

LHC/ILC実験の相乗効果による 拡張ヒッグスモデルの検証

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共同研究者

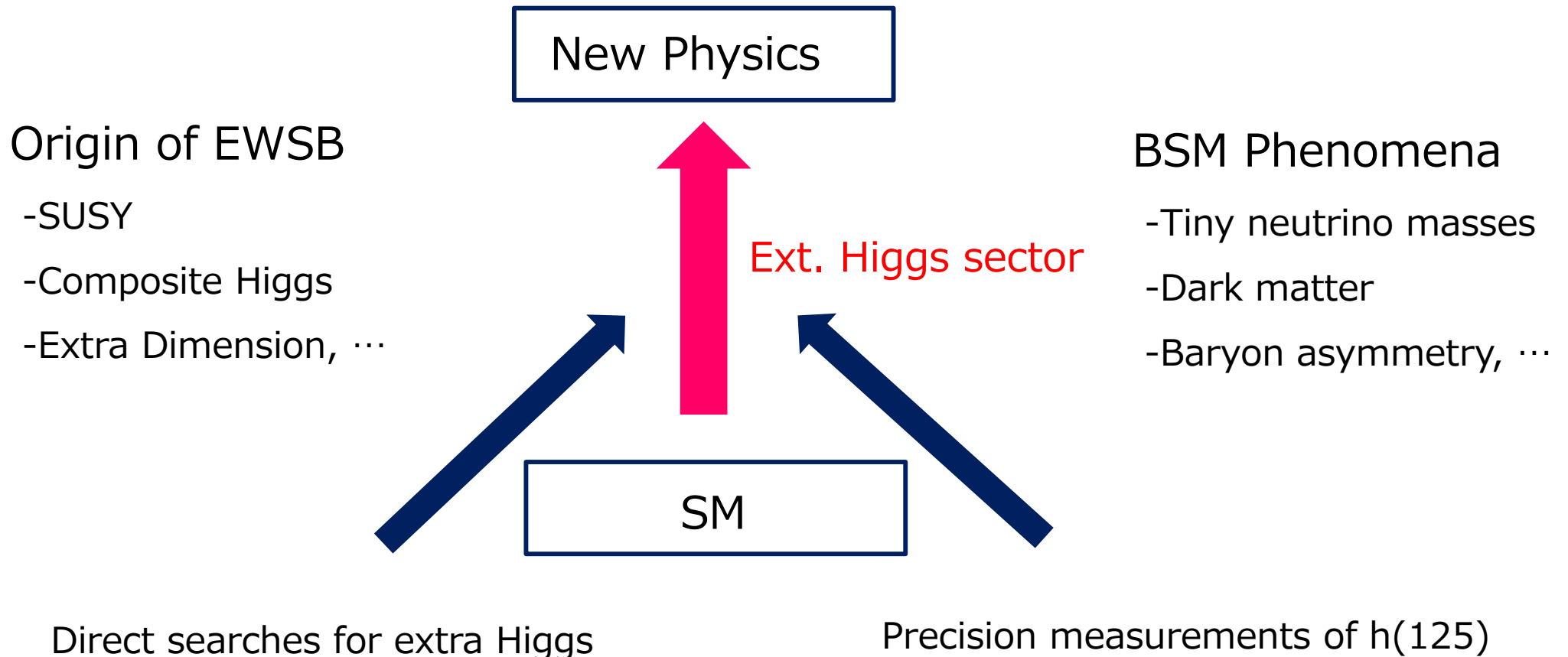
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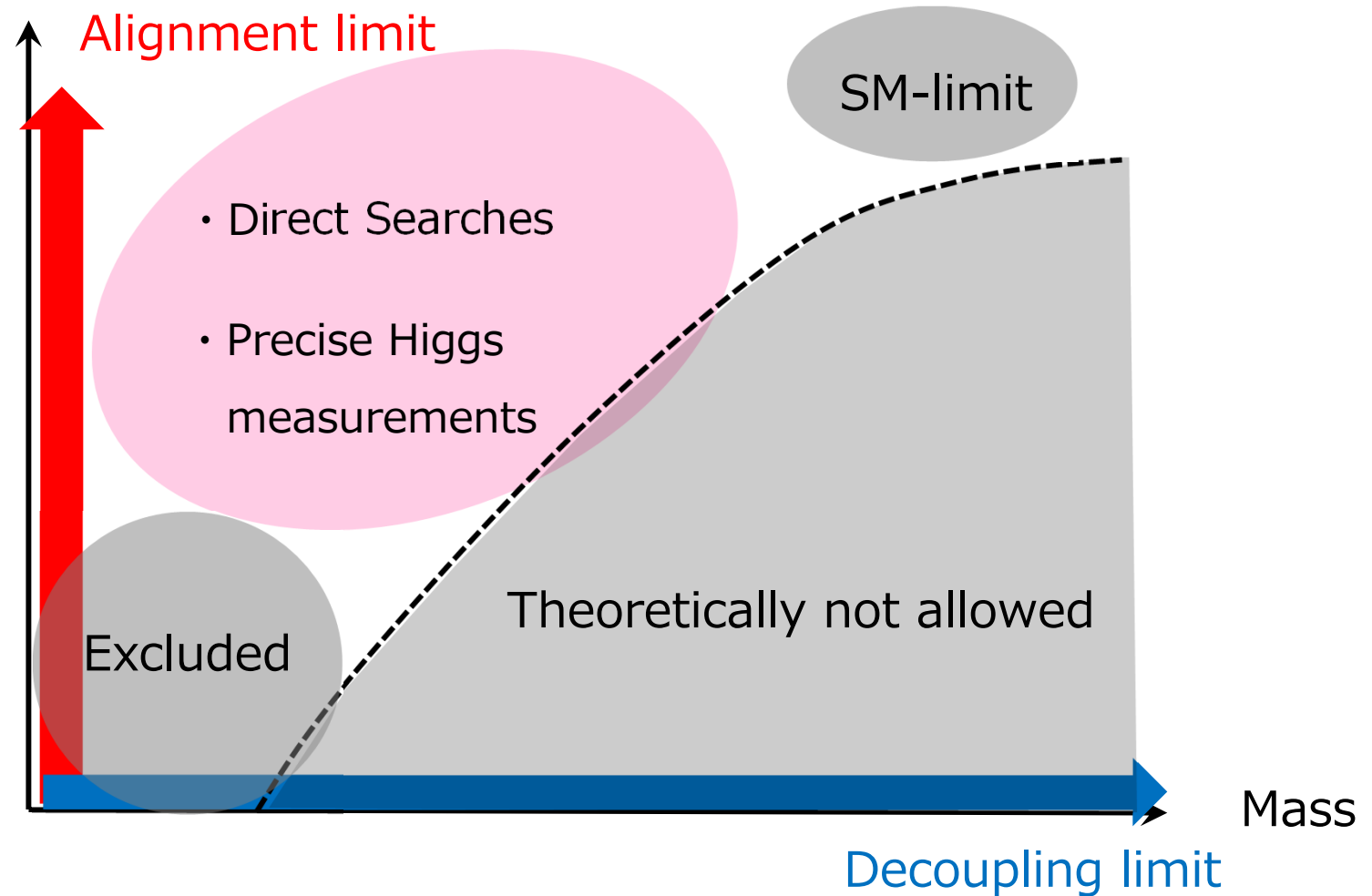
Introduction



