$H \to hh$ decay in extended Higgs sectors with a nearly alignment scenario

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Collaboration with

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Paper in preparation

ILC Workshop on Potential Experiments (ILCX)

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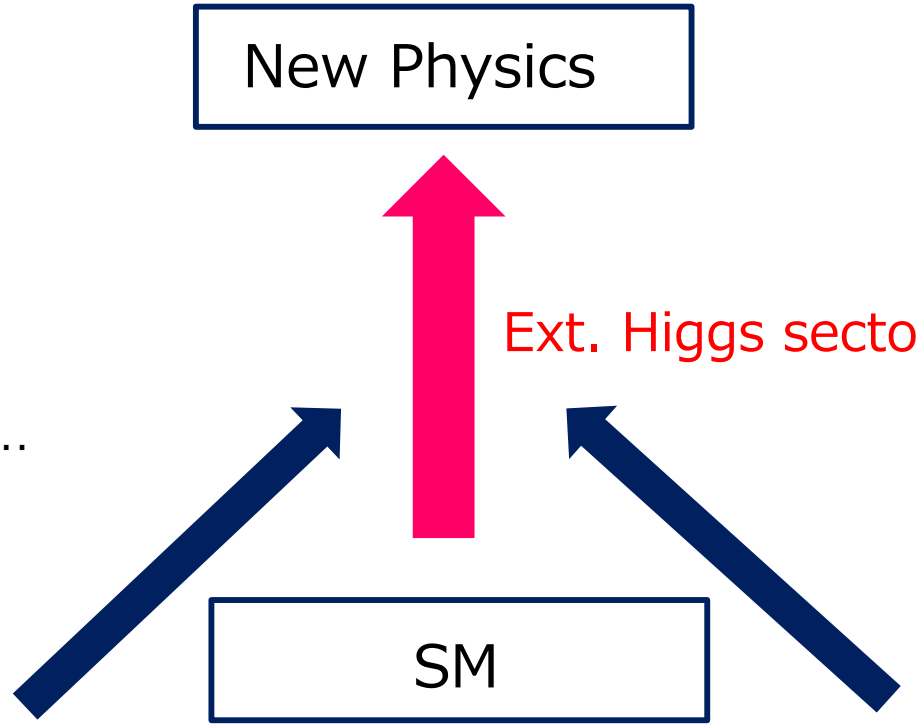
Introduction



Origin of EWSB

-SUSY

-Composite Higgs

-Extra Dimension, …

BSM Phenomena

-Tiny neutrino masses

-Dark matter

-Baryon asymmetry, …

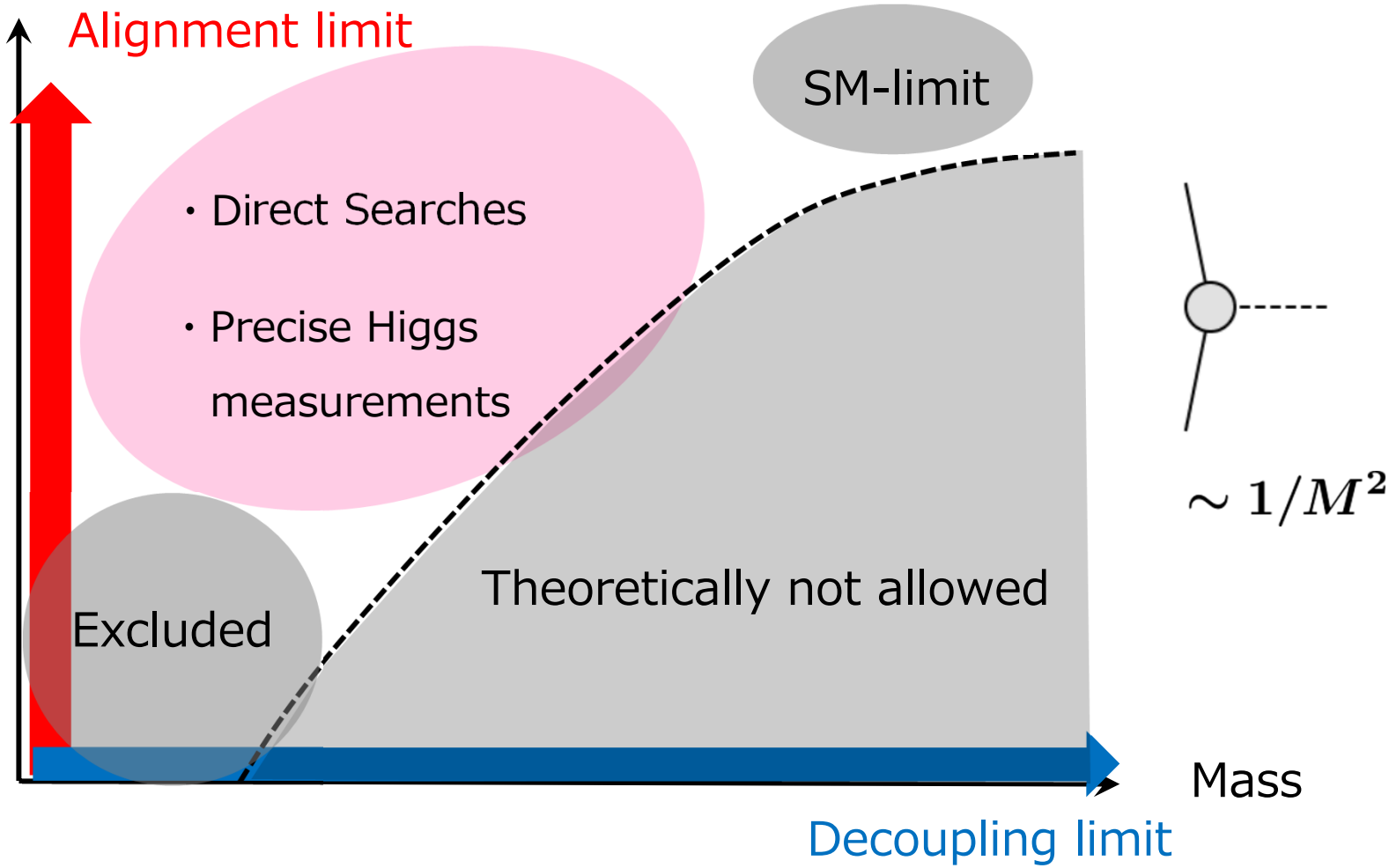
Direct searches for extra Higgs

Precision measurements of h(125)

"Synergy" is important to determine the structure of the Higgs sector!

