Discovering new physics through precision measurements at CEPC

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Collaboration with

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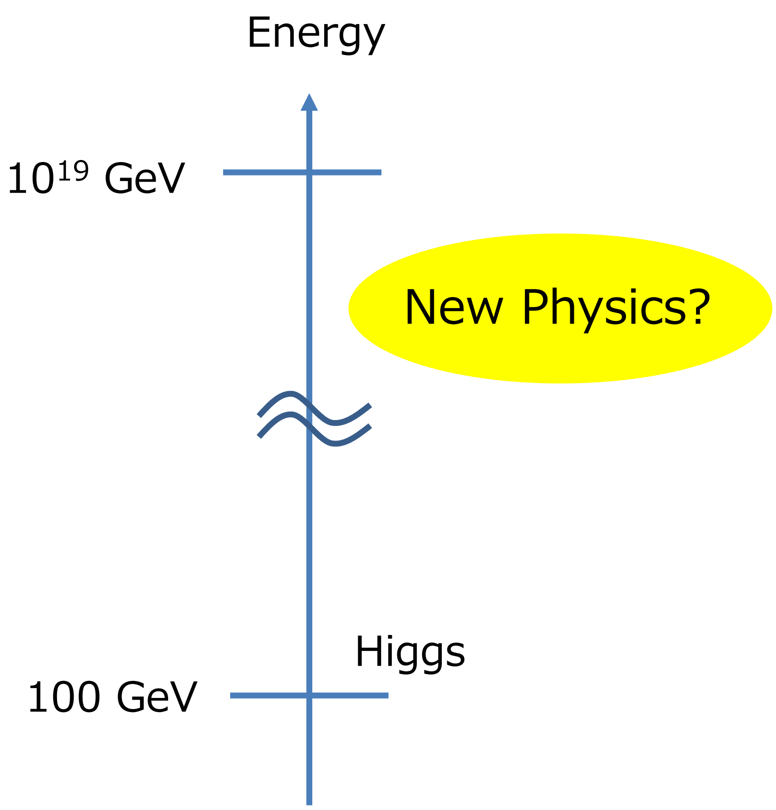
Kentarou Mawatari (Iwate U.), Kodai Sakurai (Warsaw U.)

International Workshop on the High Energy CEPC

2022, Oct. 24th, Online

10 Years After the Higgs Discovery

Decoupling scenario



10 Years After the Higgs Discovery

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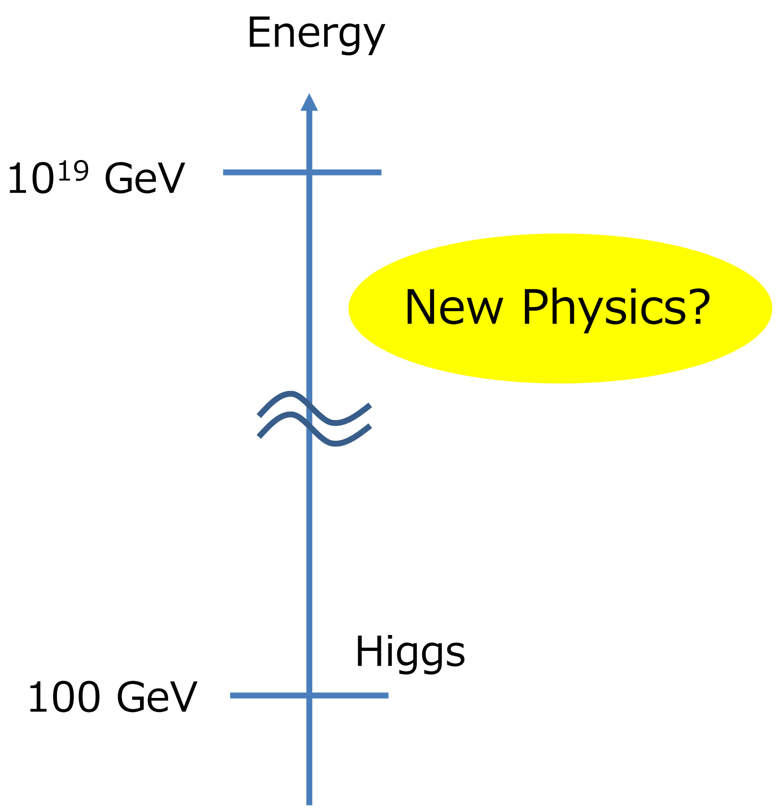
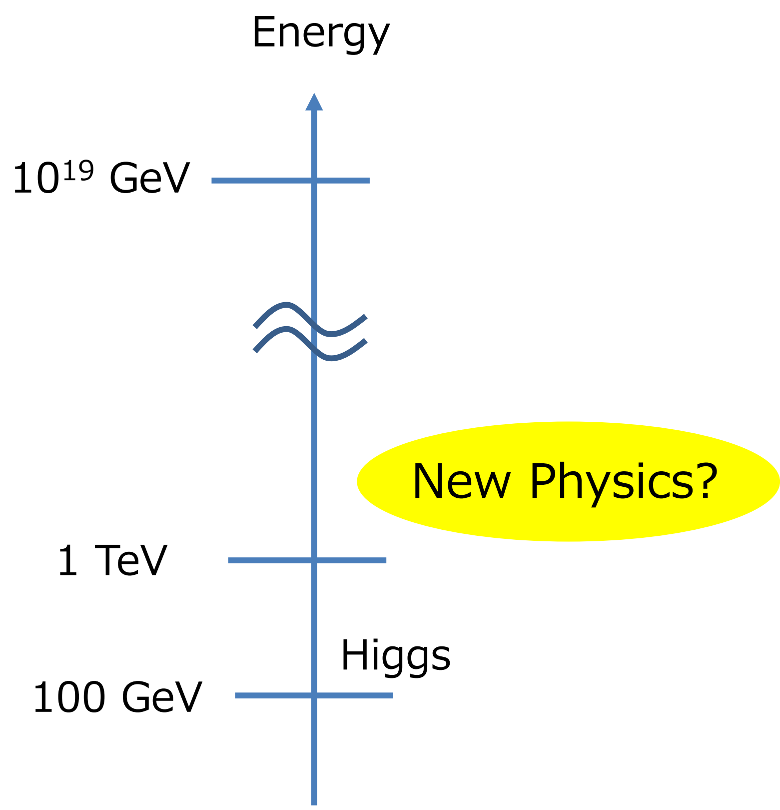


"Alignment" scenario



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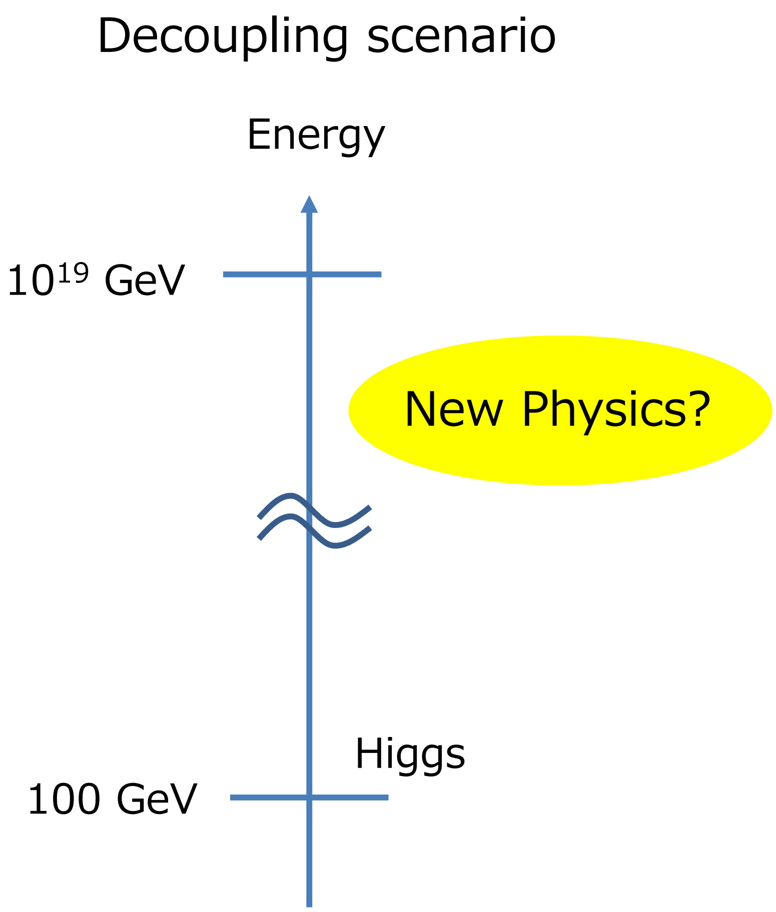