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

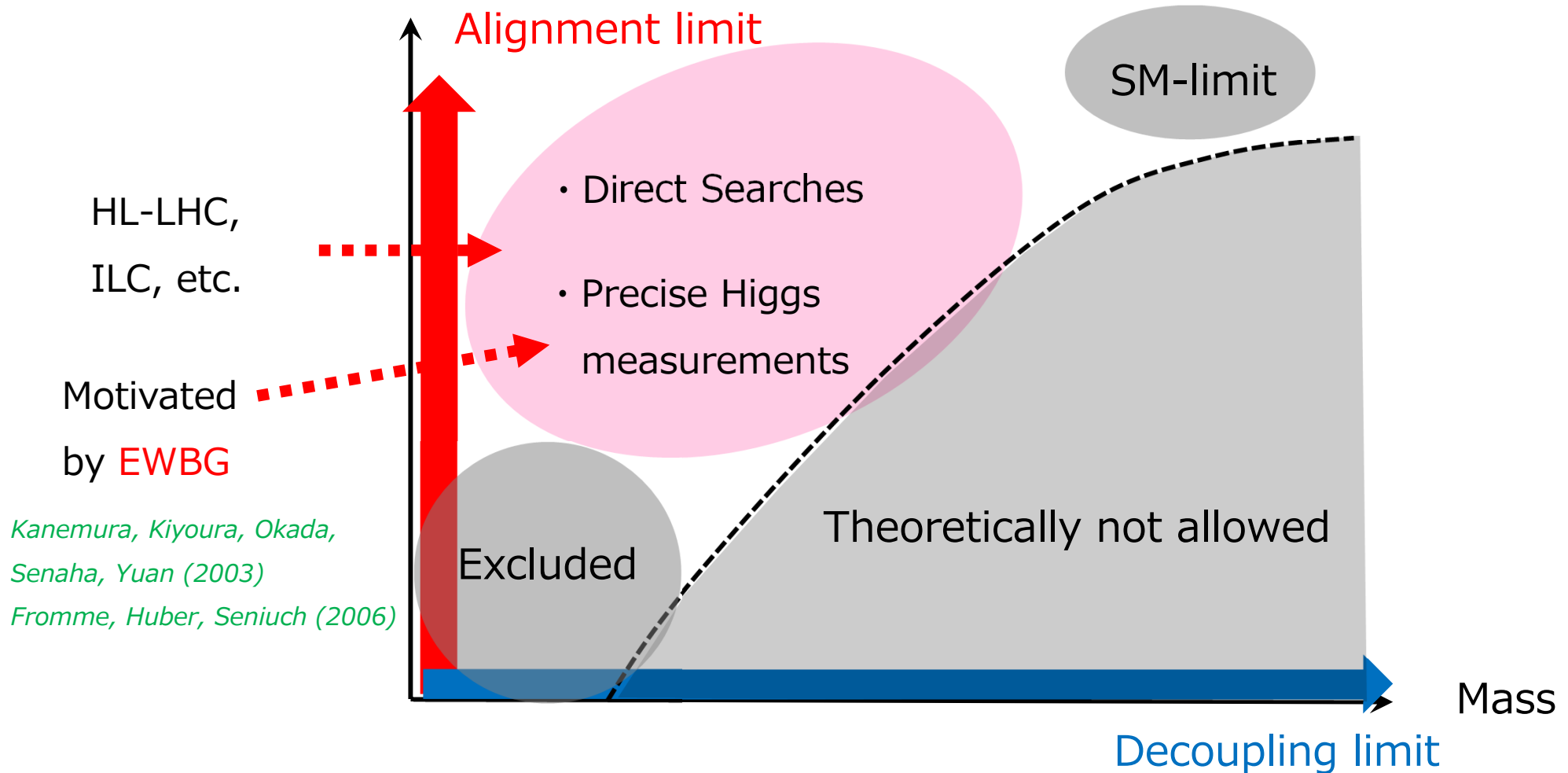
Keywords: Alignment/Decoupling

SM-likeness of $h(125)$



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(Near) **alignment** without **decoupling** scenario becomes important.

Alignment/Decoupling in the 2HDM

- 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

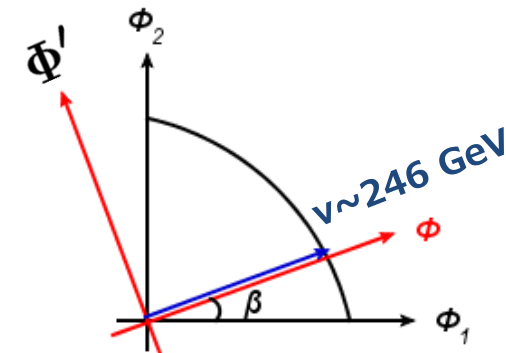
$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h'_1 + v + iG^0) \end{bmatrix}$$

CP-even Higgs

Charged Higgs

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

CP-odd Higgs



$$\begin{pmatrix} h'_1 \\ h'_2 \end{pmatrix} \begin{pmatrix} \cos(\beta - \alpha) & \sin(\beta - \alpha) \\ -\sin(\beta - \alpha) & \cos(\beta - \alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

125 GeV Higgs

- Higgs boson masses

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

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

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

Higgs boson couplings

- Z_2 invariant Lagrangian in the Higgs basis

$$\mathcal{L}_{2\text{HDM}} \supset \left[|D_\mu \Phi|^2 + Y_f \bar{\Psi}_L \Phi \Psi_R \right]$$

SM-like terms
(incl. gauge/fermion masses)

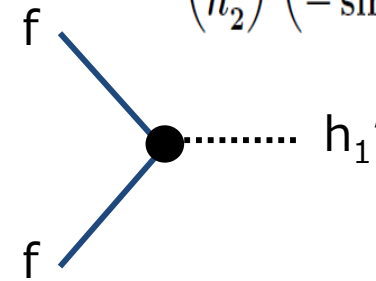
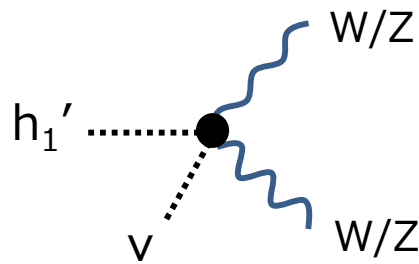
$$+ |D_\mu \Phi'|^2 + Y_f \xi_f \bar{\Psi}_L \Phi' \Psi_R$$

Additional terms
(no mass term)

Higgs boson couplings

- Z_2 invariant Lagrangian in the Higgs basis

$$\begin{pmatrix} h'_1 \\ h'_2 \end{pmatrix} \begin{pmatrix} \cos(\beta - \alpha) & \sin(\beta - \alpha) \\ -\sin(\beta - \alpha) & \cos(\beta - \alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$



$$\mathcal{L}_{2\text{HDM}} \supset \left[|D_\mu \Phi|^2 + Y_f \bar{\Psi}_L \Phi \Psi_R \right]$$

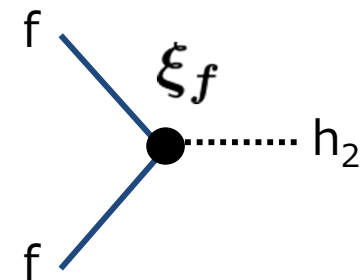
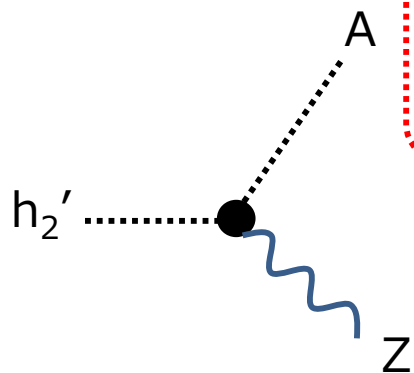
SM-like terms

(incl. gauge/fermion masses)

$$\left[+ |D_\mu \Phi'|^2 + Y_f \xi_f \bar{\Psi}_L \Phi' \Psi_R \right]$$

Additional terms

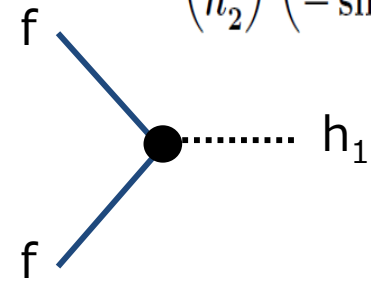
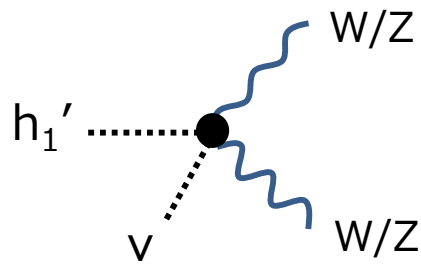
(no mass term)