Keywords: Alignment/Decoupling

SM-likeness of h(125)



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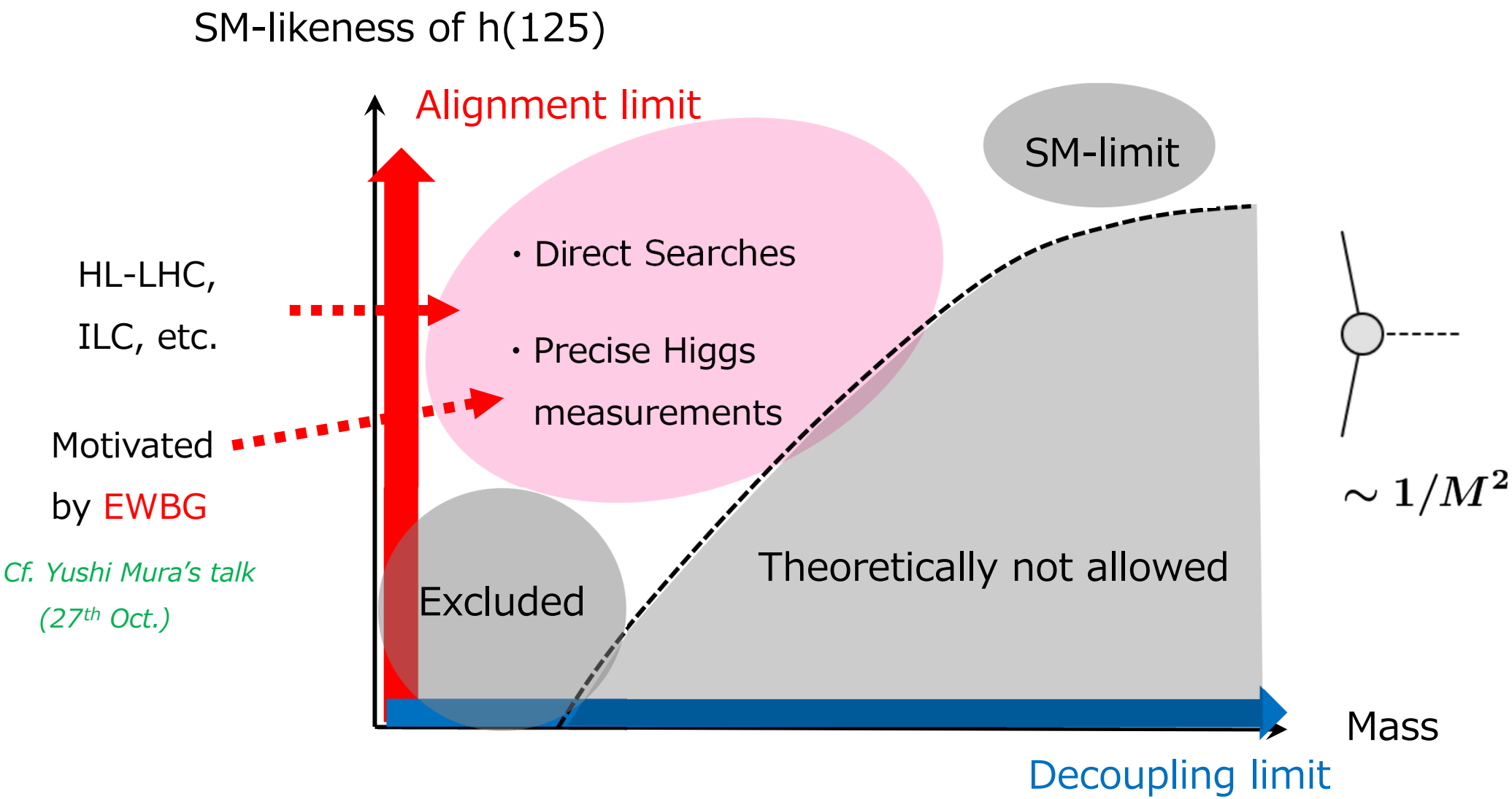


(Near) alignment without decoupling scenario becomes important.

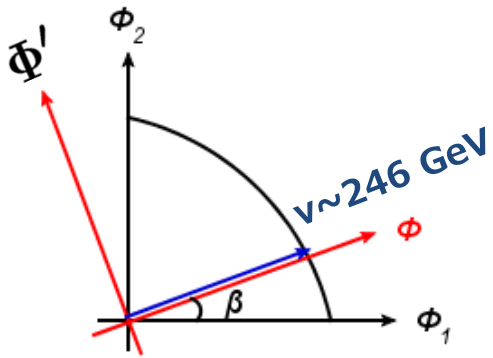
2 Higgs doublet models (2HDM)

- Simple but important example
  - Motivations: SUSY, Composite Higgs, CPV, EWBG, Neutrino masses, Flavor anomalies, etc.
  - Natural extension with $\rho_{tree} = 1$

- Higgs basis

Davidson, Haber PRD71 (2005)

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



NG boson

Charged Higgs

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix} \qquad \Phi' = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{bmatrix}$$

CP-even Higgs

CP-odd Higgs

We particularly consider the case with a softly-broken Z_2 and CP-conservation.

Higgs potential

$$V = M^2|\Phi'|^2 + \frac{\lambda_1}{2}|\Phi|^2(|\Phi|^2 - v^2) + \frac{\lambda_2}{2}|\Phi'|^4 + \lambda_3|\Phi|^2|\Phi'|^2 + \lambda_4|\Phi^\dagger\Phi'|^2$$
$$+ \frac{\lambda_5}{2}(\Phi^\dagger\Phi')^2 + \lambda_6(\Phi^\dagger\Phi')\left(|\Phi|^2 - \frac{v^2}{2}\right) + \lambda_7(\Phi^\dagger\Phi')|\Phi'|^2 + \text{h.c.}$$

$\lambda_i = \lambda_i(\lambda_1'\text{-}\lambda_5', \beta)$

Defined in the Z_2 basis

(tadpole condition imposed)

- Higgs mixing:

