau}^{\rm SM}$$

$$g_{HVV}\to 0$$

Type-II 2HDM:

$$y_{Ht\bar t}\to y_{\phi t\bar t}^{\rm SM}\cot\beta$$
$$y_{Hb\bar b}\to y_{\phi b\bar b}^{\rm SM}\tan\beta$$
$$y_{H\tau\tau}\to y_{\phi\tau\tau}^{\rm SM}\tan\beta$$