Higgs boson couplings

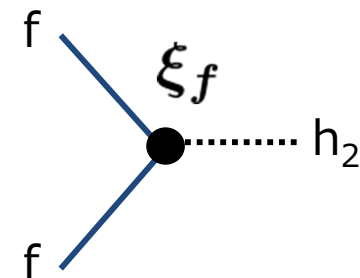
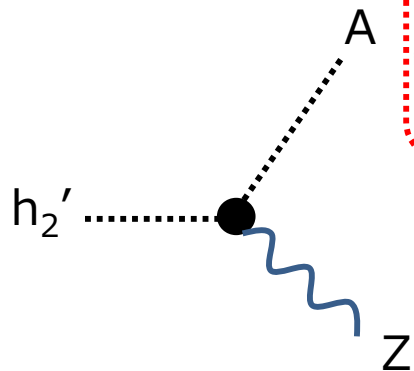
□ Z_2 invariant Lagrangian in the Higgs basis

$$\begin{pmatrix} h'_1 \\ h'_2 \end{pmatrix} \begin{pmatrix} \cos(\beta - \alpha) & \sin(\beta - \alpha) \\ -\sin(\beta - \alpha) & \cos(\beta - \alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$



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

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

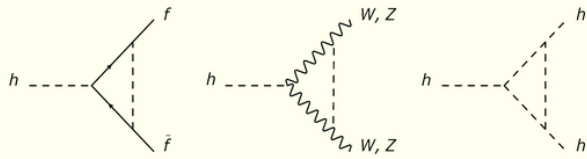


	ξ_u	ξ_d	ξ_e
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Fingerprinting the Higgs sector

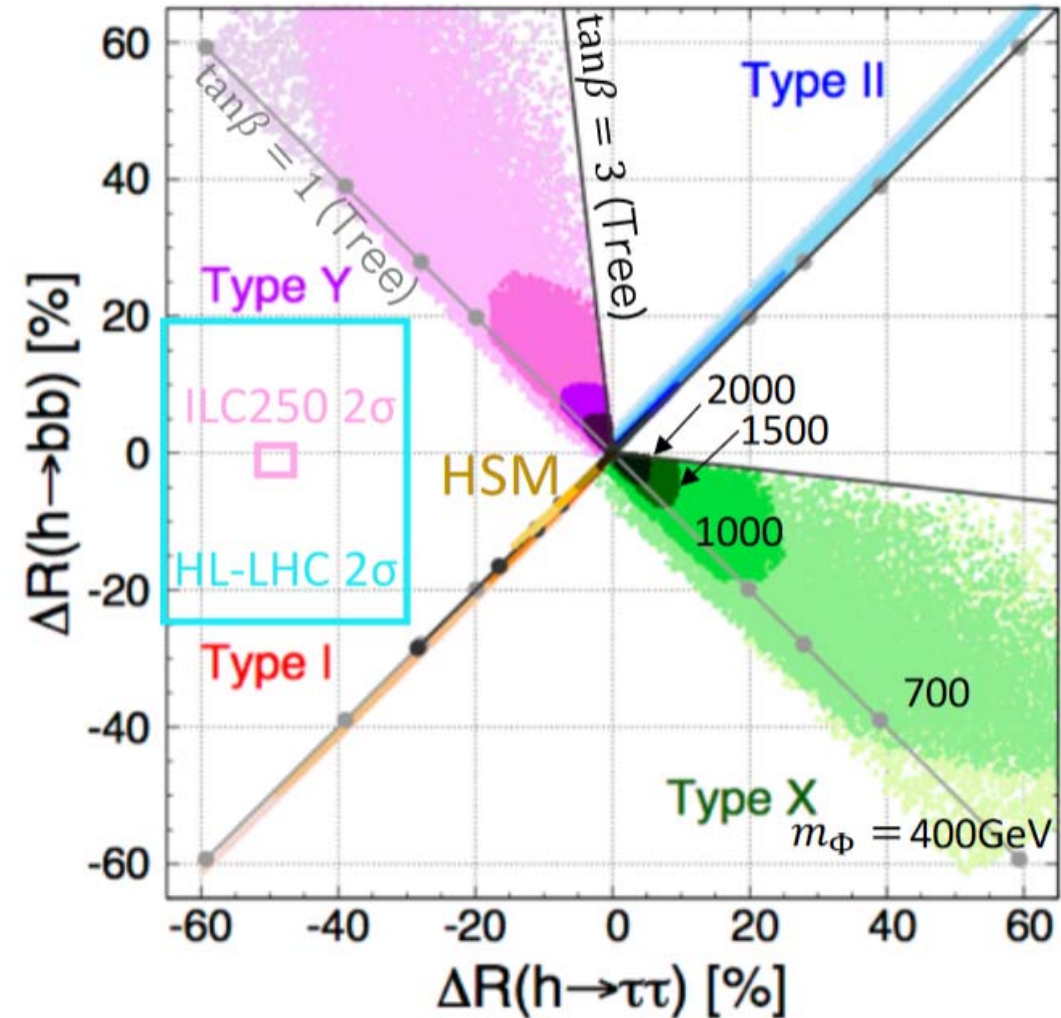
Kanemura, Kikuchi, Sakurai, Mawatari, KY, PLB714, 140-149 (2018)

H-COUP



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

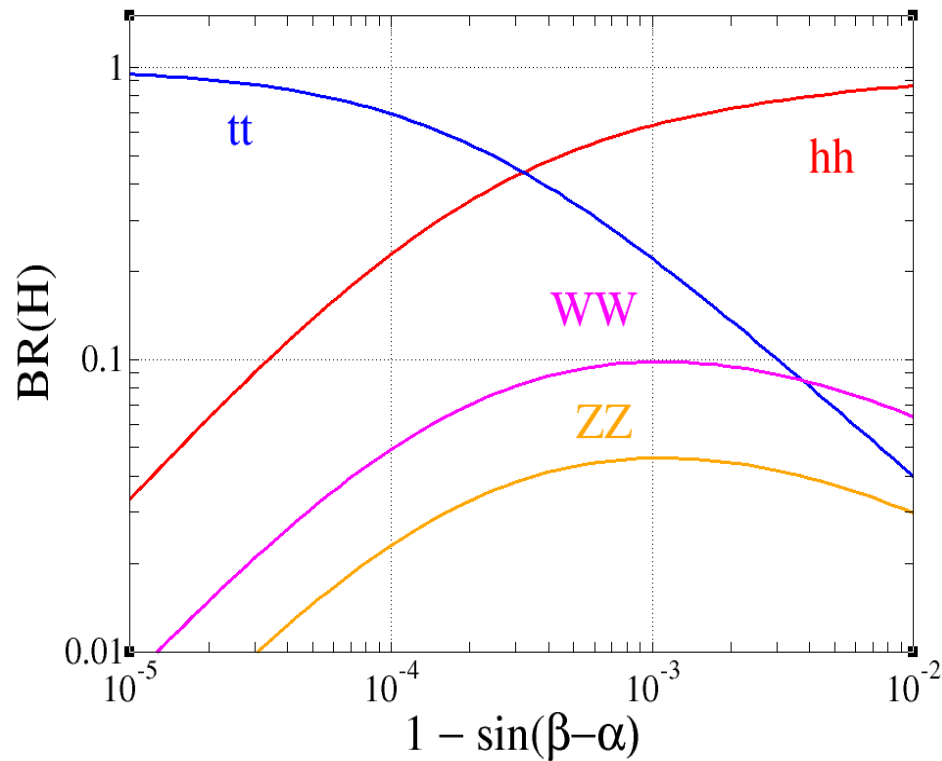
HCOUP:Ver. 2
Kanemura, Kikuchi, Sakurai, Mawatari, KY (2019)