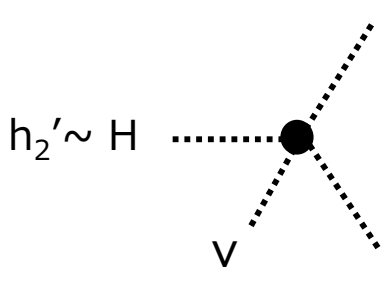
$$\mathcal{M}_H^2 = \begin{pmatrix} \lambda_1 v^2 & \lambda_6 v^2 \\ \lambda_6 v^2 & M^2 + \frac{v^2}{2}\lambda_{345} \end{pmatrix} \begin{matrix} h_1' \\ h_2' \end{matrix}$$

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{bmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{bmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

125 GeV Higgs

$$\sin 2(\beta-\alpha) \simeq \lambda_6 \frac{v^2}{m_H^2}$$

- Decoupling limit: $M^2 \to \infty$
- Alignment limit: $\sin(\beta-\alpha) \to 1$
- Hhh coupling @ near alignment



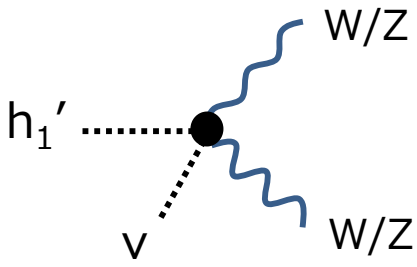
$$\sim v\lambda_6 \sim \frac{m_H^2}{v}\cos(\beta-\alpha)$$

Gauge & Yukawa sector

$$\mathcal{L}_{\mathbf{2HDM}} \supset |D_\mu \Phi|^2 + Y_f \, \bar{\Psi}_L \Phi \Psi_R$$

$$+|D_\mu \Phi'|^2 + Y_f \, \xi_f \, \bar{\Psi}_L \Phi' \Psi_R$$

Gauge & Yukawa sector



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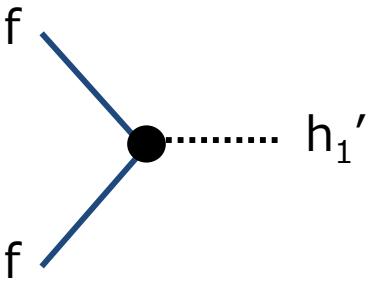
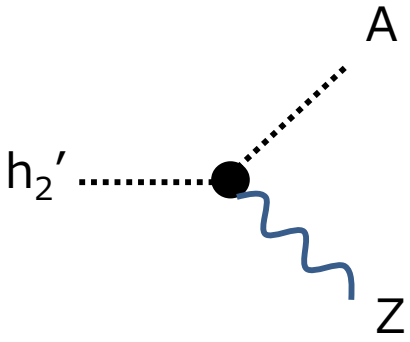
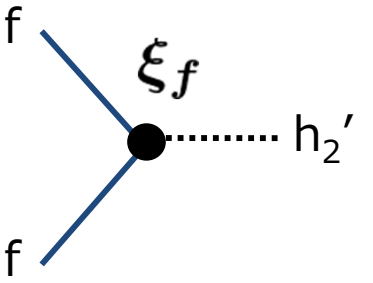


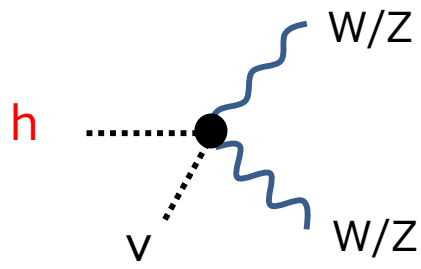


$$+|D_\mu \Phi'|^2 + Y_f \, \xi_f \bar{\Psi}_L \Phi' \Psi_R$$



	ξ_u	ξ_d	ξ_e
Type-I	cotβ	cotβ	cotβ
Type-II	cotβ	-tanβ	-tanβ
Type-X	cotβ	cotβ	-tanβ
Type-Y	cotβ	-tanβ	cotβ

Gauge & Yukawa sector at alignment limit



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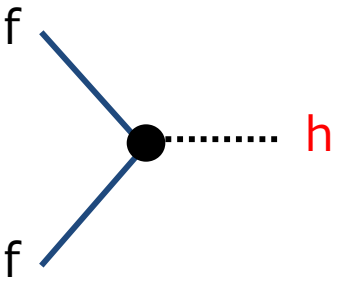

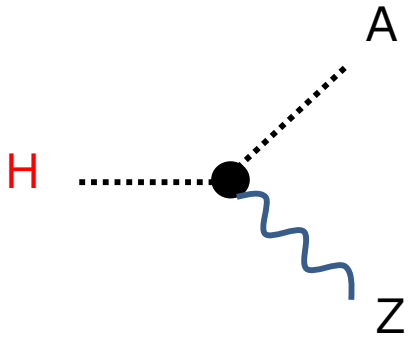

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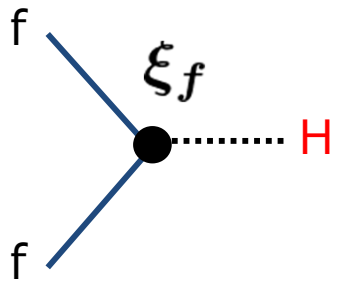

1. Exact alignment: ($h_1' \to h$ and $h_2' \to H$)
   H becomes "fermiophilic".

	ξ_u	ξ_d	ξ_e
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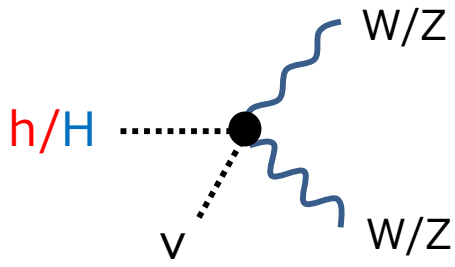
Type-II	cotβ	-tanβ	-tanβ
Type-X	cotβ	cotβ	-tanβ
Type-Y	cotβ	-tanβ	cotβ

Gauge & Yukawa sector at near alignment



with sin(β-α)/cos(β-α)

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{bmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{bmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