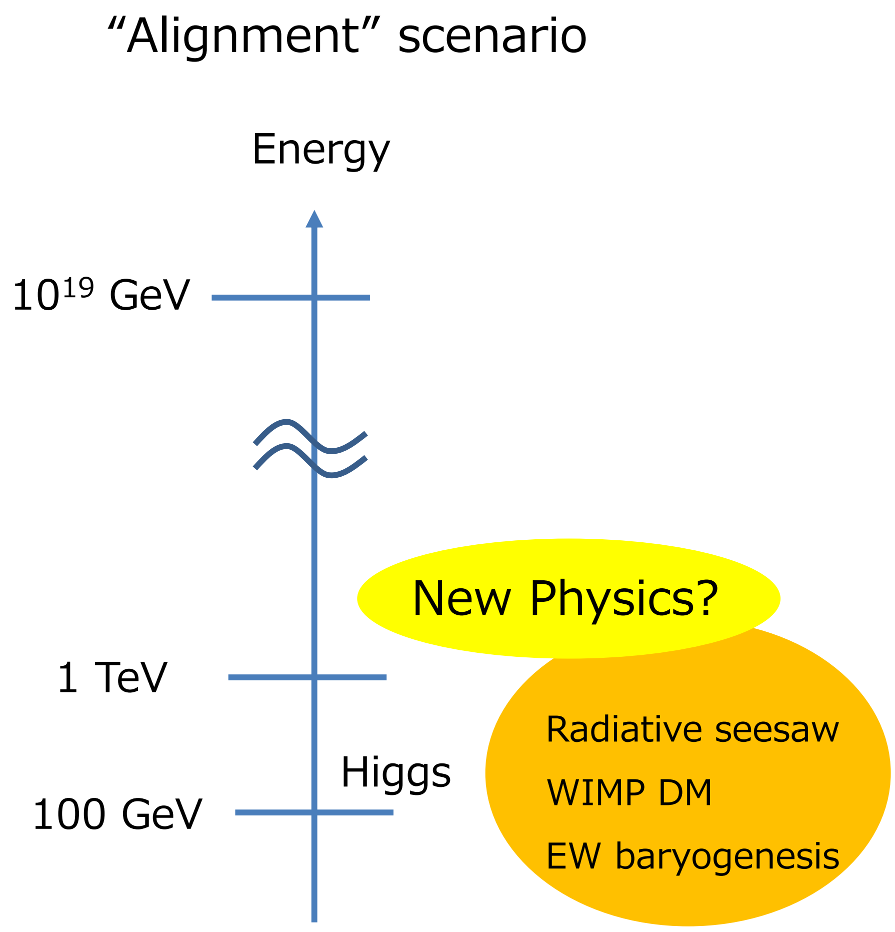

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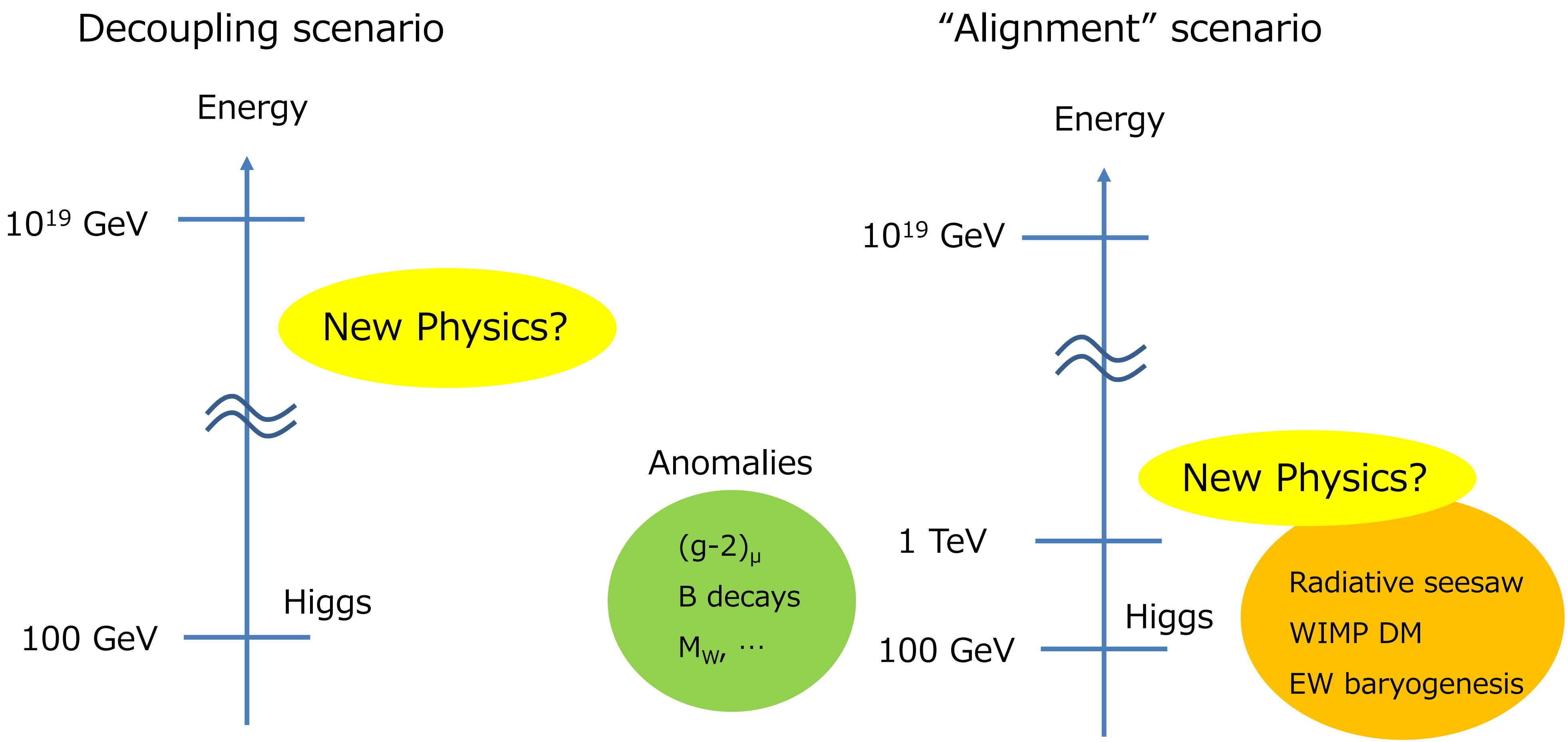
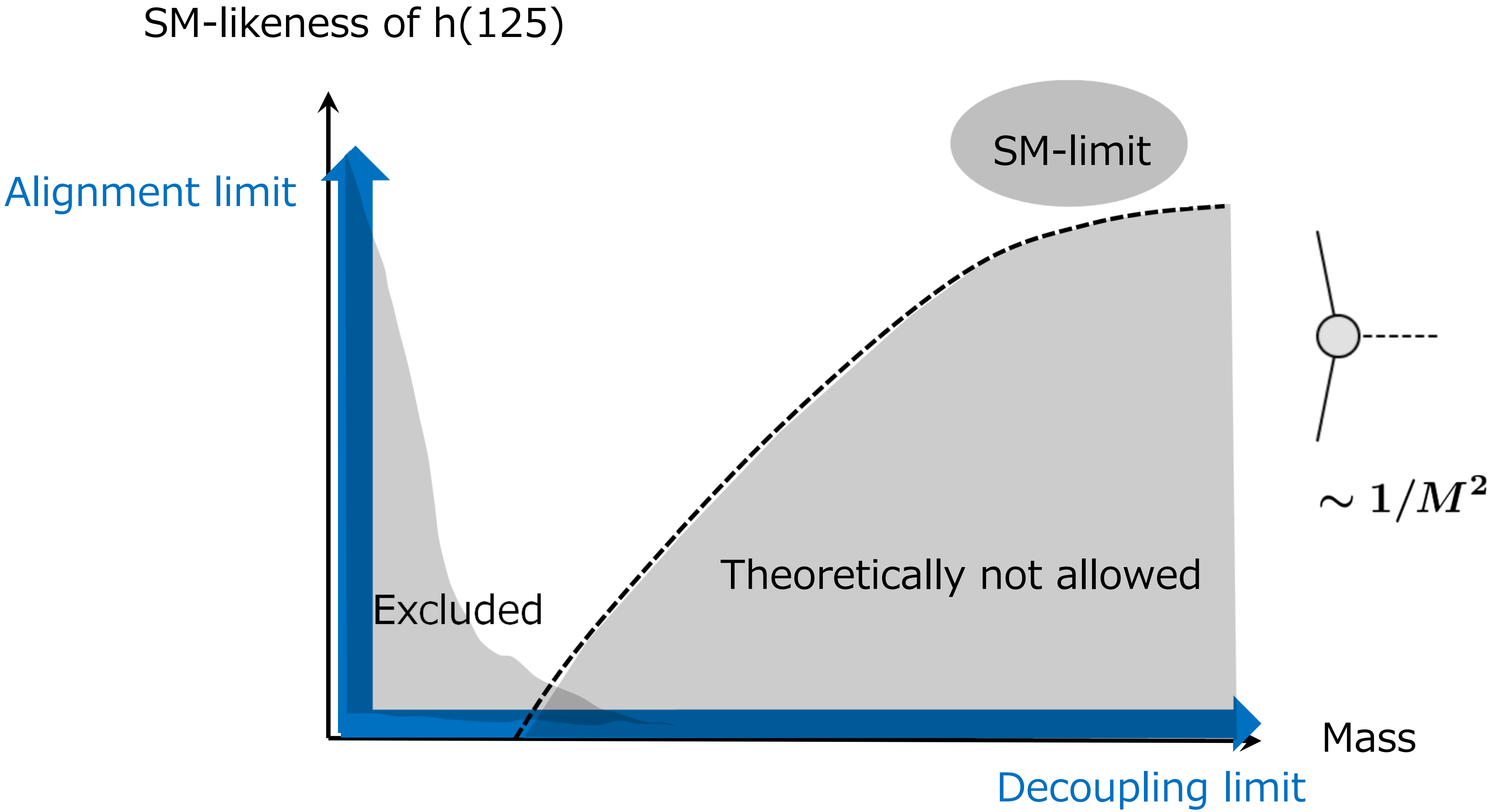


Non-minimal Higgs sectors often appear!

TeV scale NP scenarios can be tested via the Higgs physics.

Keywords: Alignment/Decoupling



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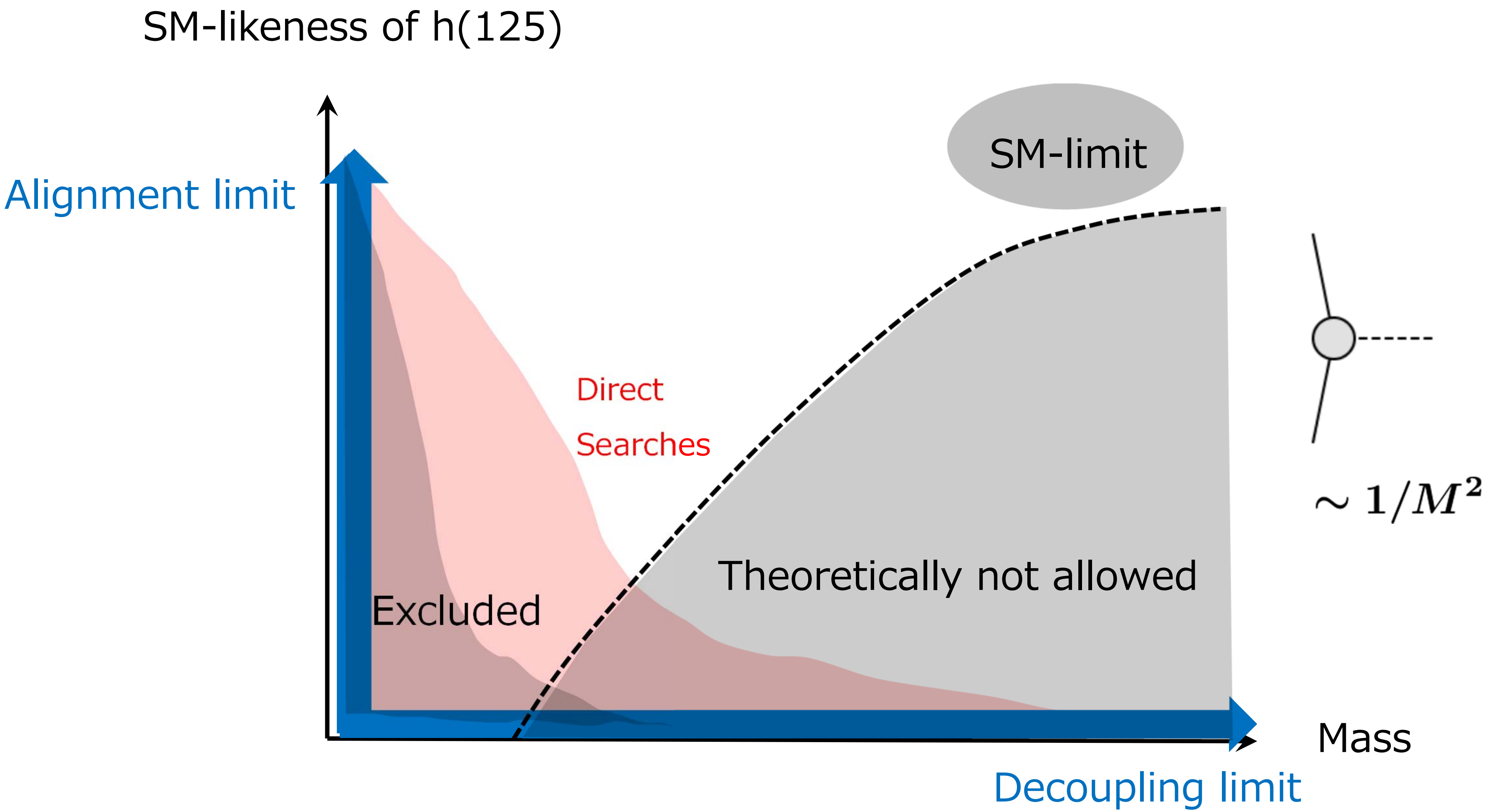