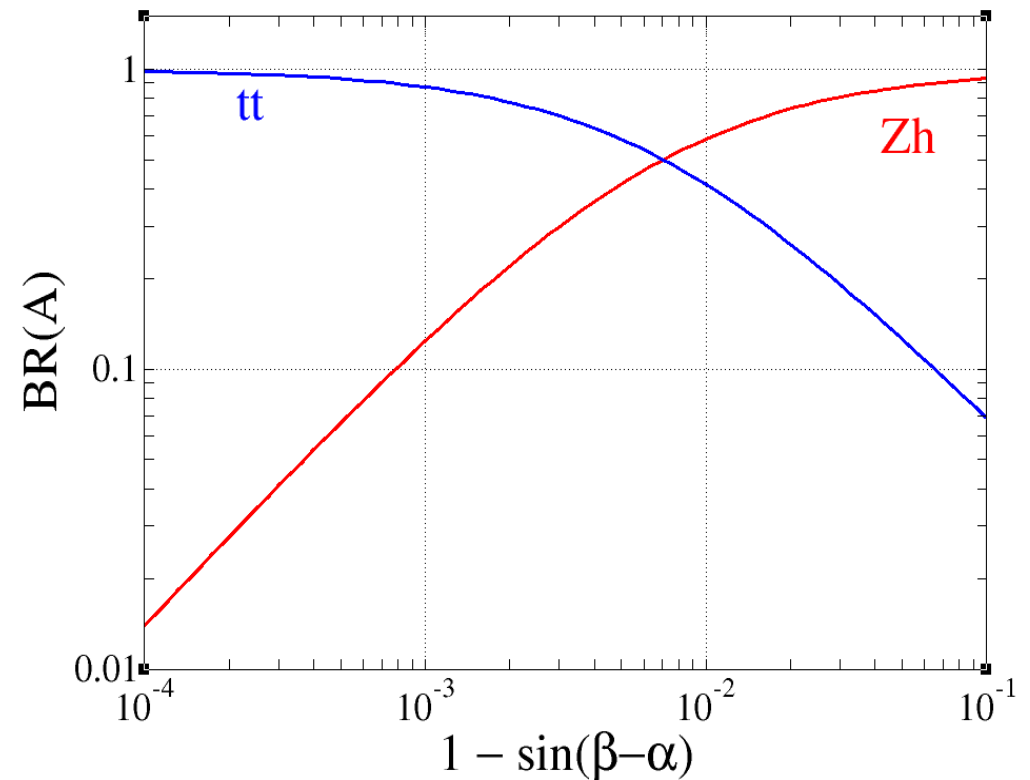
Higgs to Higgs Decays

Computed by H-COUP v3- β , Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Type-I 2HDM with $m_H = m_A = m_{H^+} = M = 400$ GeV, $\tan\beta = 10$



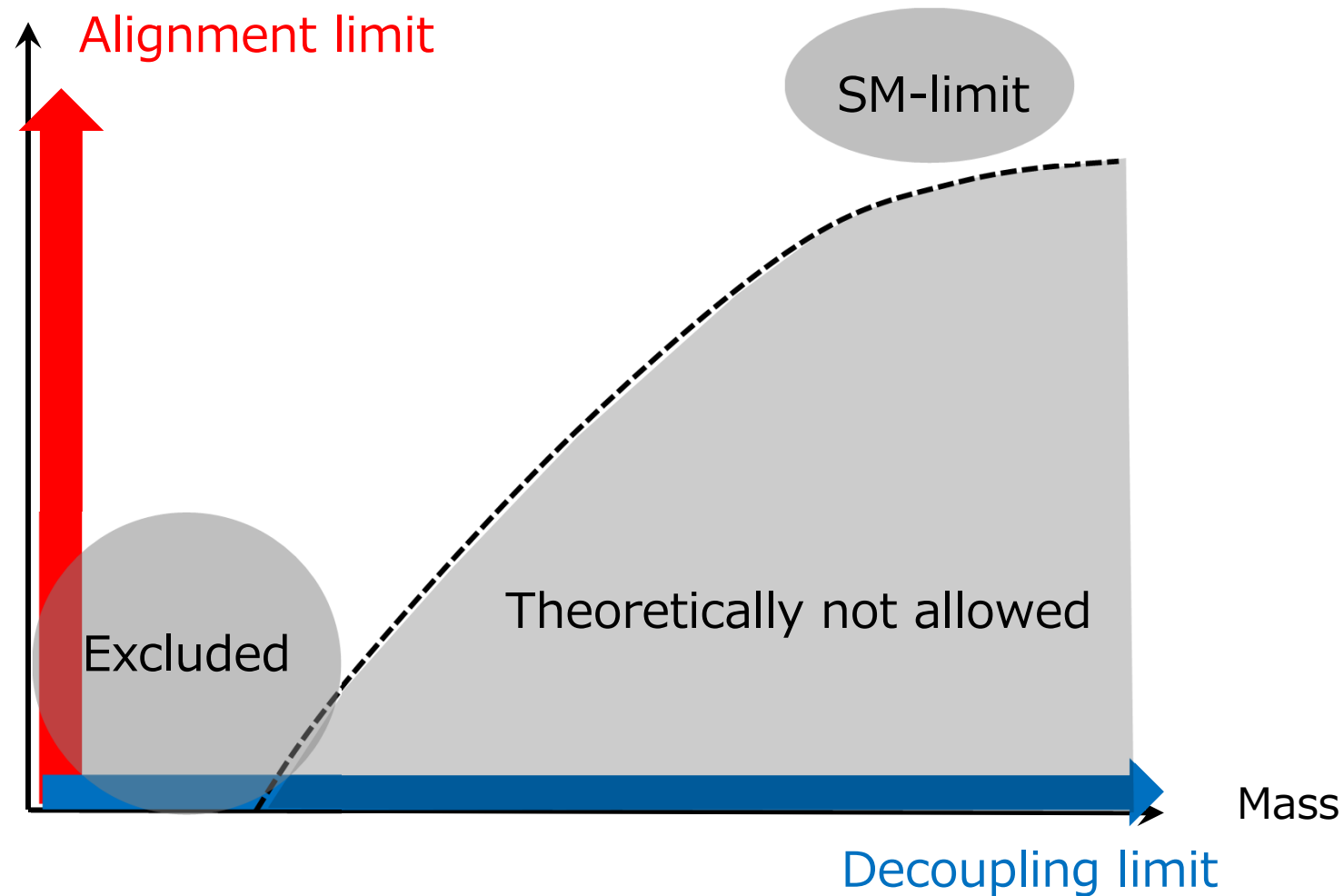
Alignment limit



$H \rightarrow hh, A \rightarrow Zh$ becomes important in near alignment region.