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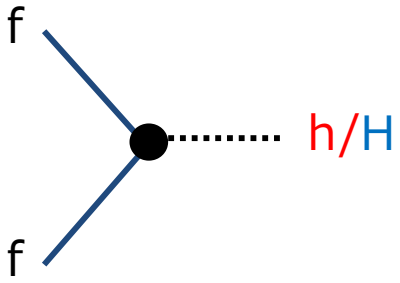
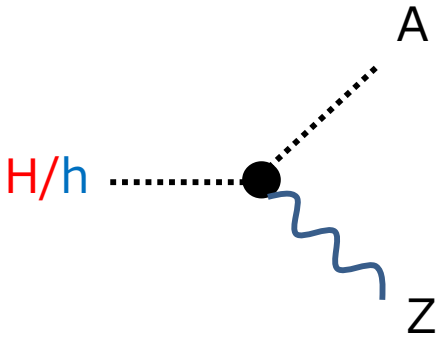
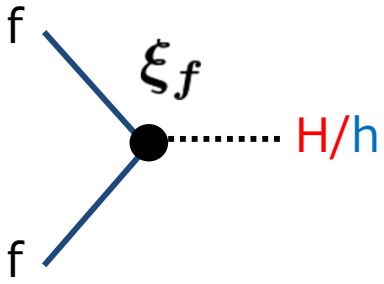


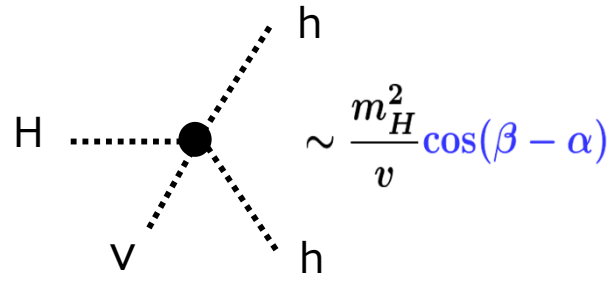


$$+|D_\mu \Phi'|^2 + Y_f \, \xi_f \bar{\Psi}_L \Phi' \Psi_R$$



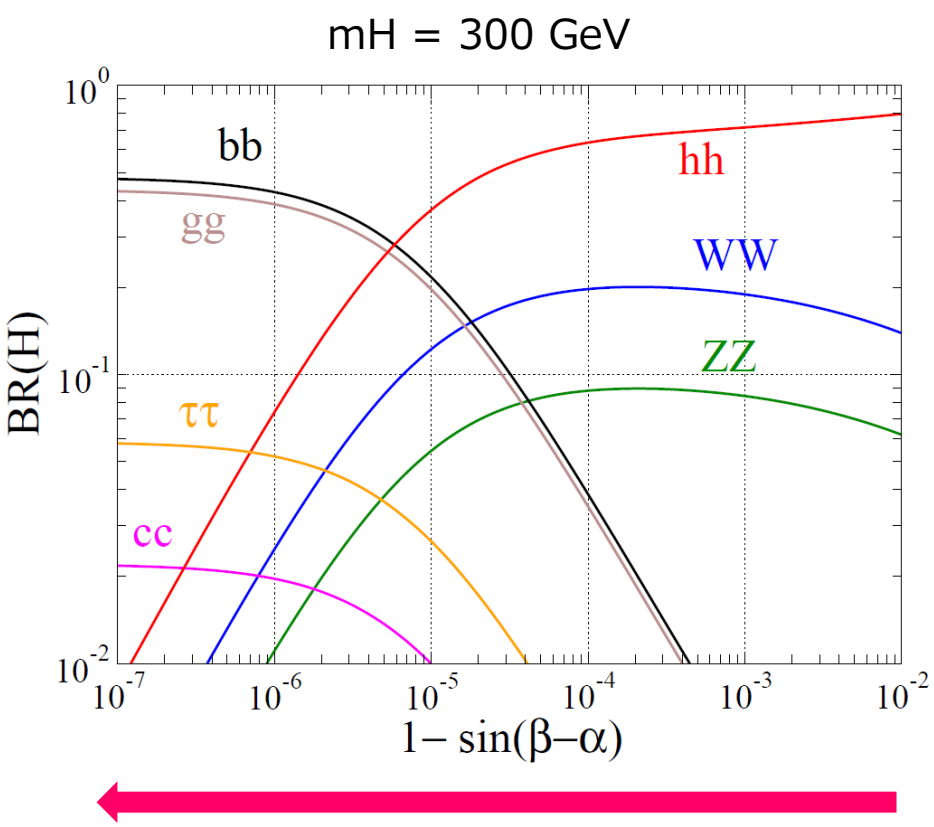
1. Exact alignment: ($h_1' \to h$ and $h_2' \to H$)
   H becomes "fermiophilic".
2. Near alignment:
   H can be "bosophilic".

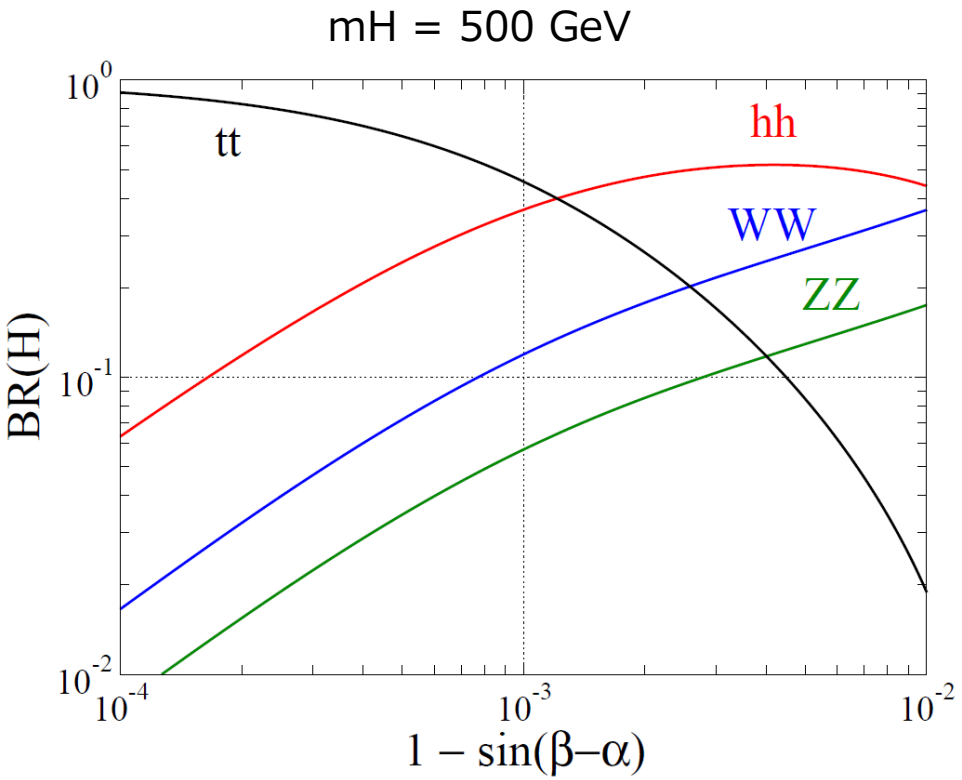
$$\frac{\Gamma(H \to BB)}{\Gamma(H \to FF)} \propto \frac{m_H^2}{m_F^2} \frac{\cos^2(\beta-\alpha)}{\xi_F^2}$$