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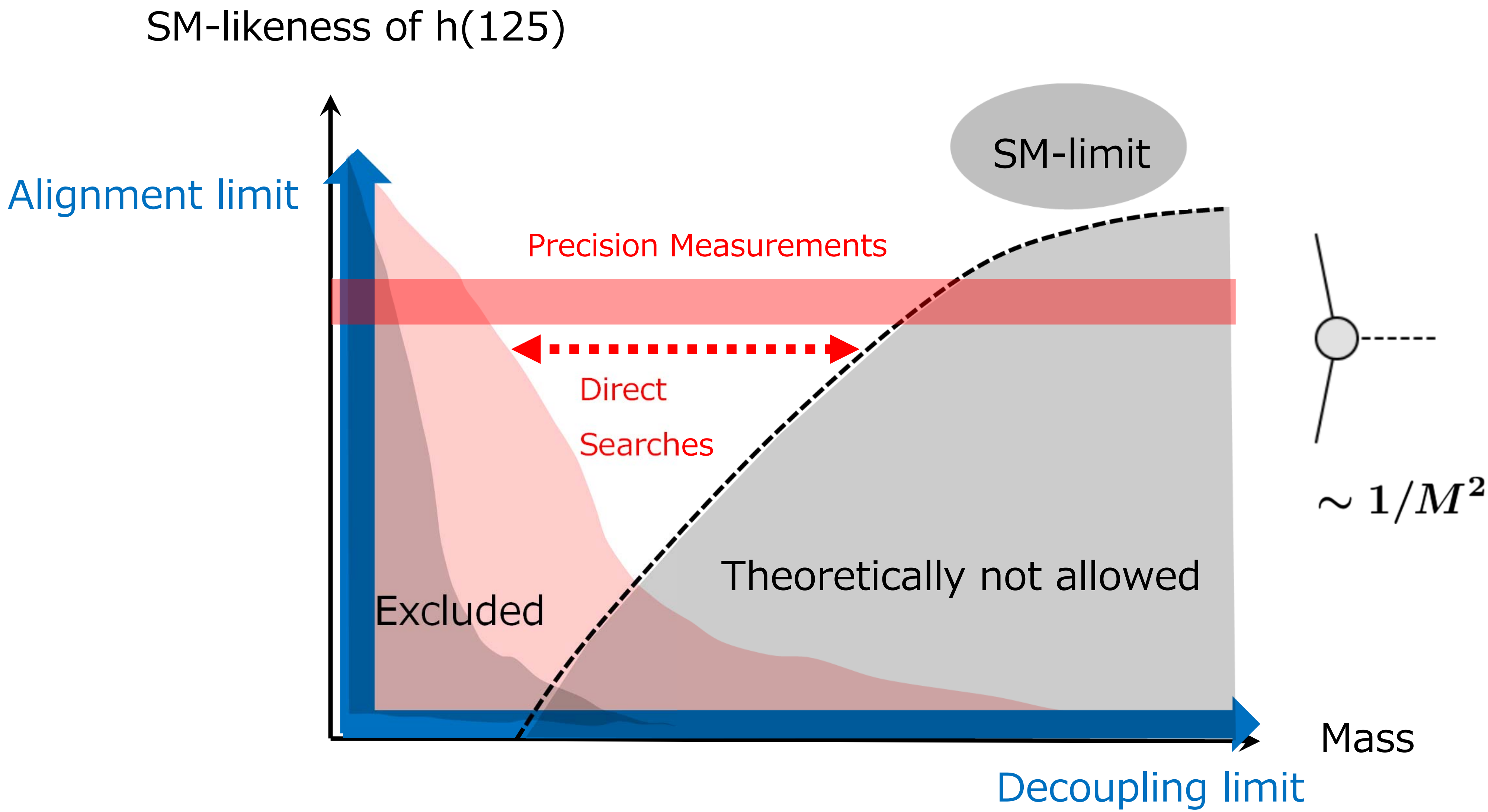


"Synergy" is important to explore extended Higgs sectors.

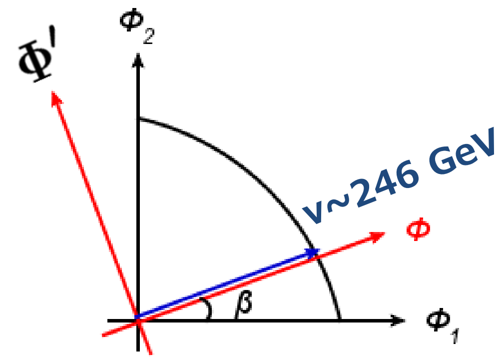
Quick review on 2 Higgs doublet models

- Higgs basis

Davidson, Haber PRD71 (2005)

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi' \end{pmatrix}$$

$\tan\beta = v_2/v_1$



NG boson

Charged Higgs

$$\boxed{\Phi = \left[\begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{array} \right]} \qquad \boxed{\Phi' = \left[\begin{array}{c} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{array} \right]}$$

CP-even Higgs

CP-odd Higgs

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

125 GeV Higgs

- Higgs boson masses

$m_h^2 \sim \lambda v^2$, $m_\Phi^2 \sim M^2 + \lambda' v^2$ $(\Phi = H^\pm, A, H)$

- Decoupling limit: $M^2 \to \infty$

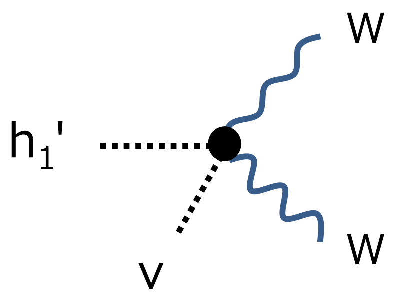
- Alignment limit: $\sin(\beta - \alpha) \to 1$

We focus on the case with a softly-broken Z_2 and CP-conservation.

Higgs Boson Couplings at Tree Level

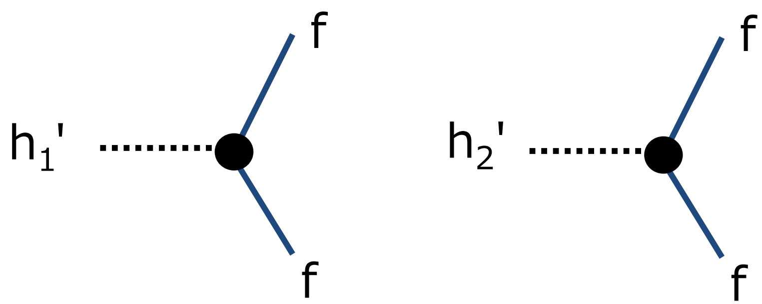
$$\mathcal{L}_{\mathrm{2HDM}} \supset |D_\mu \Phi|^2 + |D_\mu \Phi'|^2 - Y_f^{\mathrm{SM}} \bar{f}_L (\Phi + \zeta_f \Phi') f_R$$

ζ_f = 1/tanβ or −tanβ



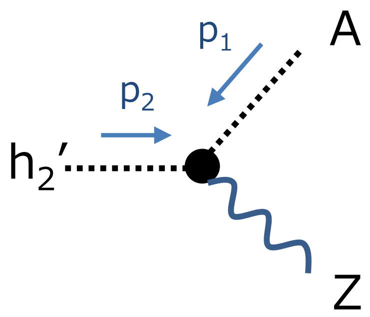
$$(\mathrm{SM}) \times \sin(\beta - \alpha) \quad \text{for h}$$

$$(\mathrm{SM}) \times \cos(\beta - \alpha) \quad \text{for H}$$



$$(\mathrm{SM}) \times [\sin(\beta - \alpha) + \zeta_f \cos(\beta - \alpha)] \quad \text{for h}$$

$$(\mathrm{SM}) \times [\cos(\beta - \alpha) - \zeta_f \sin(\beta - \alpha)] \quad \text{for H}$$

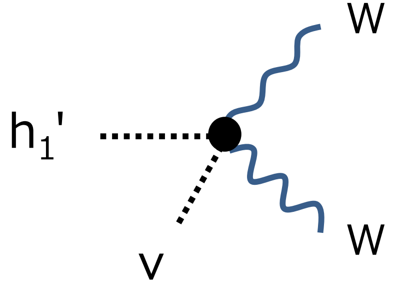


$$\frac{g}{2\cos\theta_W}(p_1 - p_2)^\mu \cos(\beta - \alpha) \quad \text{for h}$$

$$-\frac{g}{2\cos\theta_W}(p_1 - p_2)^\mu \sin(\beta - \alpha) \quad \text{for H}$$

Higgs Boson Couplings at Tree Level

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



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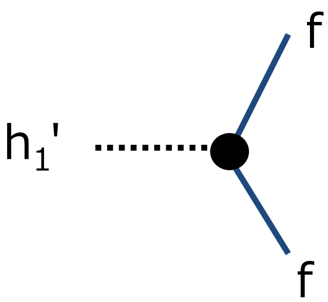

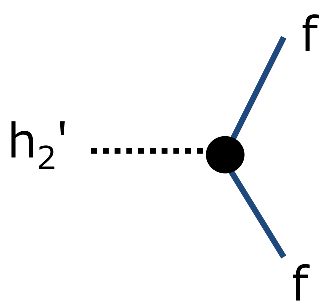

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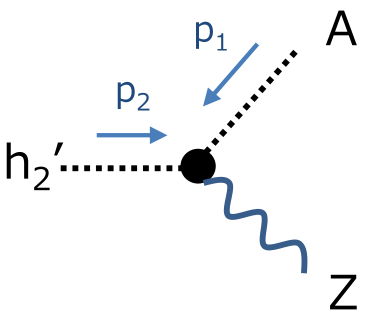
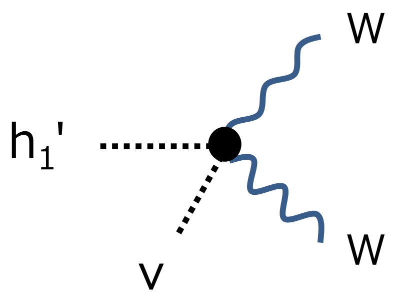


$$\frac{g}{2\cos\theta_W}(p_1-p_2)^\mu \cos(\beta-\alpha) \qquad \text{for h}$$

$$\boxed{-\frac{g}{2\cos\theta_W}(p_1-p_2)^\mu \sin(\beta-\alpha)} \qquad \text{for H}$$