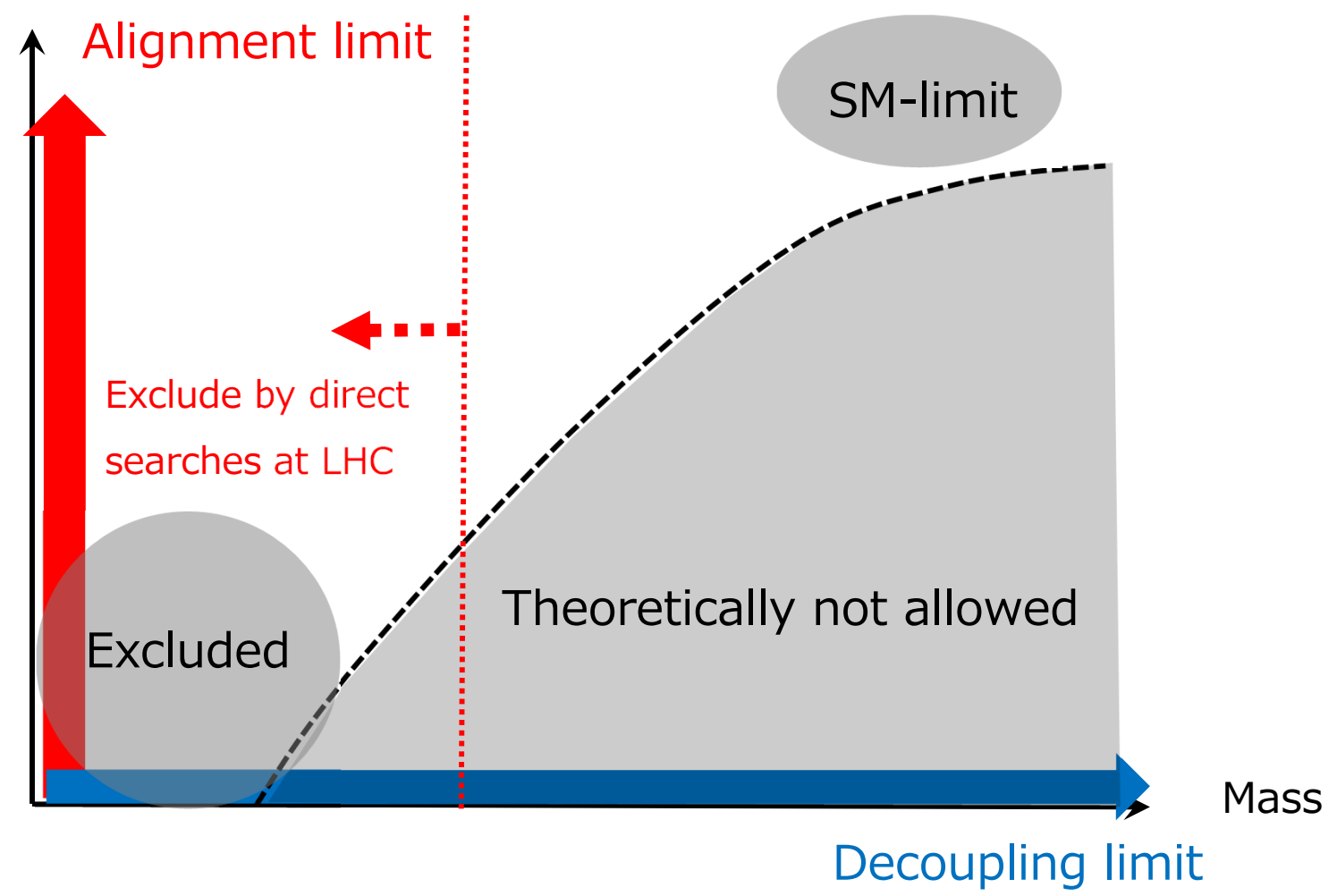
Exploring the Higgs sector

SM-likeness of $h(125)$



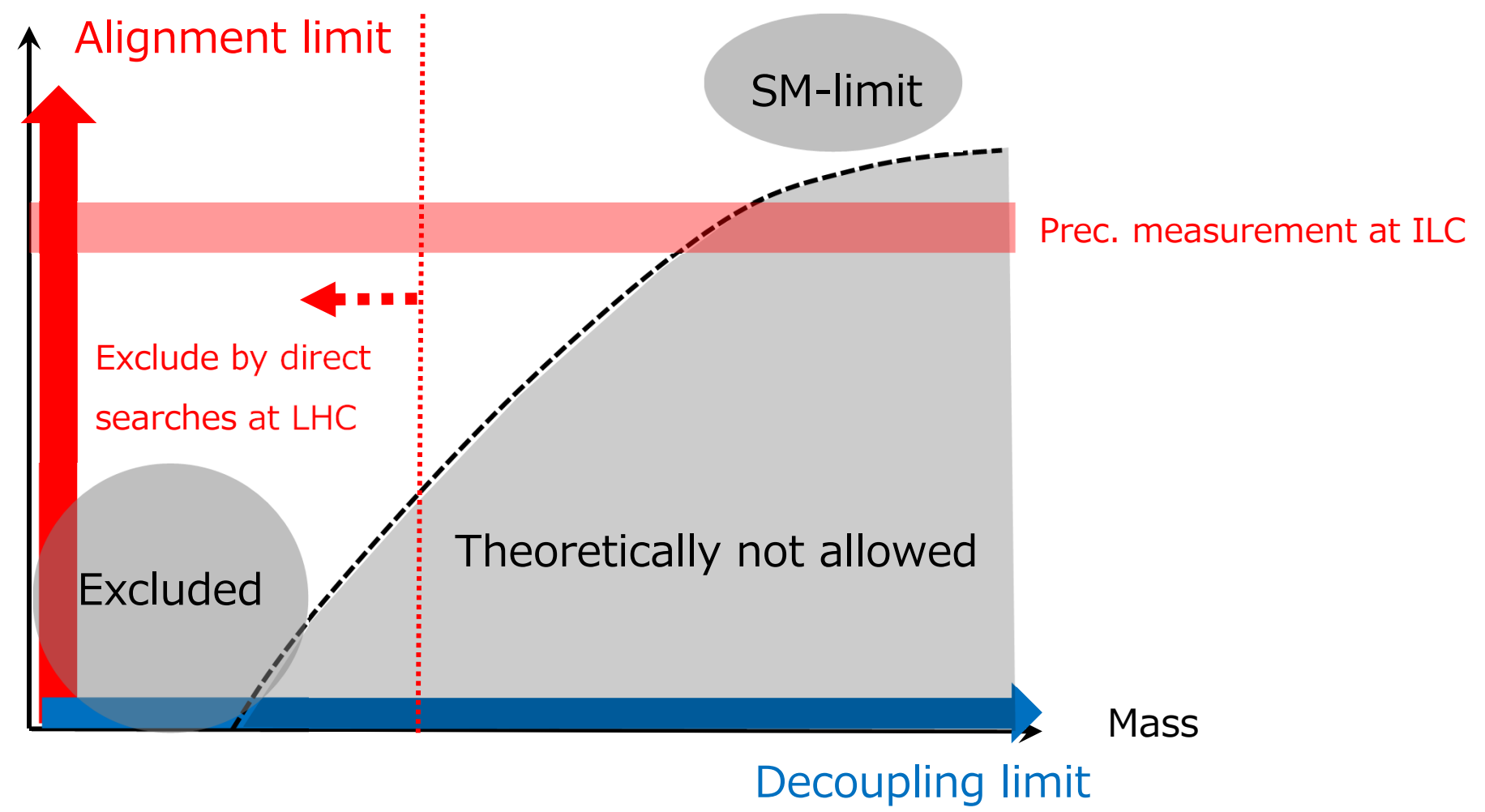
Exploring the Higgs sector

SM-likeness of h(125)