H decay at tree level

Type-I 2HDM with $m_H = m_A = m_{H+} = M$, $\tan\beta = 5$





Alignment limit

H → hh/WW/ZZ modes become important in the near alignment region.

Q. What happens at one-loop level?

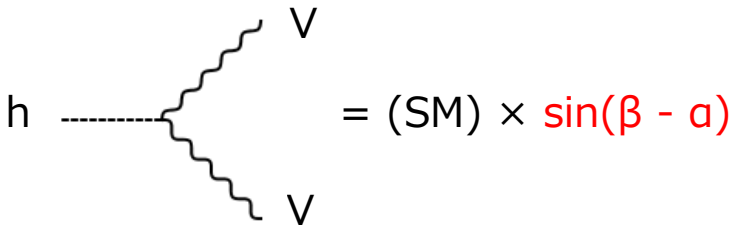
1. Definition of the alignment limit
2. Non-decoupling effects in the H → hh decay

What is the alignment?

- It could be defined by the deviation in the Higgs decay rate :

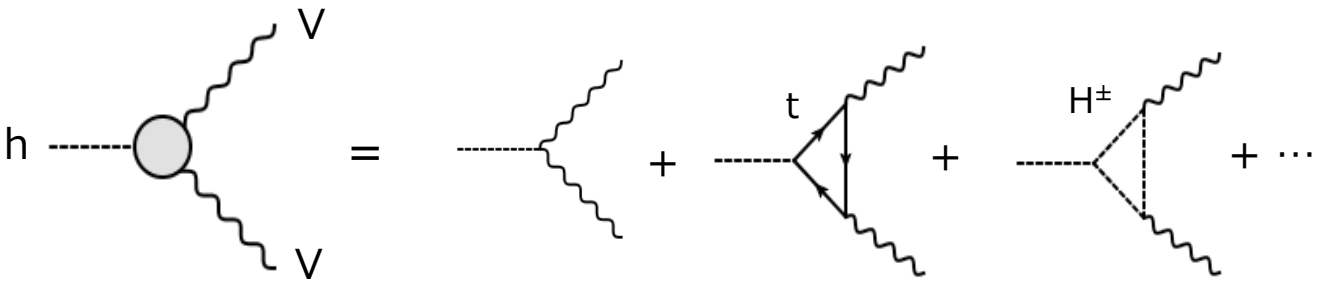
$$\text{“Alignment-ness”} = \Gamma(h \to VV)^{\mathrm{NP}} / \Gamma(h \to VV)^{\mathrm{SM}}$$

- Tree level: sin(β-α) is a good parameter to express the alignment-ness.



= (SM) × sin(β - α)

- Loop level: sin(β-α) does no longer express the alignment-ness.



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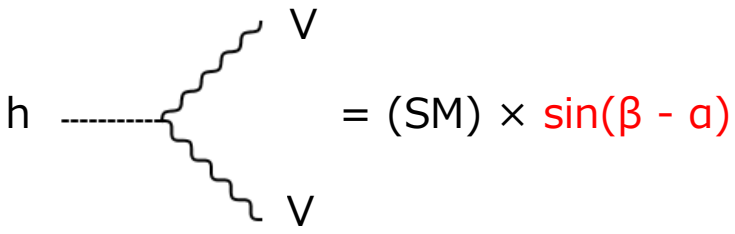
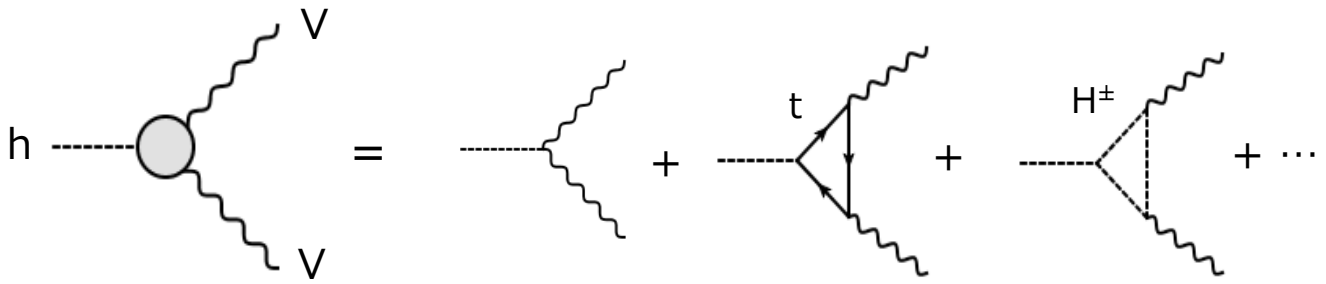
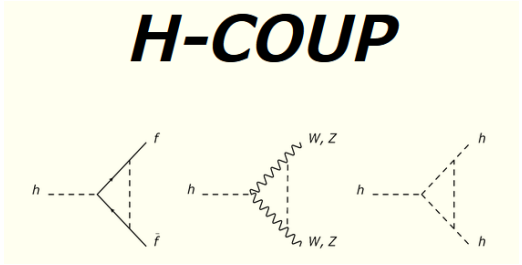


HCOUP:Ver. 1
Kanemura, Kikuchi, Sakurai, KY (2017)

HCOUP:Ver. 2
Kanemura, Kikuchi, Sakurai, Mawatari, KY (2019)

- Loop level: sin(β-α) does no longer express the alignment-ness.