Higgs Boson Couplings at Tree Level

Nearly alignment: sin(β-α) ~ 1



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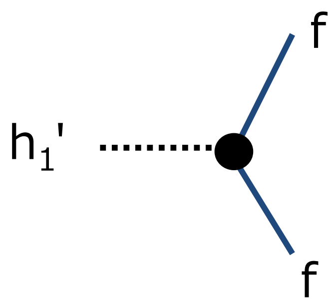

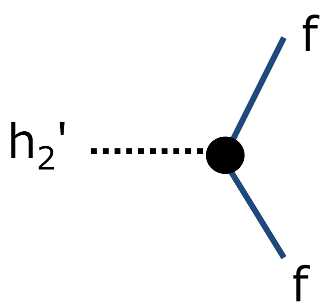

$$(\mathrm{SM}) \times [\sin(\beta - \alpha) + \zeta_f \cos(\beta - \alpha)] \quad \text{for } h$$

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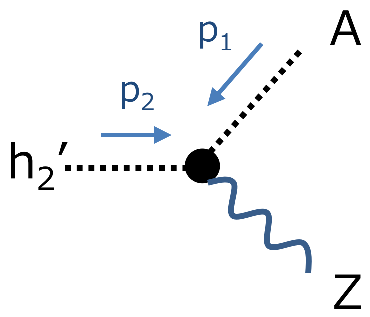
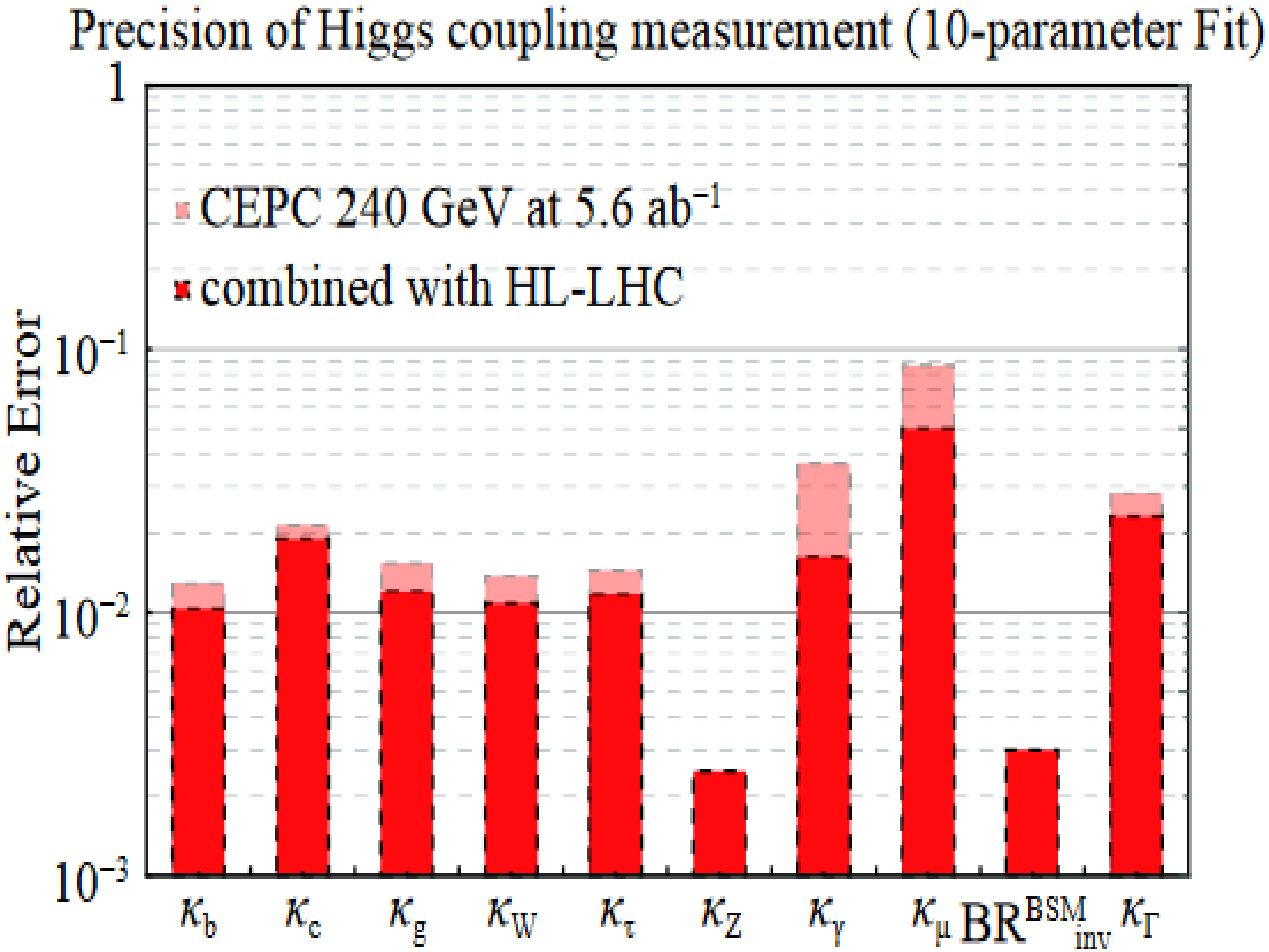


$$\frac{g}{2\cos\theta_W}(p_1 - p_2)^\mu \cos(\beta - \alpha) \quad \text{for } h$$

$$-\frac{g}{2\cos\theta_W}(p_1 - p_2)^\mu \sin(\beta - \alpha) \quad \text{for } H$$

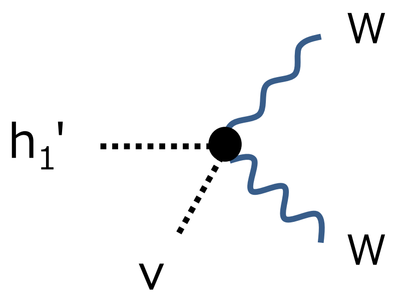
Higgs Coupling Measurements at CEPC

F. An et al, Chinese Phys. C43, 4 (2019)



Higgs Boson Couplings at Tree Level

Nearly alignment: sin(β-α) ~ 1



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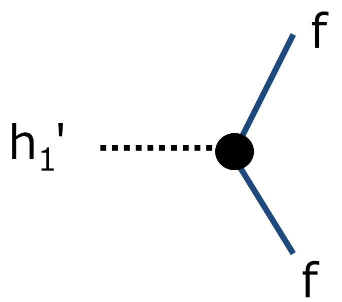
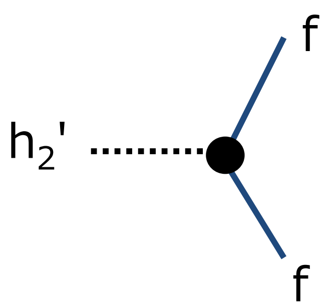
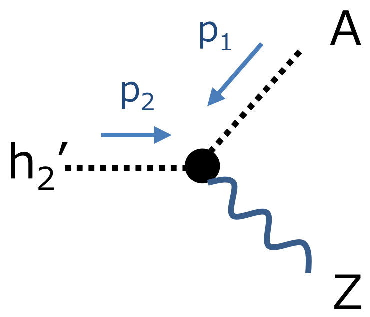




$$(\mathrm{SM}) \times [\sin(\beta - \alpha) + \zeta_f \cos(\beta - \alpha)]$$ for h

$$(\mathrm{SM}) \times [\cos(\beta - \alpha) - \zeta_f \sin(\beta - \alpha)]$$ for H