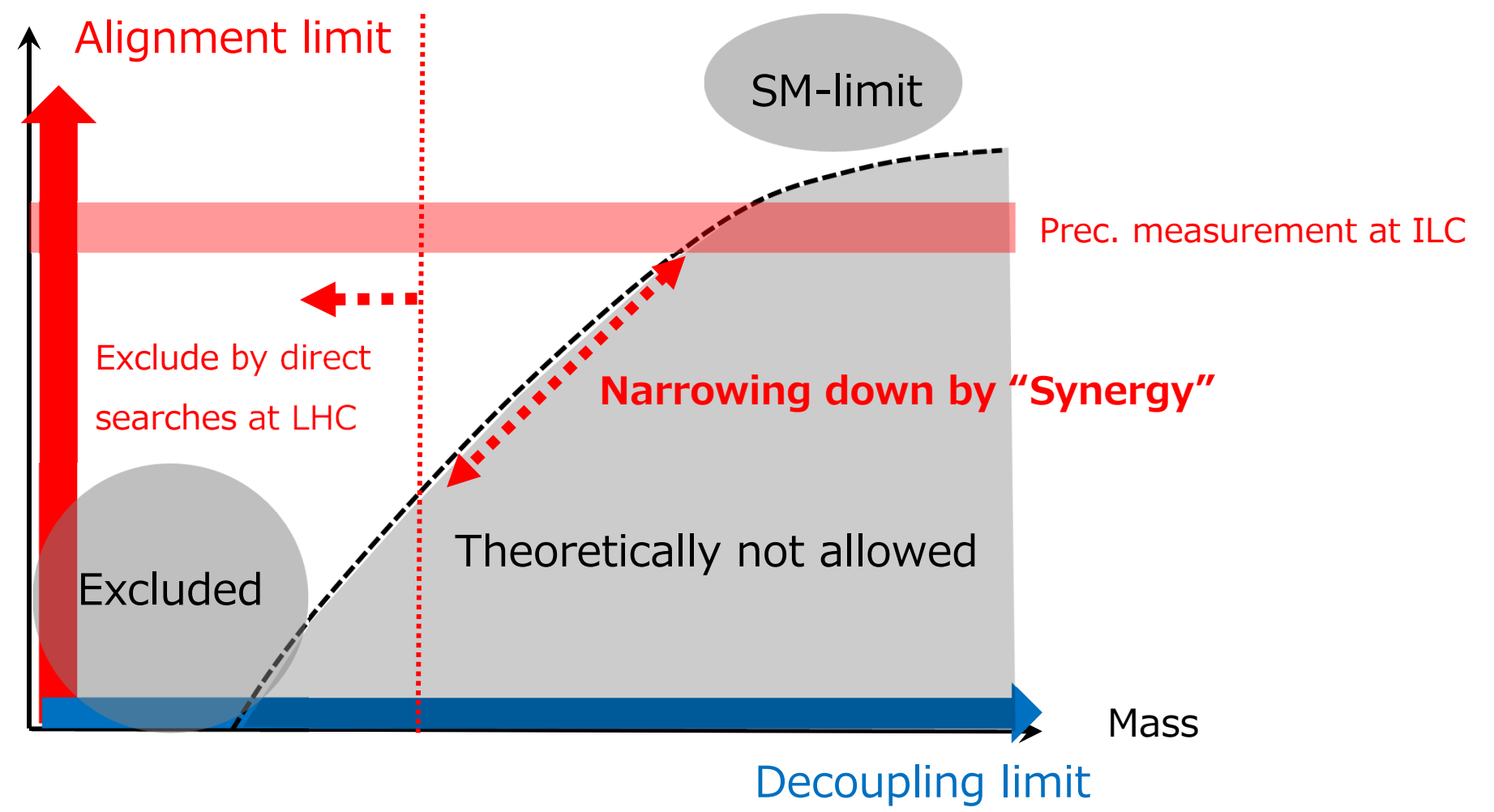
Exploring the Higgs sector

SM-likeness of h(125)



Exploring the Higgs sector

SM-likeness of h(125)

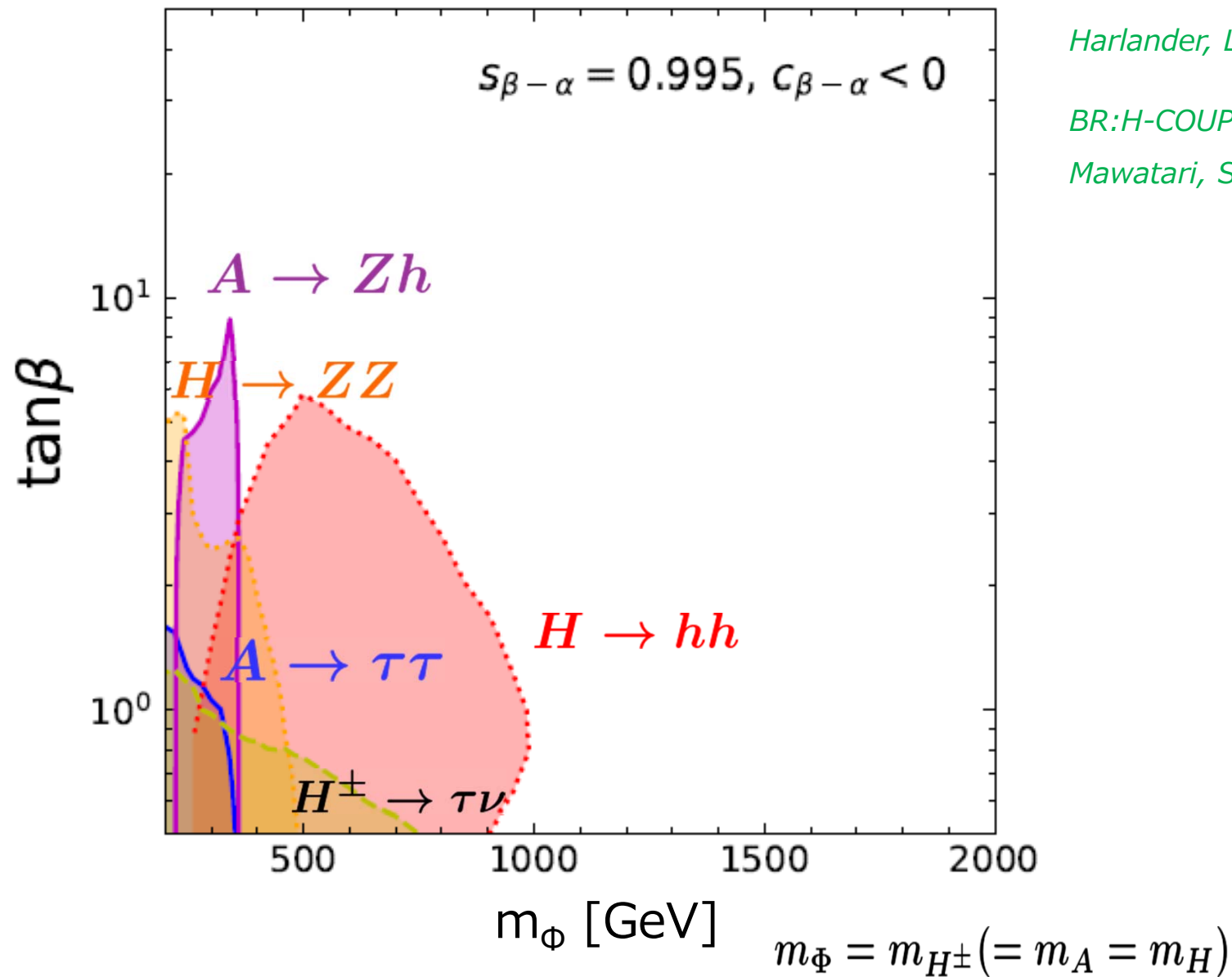


"New No Loose Theorem"