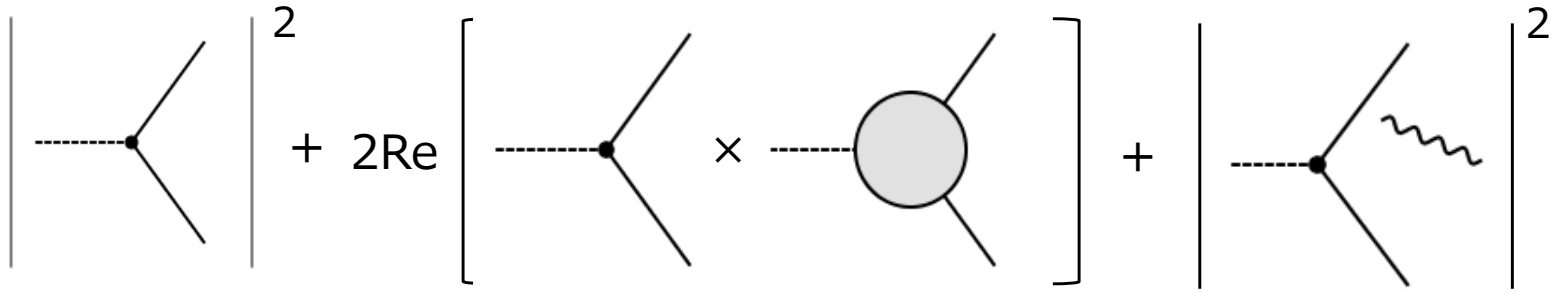
Details of HCOUP, see my talk at F2.

H decay should be evaluated as a function of the "alignment-ness" at one-loop level.

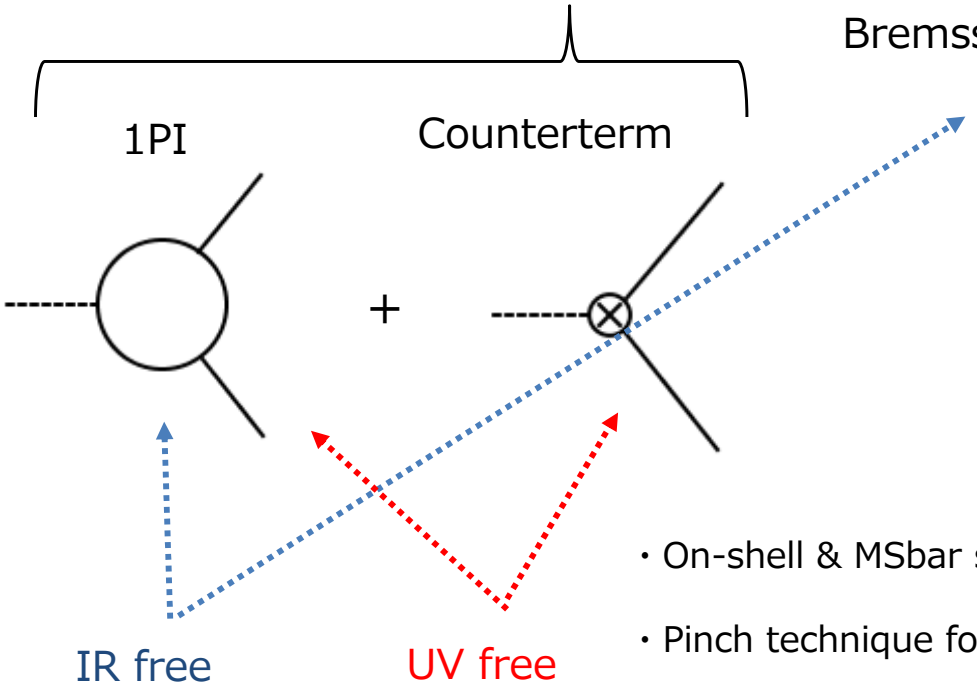
1-loop corrected decay rates

See also Kodai Sakurai's talk for $H^{\pm}$ decays (today, 20:40- JST)

$$\Gamma_{\mathrm{NLO}}(H \to XX) =$$



Bremsstrahlung



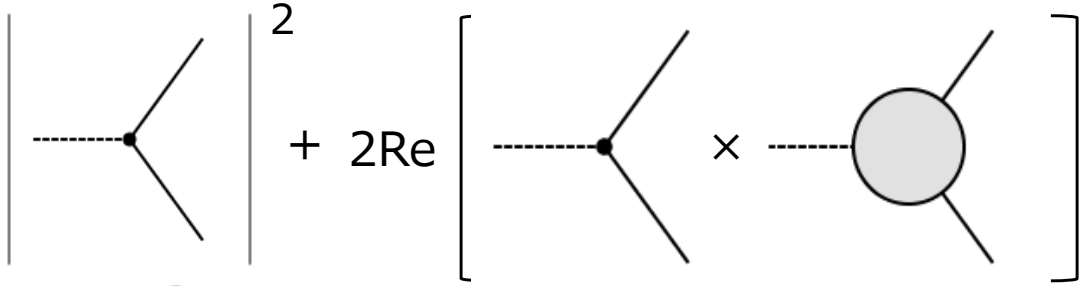
- On-shell & MSbar scheme
- Pinch technique for gauge inv.

1-loop corrected decay rates

See also Kodai Sakurai's talk for H± decays (today, 20:40- JST)