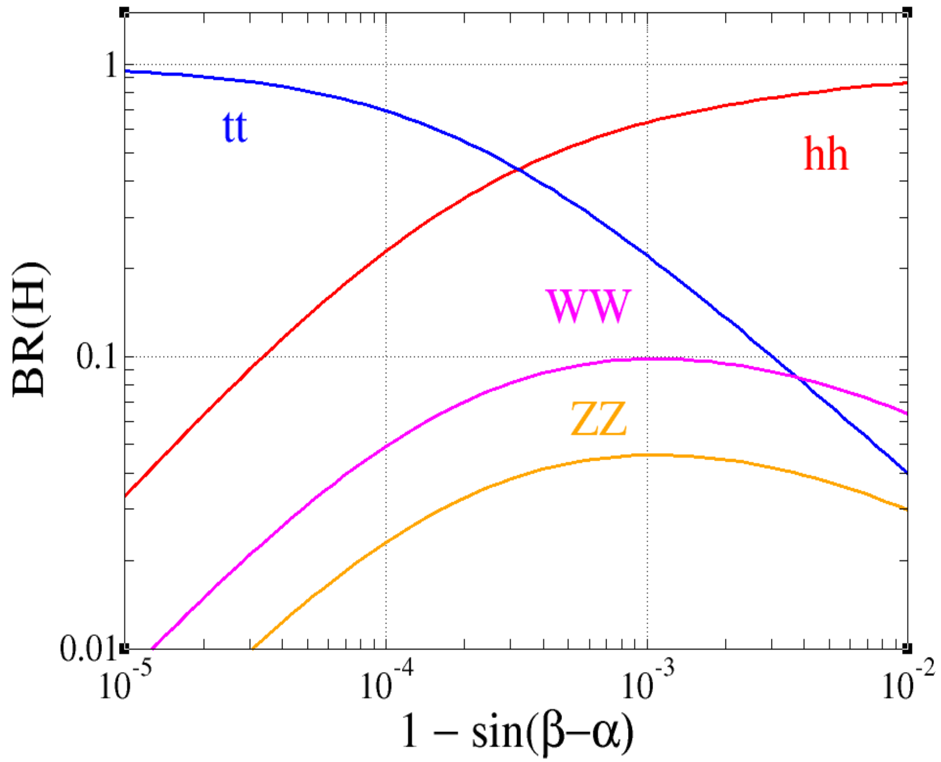


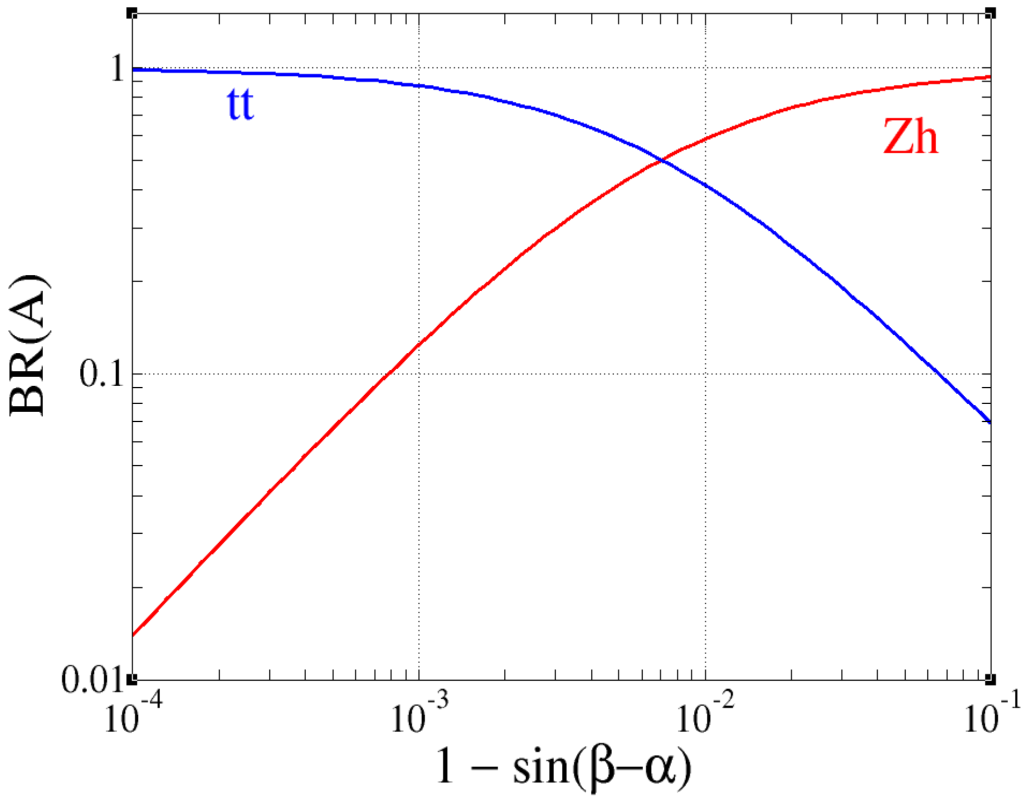
$$\frac{g}{2\cos\theta_W}(p_1 - p_2)^\mu \cos(\beta - \alpha)$$ for h

$$-\frac{g}{2\cos\theta_W}(p_1 - p_2)^\mu \sin(\beta - \alpha)$$ for H

Decays of Extra Higgs Bosons

Type-I 2HDM with mH = mA = mH⁺ = M = 400 GeV, tanβ = 10 @ LO in EW

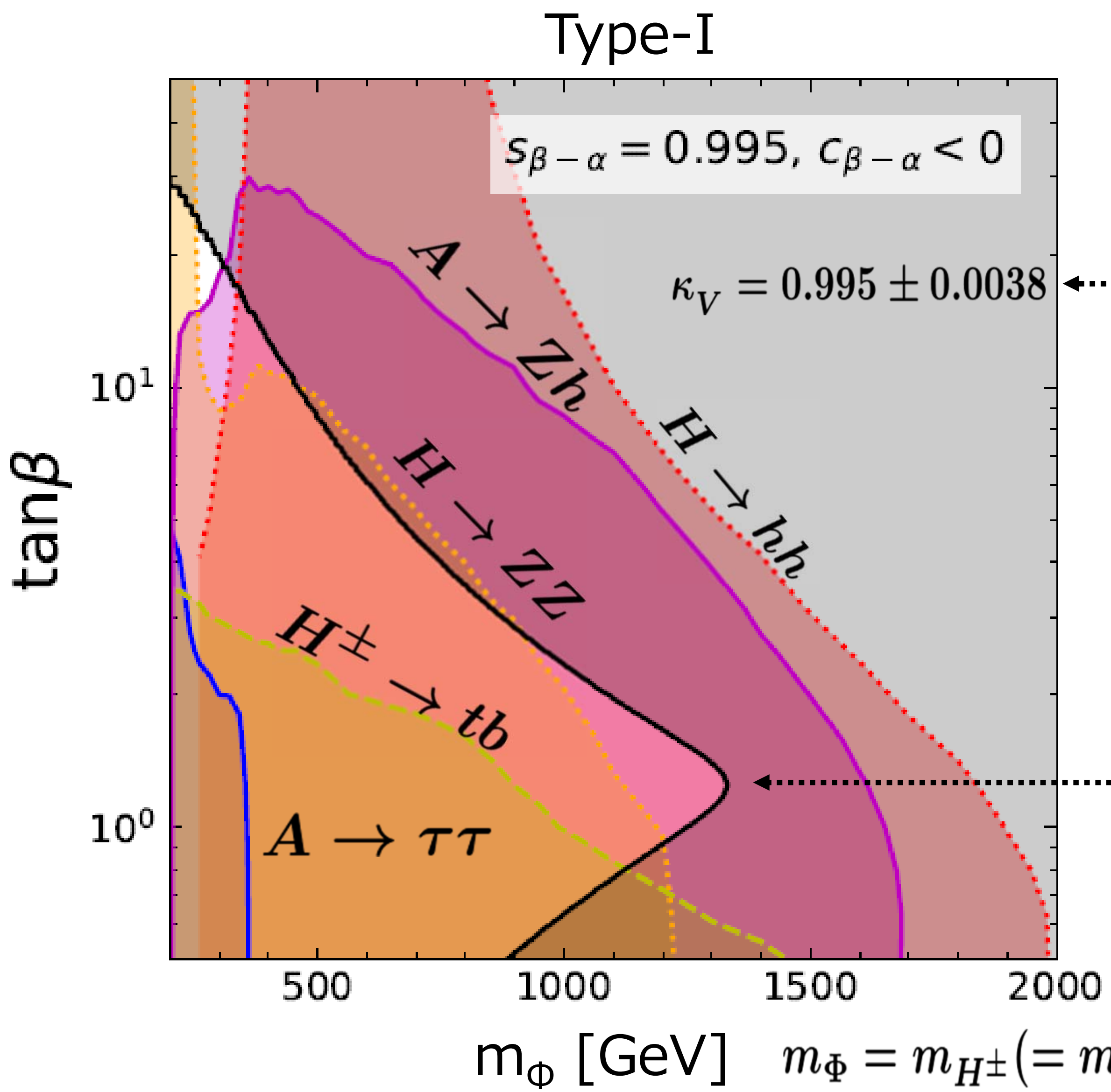




Higgs to Higgs decays become important in the nearly alignment case.

Synergy b/w Direct Search & Precision

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY (2020)



Decay & κ_V are calculated at LO.

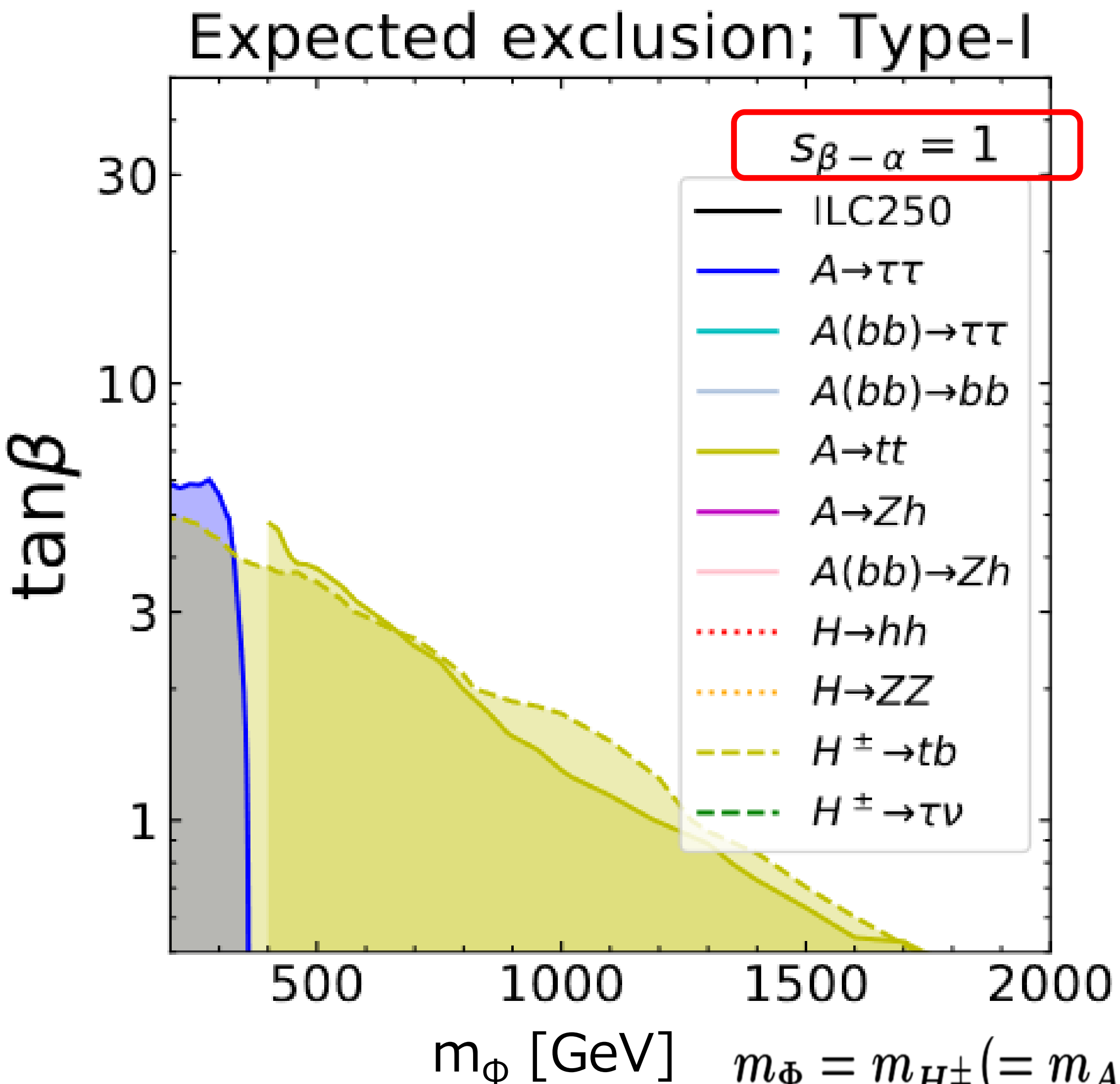
Assuming 1σ accuracy at ILC250

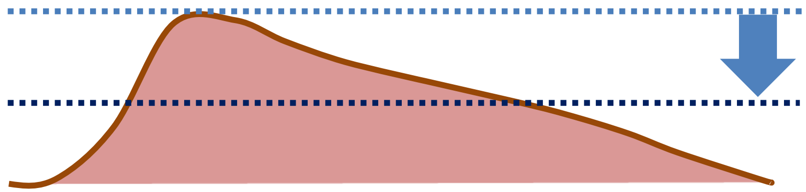
Excluded by unitarity or vacuum stability.