Current bound at LHC

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

Type-I



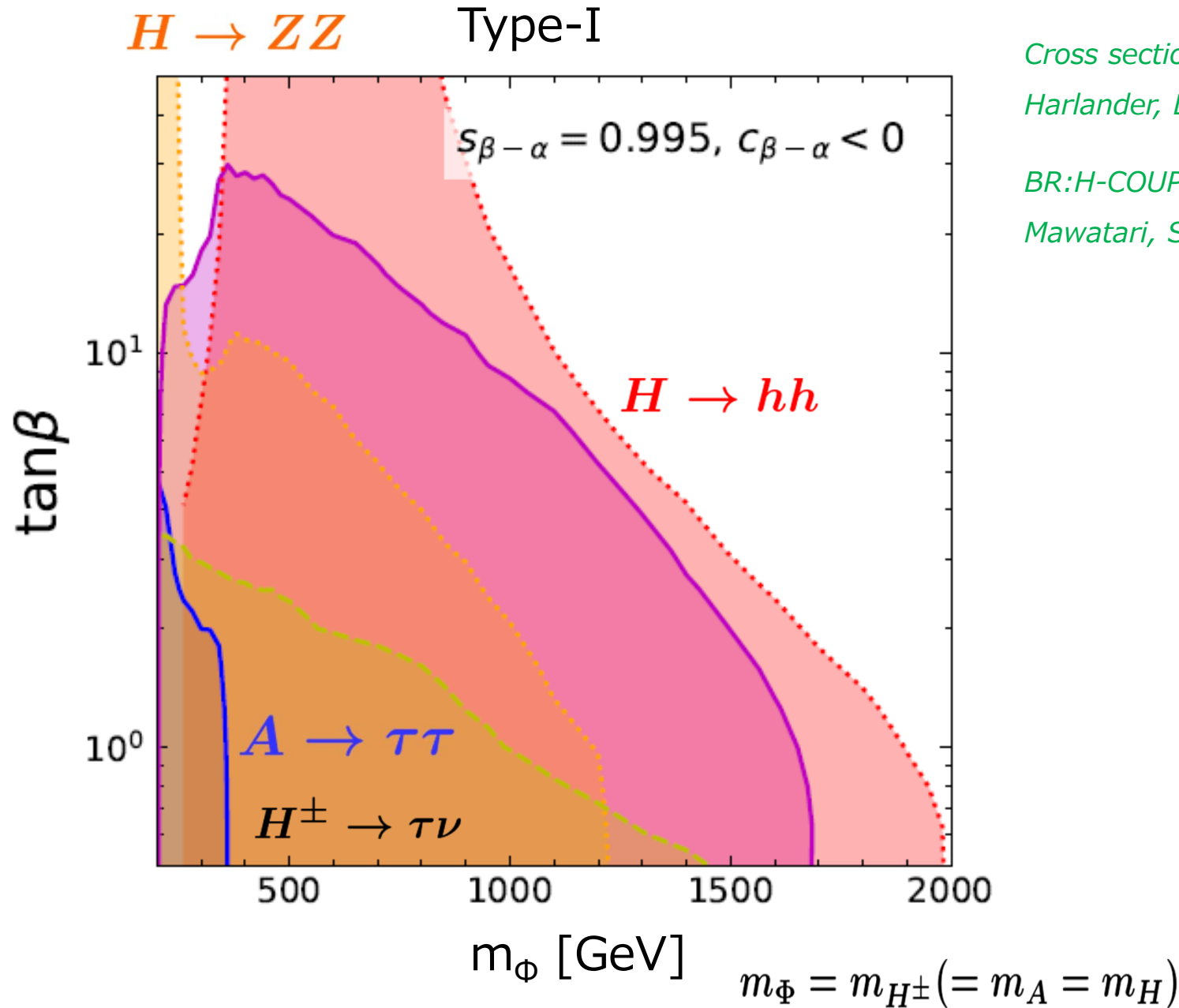
Cross section: SusHi v1-7-0

Harlander, Liebler, Mantler

*BR:H-COUP v3- β :Aiko, Kanemura, Kikuchi,
Mawatari, Sakurai, Yagyu*

Future expected bound at HL-LHC

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



Cross section: SusHi v1-7-0

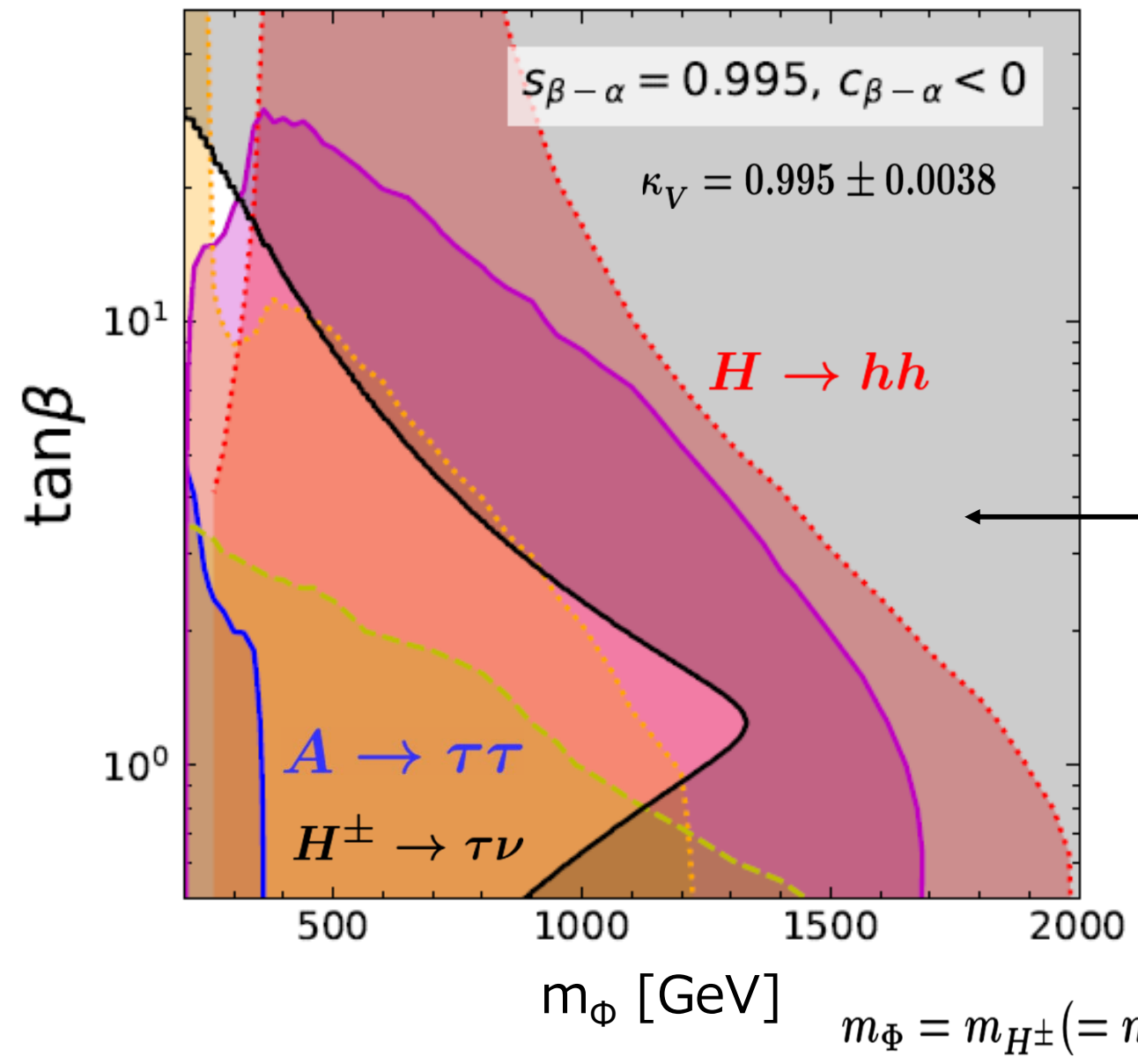
Harlander, Liebler, Mantler

*BR:H-COUP v3-beta :Aiko, Kanemura, Kikuchi,
Mawatari, Sakurai, Yagyu*

Synergy between HL-LHC and ILC

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