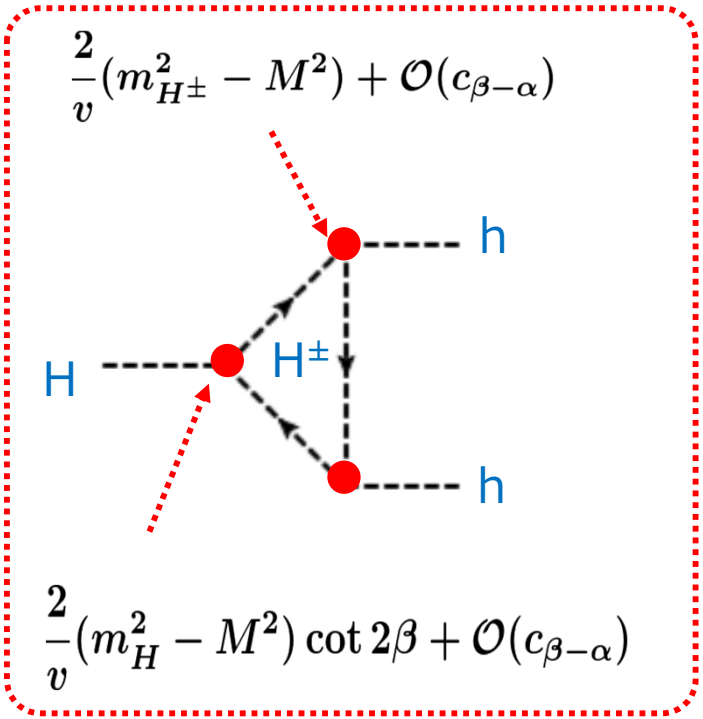
For X = h

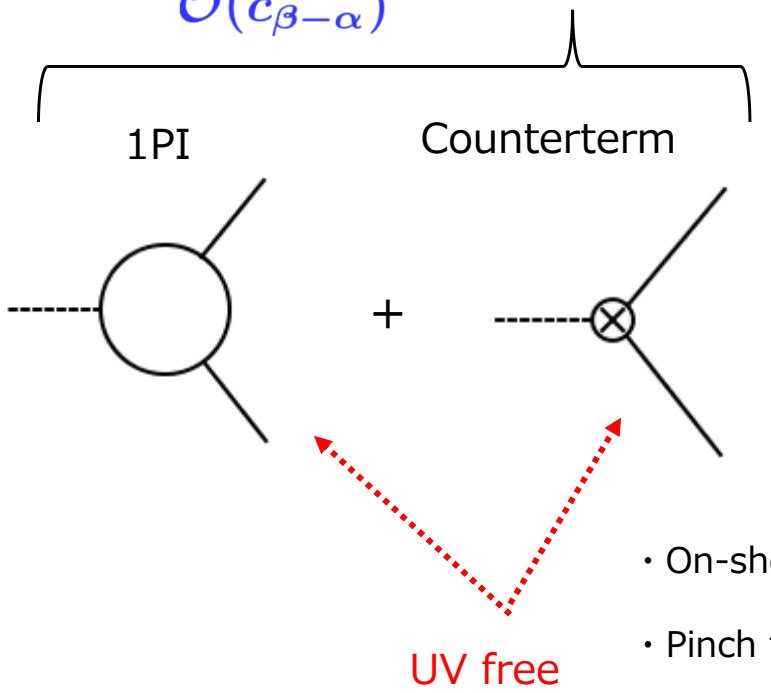
$$\Gamma_{\rm NLO}(H \to XX) =$$



$\mathcal{O}(c^2_{\beta-\alpha})$ $\mathcal{O}(c_{\beta-\alpha})$

Krause, Muhlleitner, Santos, Ziesche (2017)





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

- 1-loop amplitude is NOT suppressed by cos(β - α).
- Non-decoupling case (M « m_Φ) can enhance the decay rate.