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

Alignment limit

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY (2020)





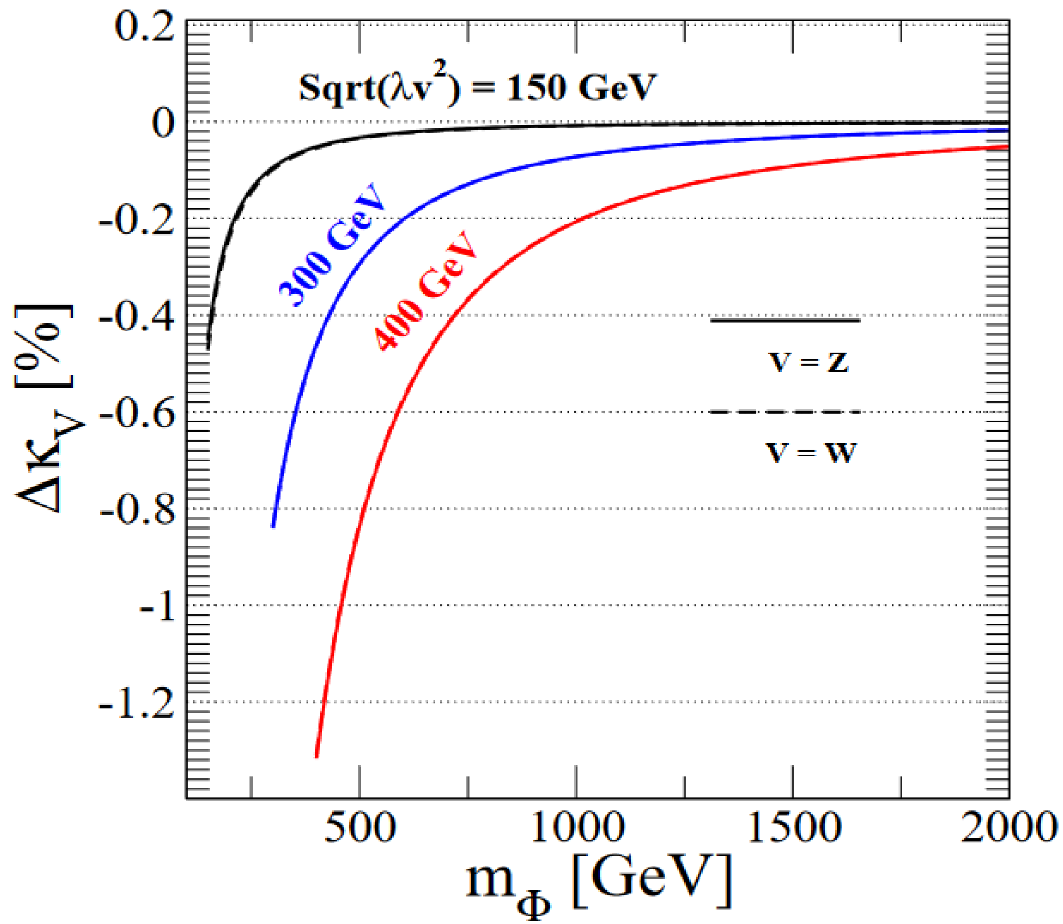
$m_\Phi = m_{H^\pm}(= m_A = m_H)$

This must be done at LOOP LEVELS !!

Why do we need loop calculations?

- sin(β-α) does not measure the “alignmentness” at loop levels.

Kanemura, Kikuchi and KY (1502.07716)



2HDM with sin(β - α) = 1

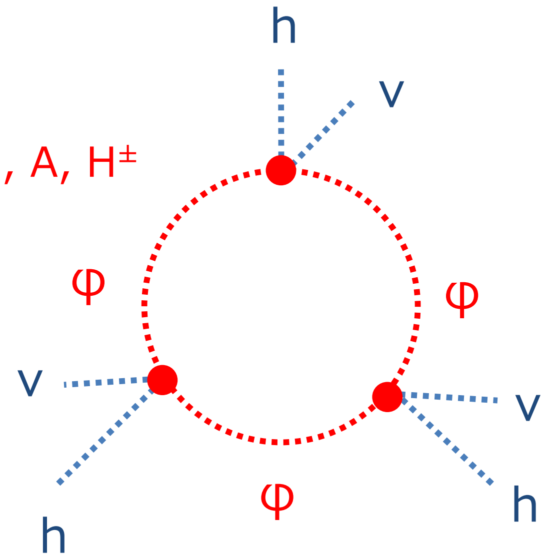
O(1)% deviation is given by quantum effects in the sin(β-α) = 1 case.

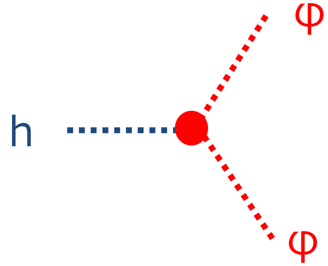
Why do we need loop calculations?

- Extra Higgs decays can significantly be modified by nondecoupling loop effects.

For hhh

φ:H, A, H$^\pm$





$$\simeq \frac{M^2 - m_\varphi^2}{v}$$

$m_\varphi^2 \sim M^2 + \lambda' v^2$

$c_\varphi = 2(1)$ for $H^\pm$ (H, A)

$$\simeq \frac{1}{32\pi^2} \sum_\varphi c_\varphi \frac{\lambda^3_{h\varphi\varphi}}{m_\varphi^2}$$

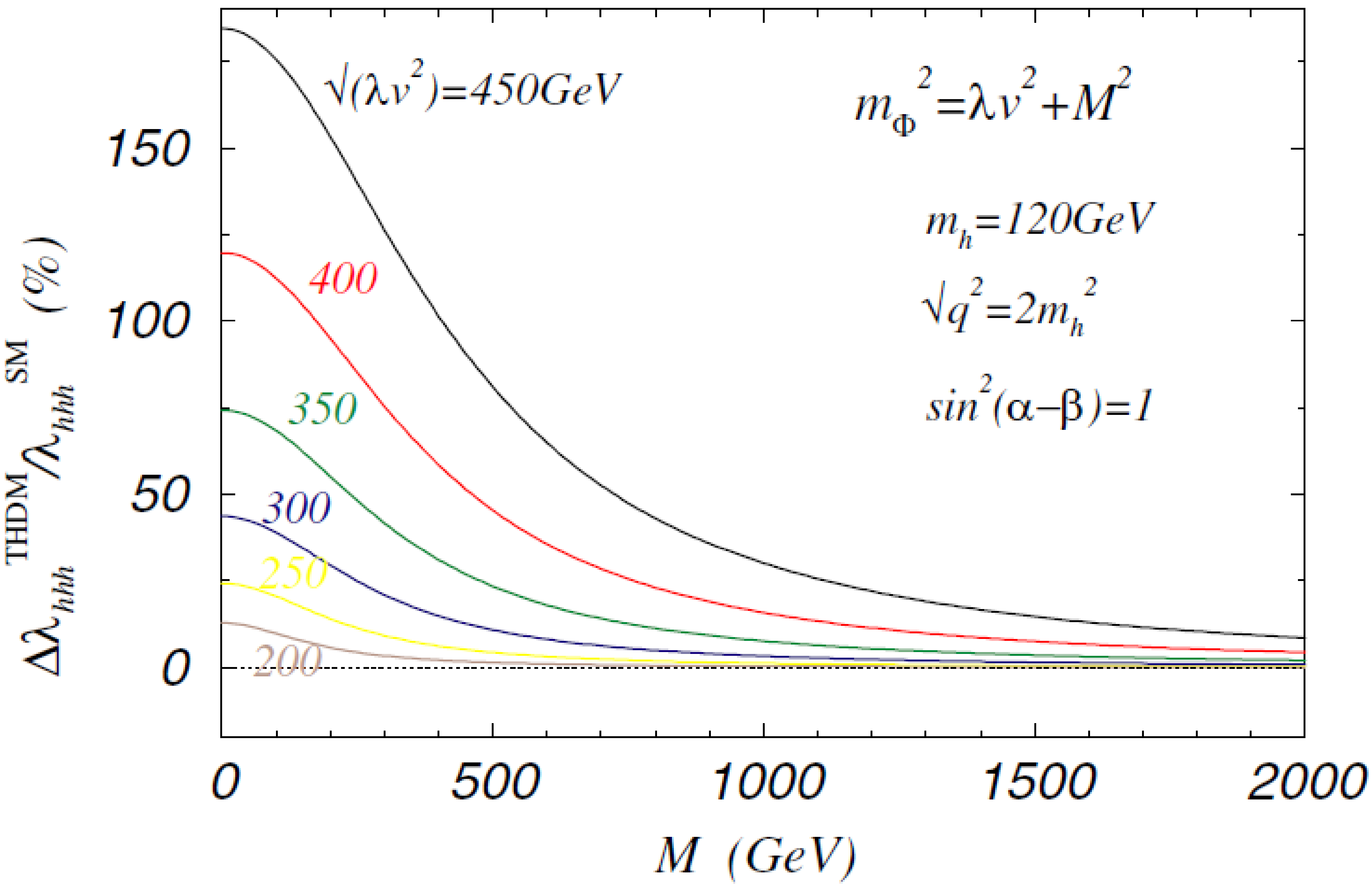
$$= -\frac{1}{32\pi^2} \sum_\varphi c_\varphi \frac{m_\varphi^4}{v^3} \left(1 - \frac{M^2}{m_\varphi^2}\right)^3$$

$$\begin{cases} \sim \dfrac{v^3}{M^2} & \text{Decoupling case } (M \sim m_\varphi) \\ \sim \dfrac{m_\varphi^4}{v^3} & \text{Non-dec. case } (M \ll m_\varphi) \end{cases}$$

O(100)% correction is possible. Similar effects appear in the heavy Higgs decays.

Deviation in the hhh coupling

Kanemura, Okada, Senaha, Yuan (2004)



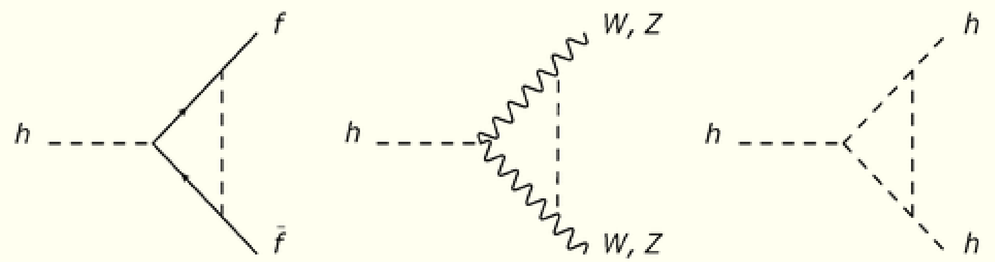
H-COUP

Kanemura, Kikuchi, Sakurai, KY (2017)

Kanemura, Kikuchi, Sakurai, Mawatari, KY (2019)

HCOUP

H-COUP



What is H-COUP?

A fortran code to calculate 1-loop corrected
Higgs couplings, decay rates, BRs
based on the improved OS renormalization scheme.

Downloads

- H-COUP version 2.3 : [HCOUP-2.3.zip] [The manual for H-COUP ver. 2 is here]
- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual for H-COUP ver. 1 is here]

In order to run H-COUP programs, you need to install LoopTools (www.feynarts.de/looptools/).

You can download the source code from here.