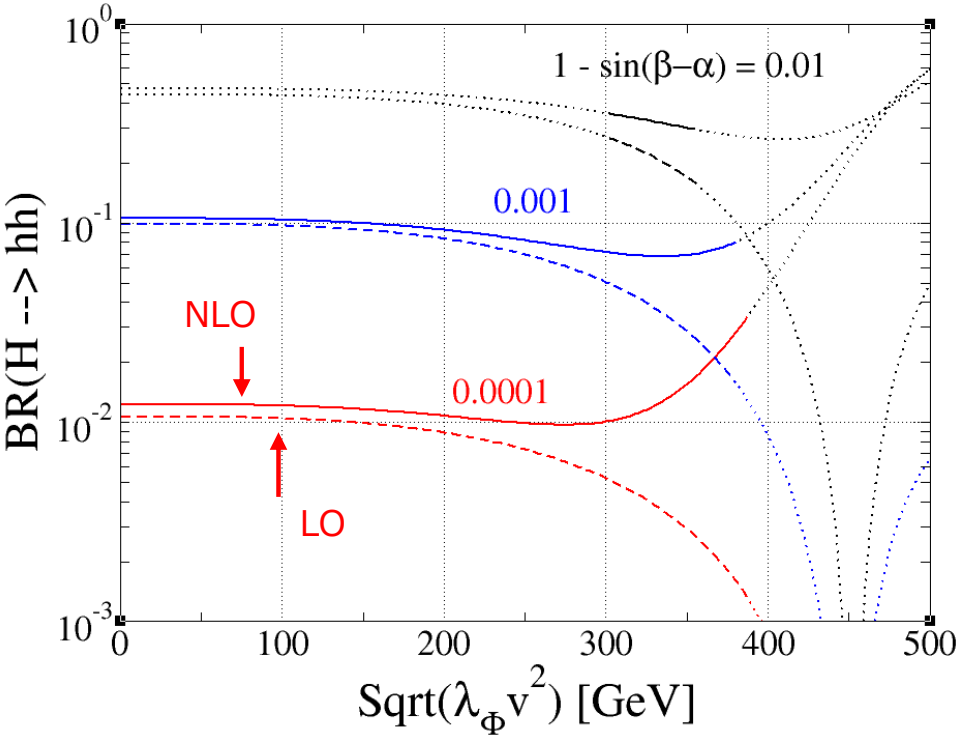
H → hh decay at one-loop level

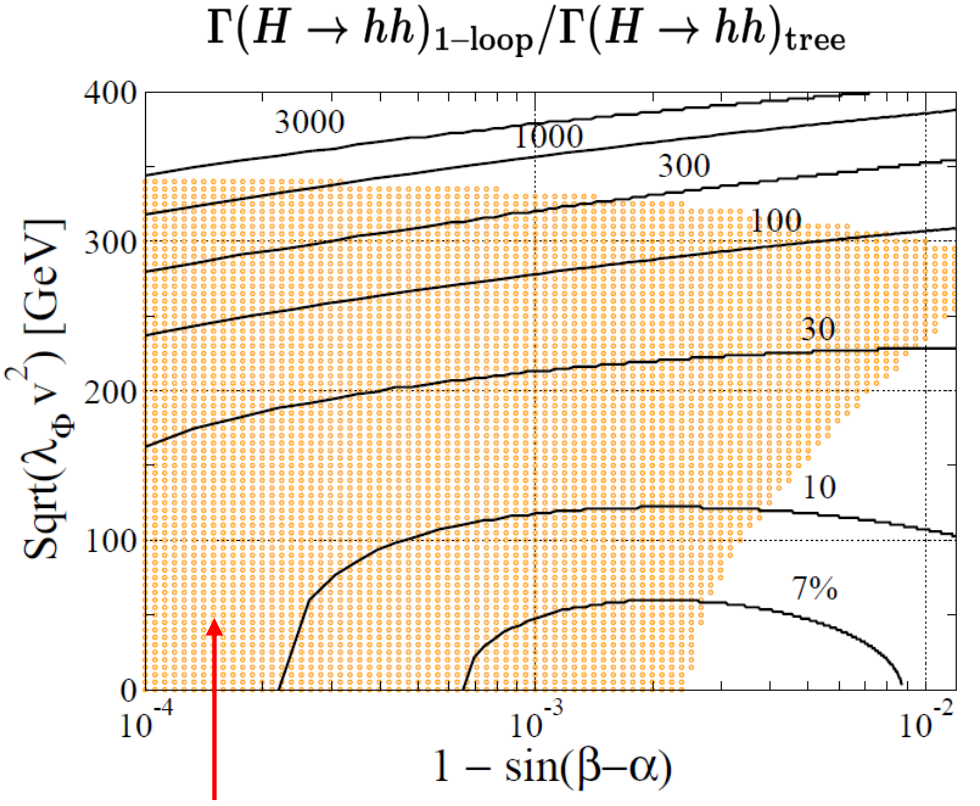
Kanemura, Kikuchi, KY, in preparation

- Decay BR of H → hh at one-loop level.
  - 2HDM type-I, tanβ = 2, mH = mA = mH⁺ = 500 GeV, cos(β-α) > 0

Φ = H, A and H⁺

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





Allowed by perturbative unitarity & vacuum stability

Large corrections can appear due to the non-decoupling effects.

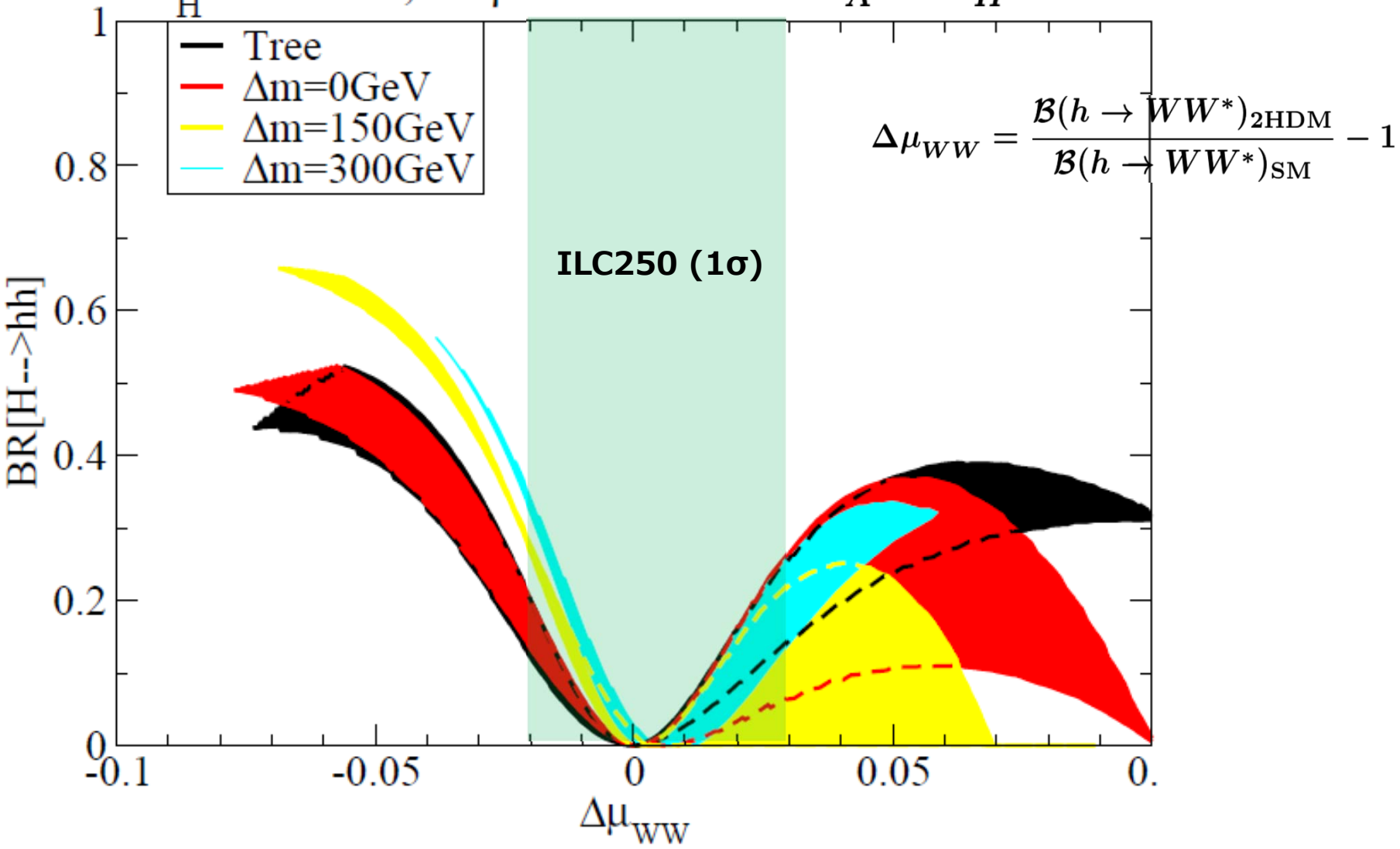
Correlation b/w h decay & H decay

Kanemura, Kikuchi, KY, in preparation

Type-I 2HDM

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

$\Delta m = m_A - m_H$



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

Summary

- H → hh decay can be important at near alignment region.

- This should be evaluated at one-loop level:

  1. Tree level definition of “alignment-ness” does no longer valid at loop levels.

  2. Non-decoupling effects can sizably change the decay rate,

     which is not suppressed by cos(β - α).

- One-loop corrections can change the BR by the factor level.

  Combining h_{125} decays, we can further extract inner parameters.

- Extra Higgs decays will be implemented in HCOUPv3.

H-COUP v3