H-COUP Project

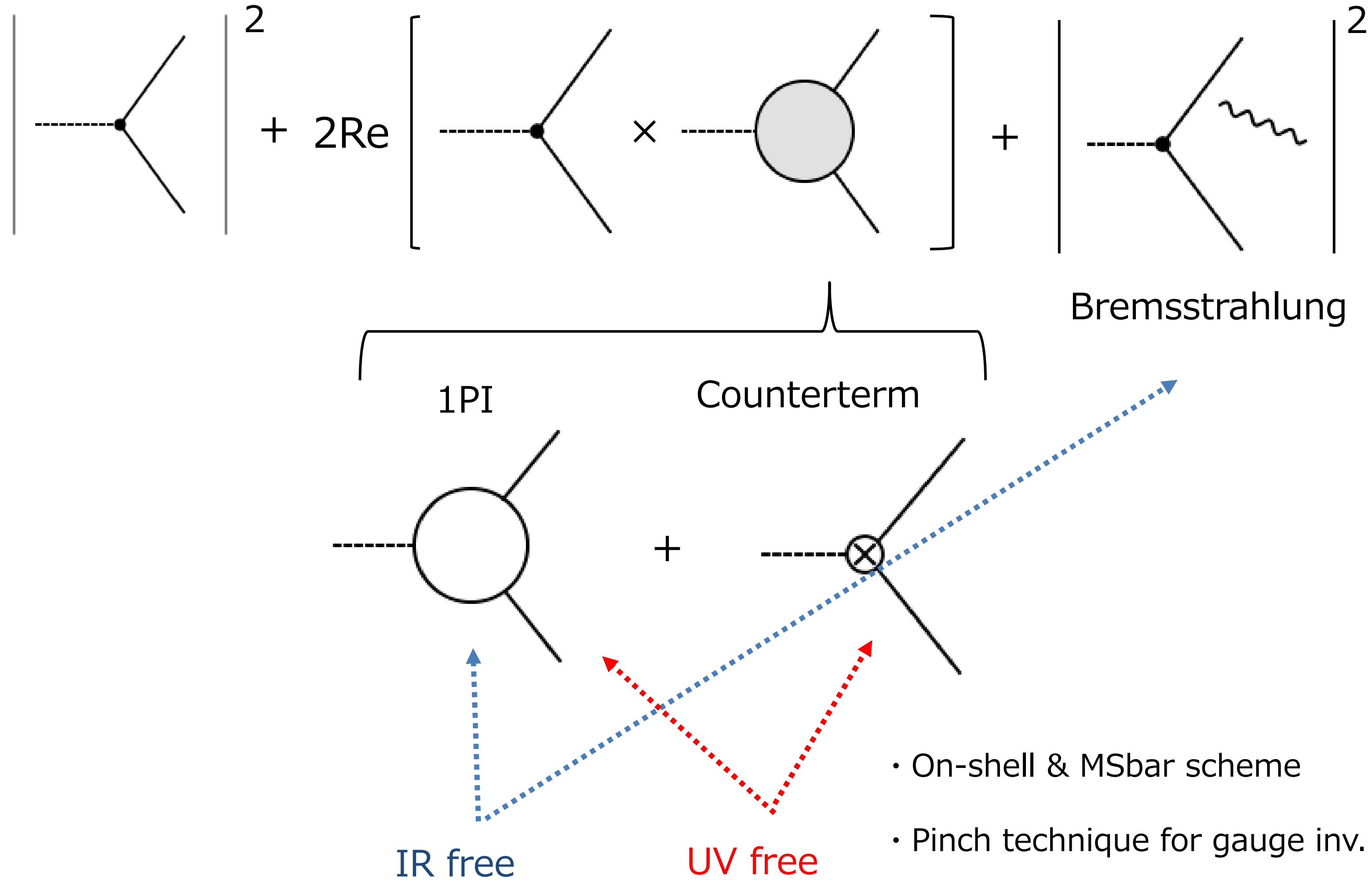
- Before publication of H-COUP *Kanemura, Senaha, Okada, Yuan, 0408364 (PRD)* *Kanemura, Kikuchi, KY, 1502.07716 (NPB)*
  - ・Development of the OS-scheme in the 2HDM *Kanemura, Kikuchi, Sakurai, 1511.06211 (PRD)* *Kanemura, Kikuchi, KY, 1511.06211 (NPB)*
  - ・Development of the OS-scheme in the Higgs singlet model and the inert doublet model
  - ・Development of the gauge independent OS-scheme *Kanemura, Kikuchi, Sakurai, KY, 1705.05399 (PRD)*
- 2017: H-COUP Ver. 1 *Kanemura, Kikuchi, Sakurai, KY, 1710.04603 (CPC)*
  - ・1-loop corrected h_{125} couplings can be calculated in the improved OS-scheme.

    4 types of the 2HDM, the Higgs singlet model and the inert doublet model are implemented.
- 2019: H-COUP Ver. 2 *Kanemura, Kikuchi, Mawatari, Sakurai, KY, 1910.12769 (CPC)*
  - ・h_{125} decay rates and BRs can be calculated at NLO EW/QCD.
- 2019-: H-COUP Ver. 3 and beyond *Aiko, Kanemura, Sakurai, 2108.11868 (NPB)* *Aiko, Kanemura, Sakurai, 2207.01032* *Kanemura, Kikuchi, Yagyu, 2203.08337 (NPB)*
  - ・Decays of extra Higgs bosons (H, A, $H^{\pm}$) have been calculated.
  - ・Now, we are implementing (H, A, $H^{\pm}$) decays into H-COUPP Ver. 3. ← Now

We show the loop effect on extra Higgs decays.

1-loop corrected decay rates

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

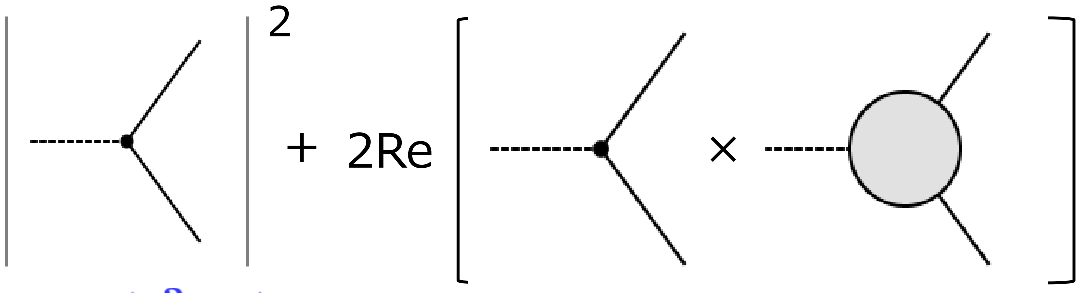


- On-shell & MSbar scheme
- Pinch technique for gauge inv.

1-loop corrected decay rates

For X = h

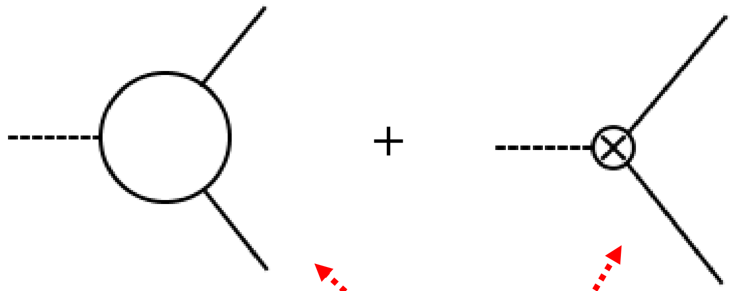
$$\Gamma_{\rm NLO}(H \to XX) =$$



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

Krause, Muhlleitner, Santos, Ziesche (2017)

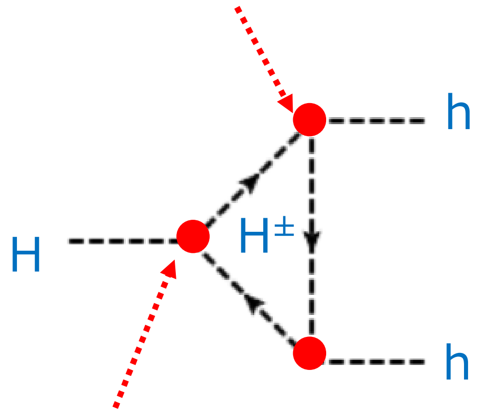
1PI Counterterm



UV free

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

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



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

- 1-loop amplitude is NOT suppressed by cos(β - α).
- Non-decoupling case (M « m$_\Phi$) can change the decay rate.

H → hh decay at one-loop level

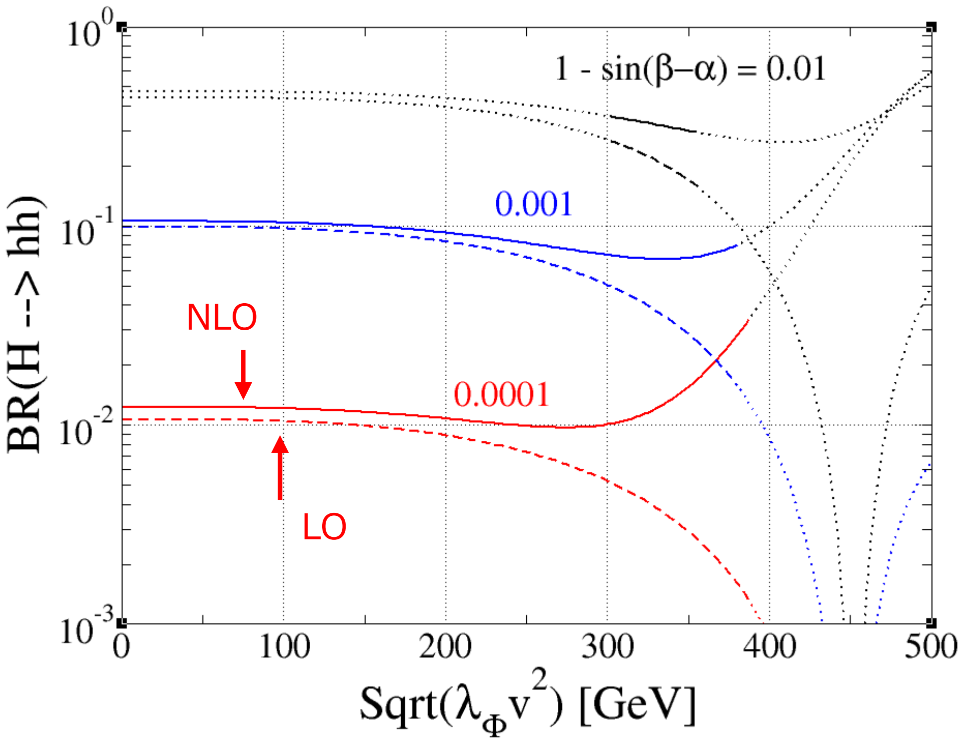
Kanemura, Kikuchi, KY, 2203.08337

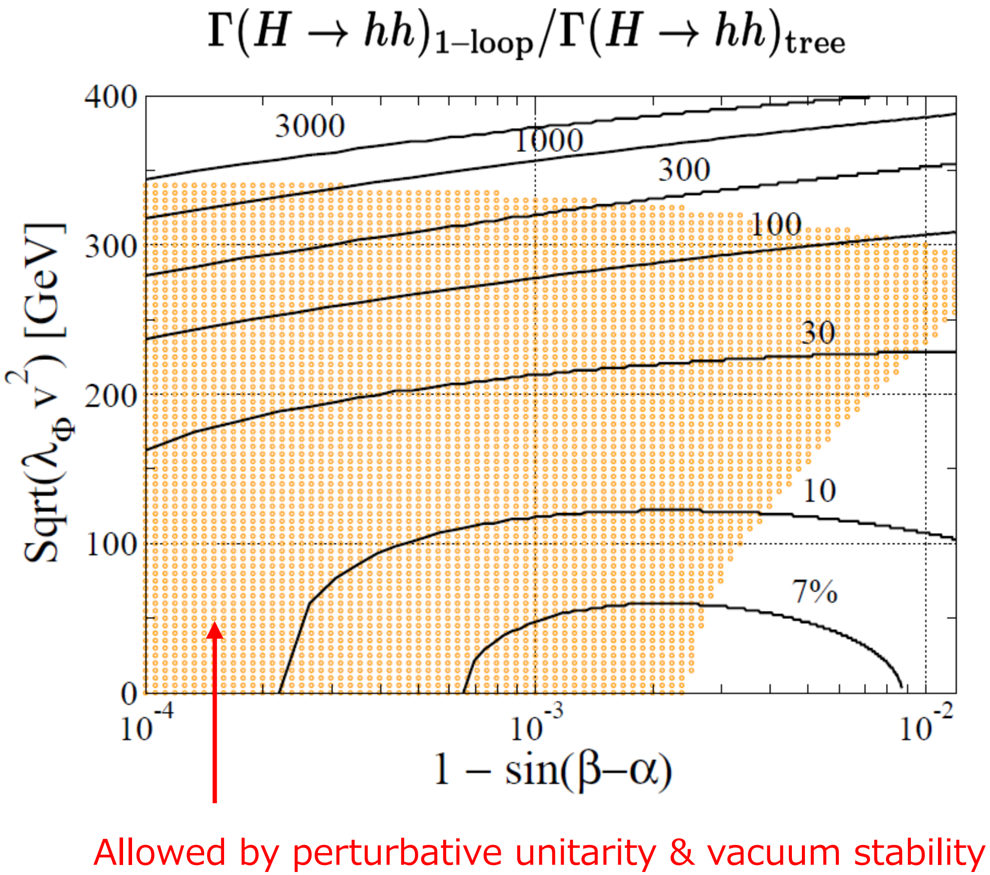
□ Decay BR of H → hh at one-loop level.

・2HDM type-I, tanβ = 2, mH = mA = mH⁺ = 500 GeV, cos(β-α) > 0

Φ = H, A and H⁺

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





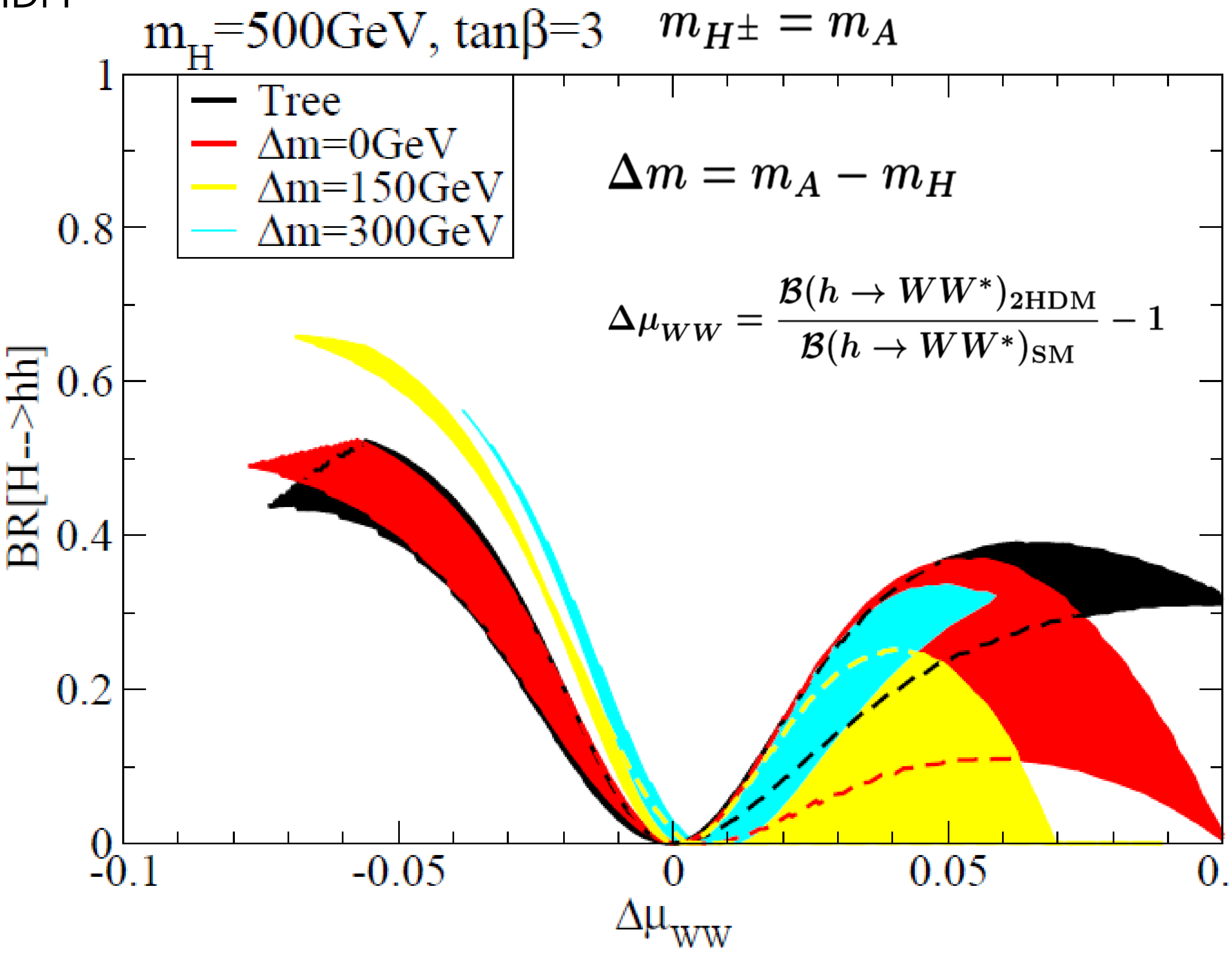
Large corrections can appear due to the non-decoupling effects.

Correlation b/w h decay & H decay

Kanemura, Kikuchi, KY, 2203.08337

[sin(β-α) and M are scanned]

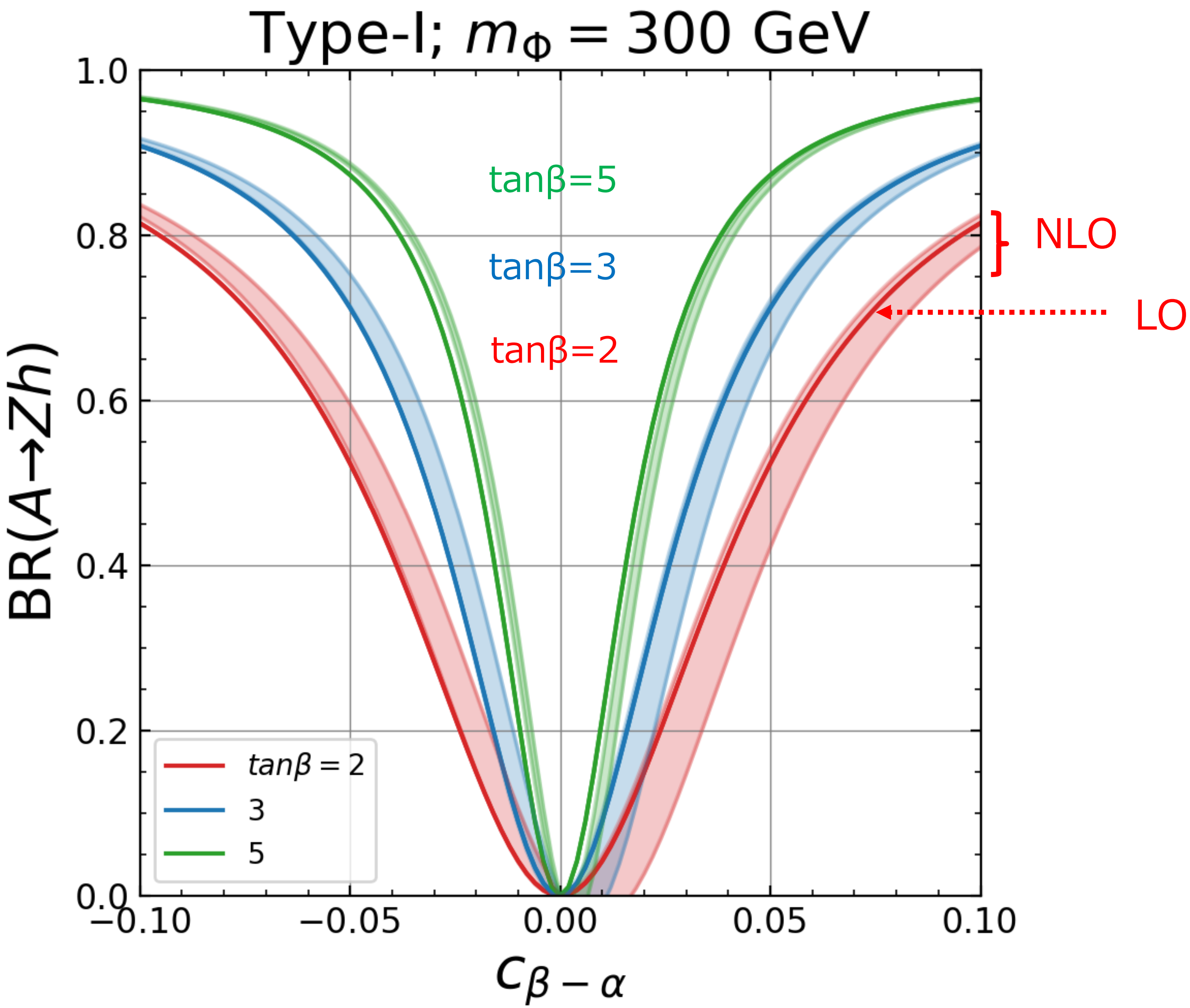
Type-I 2HDM



Decay of A

$m_H = m_A = m_{H+} = 300\text{GeV}$

Aiko, Kanemura, Sakurai, 2207.01032



Summary

- Synergy between direct searches & precise measurements is important to explore non-minimal Higgs sectors.

- In order to maximize the synergy between HL-LHC and CEPC, loop calculations are essentially important in the nearly alignment case.

- H-COUP v3 is now under construction, and it will be able to provide one-loop corrected additional Higgs decays.