$H \rightarrow ZZ$ Type-I



Cross section: SusHi v1-7-0

Harlander, Liebler, Mantler

BR:H-COUP v3-beta :Aiko, Kanemura, Kikuchi,

Mawatari, Sakurai, Yagyu

Excluded by perturbative unitarity and/or vacuum stability

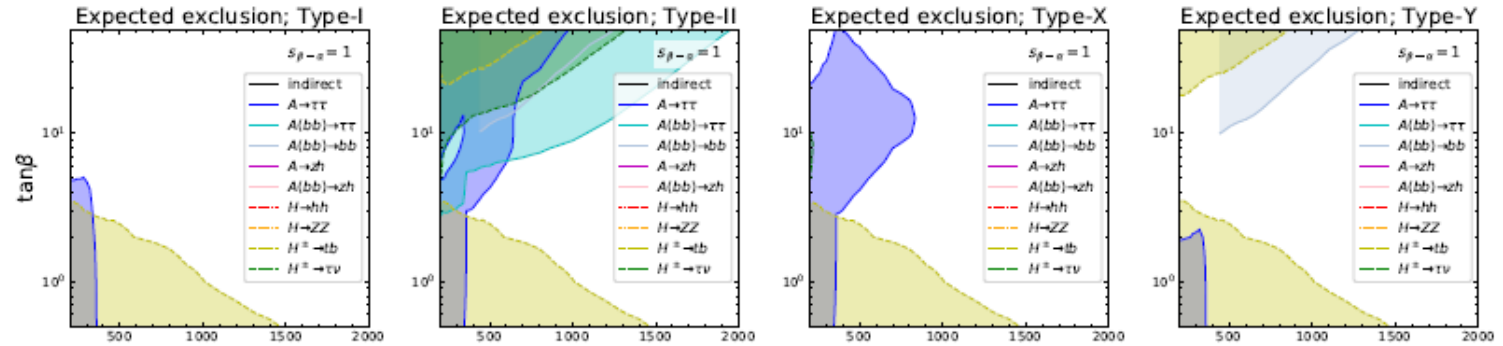
Type-I

Type-II

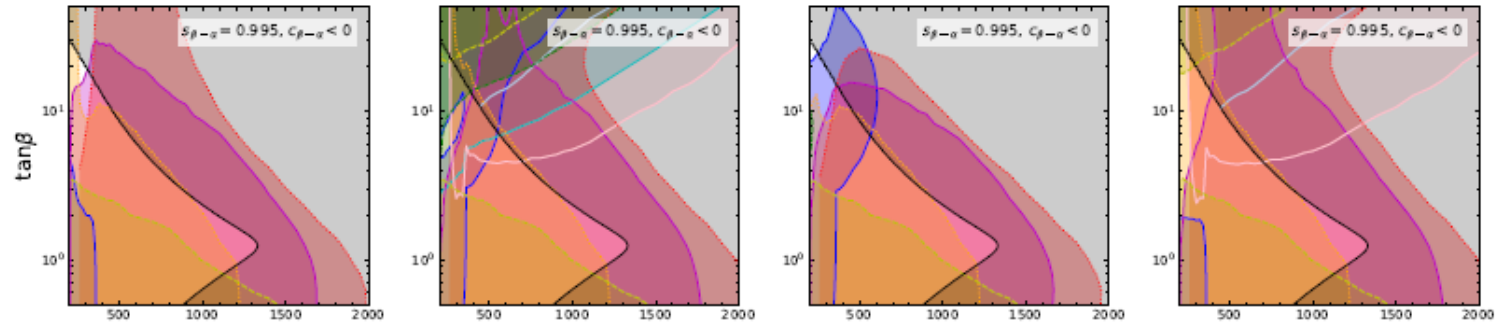
Type-X

Type-Y

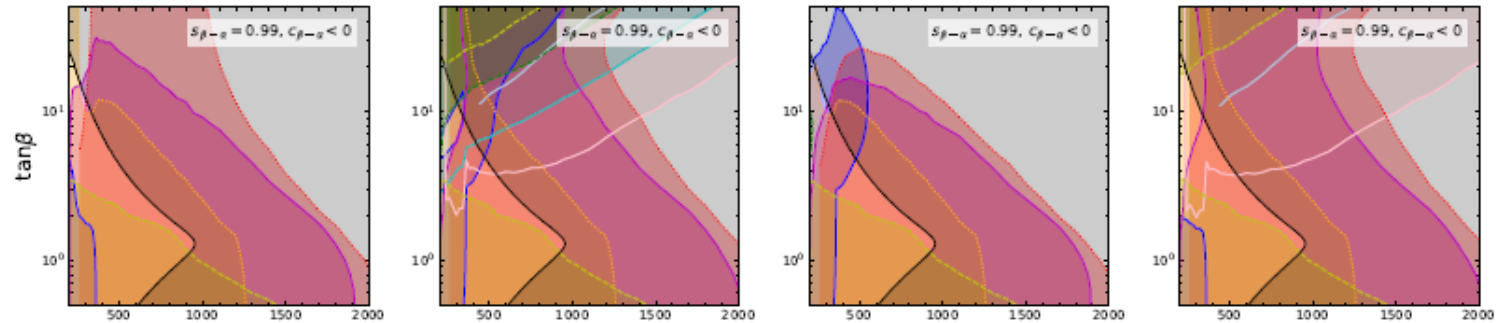
$\sin(\beta-\alpha) = 1$



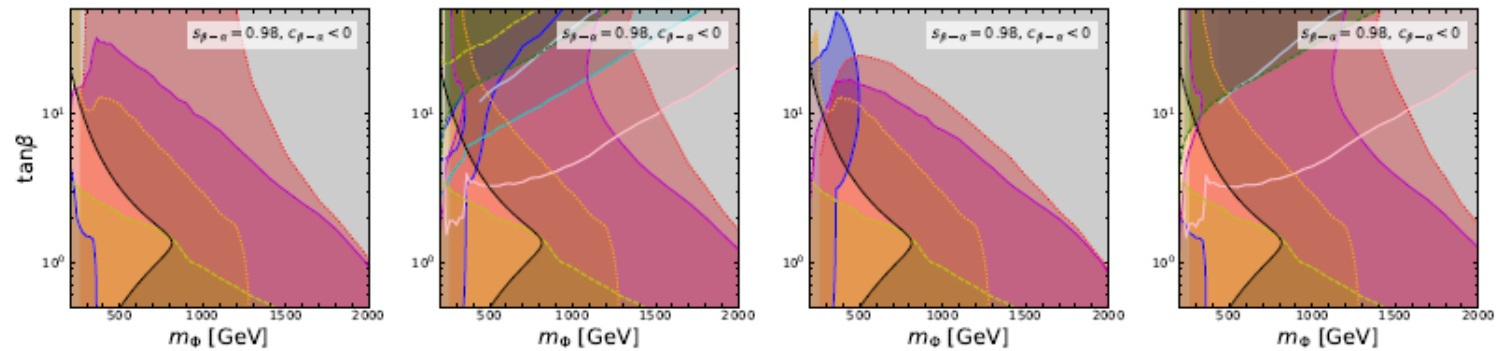
$\sin(\beta-\alpha) = 0.995$



$\sin(\beta-\alpha) = 0.99$



$\sin(\beta-\alpha) = 0.98$



Higgs to Higgs Decay @ 1-loop

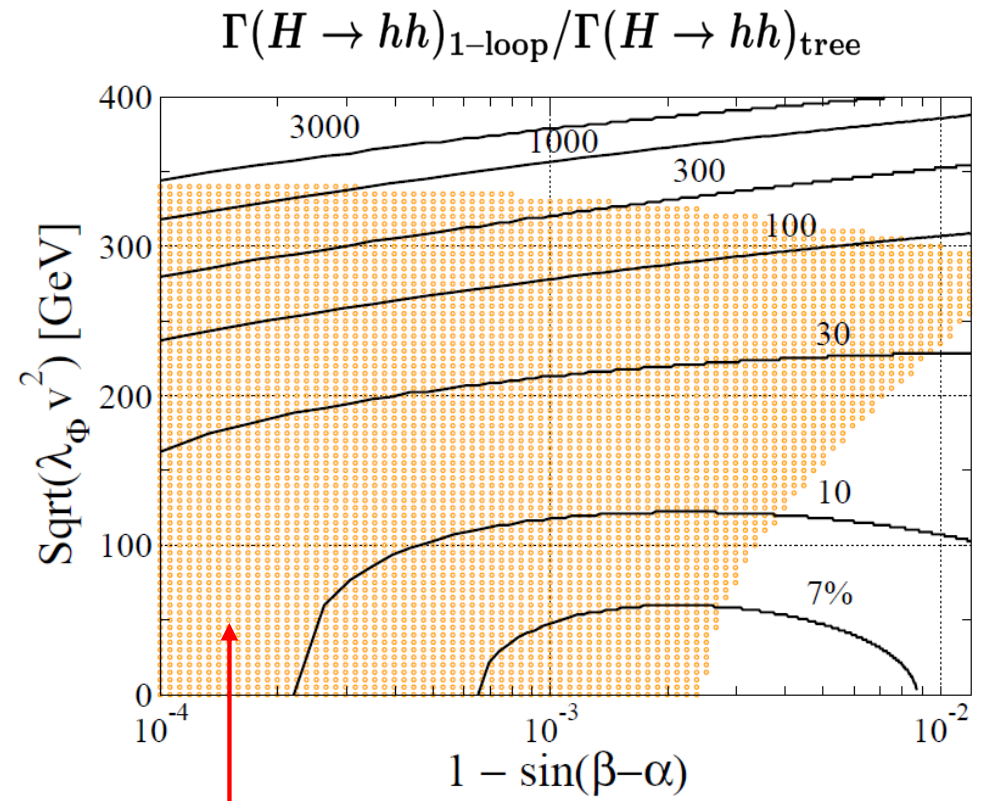
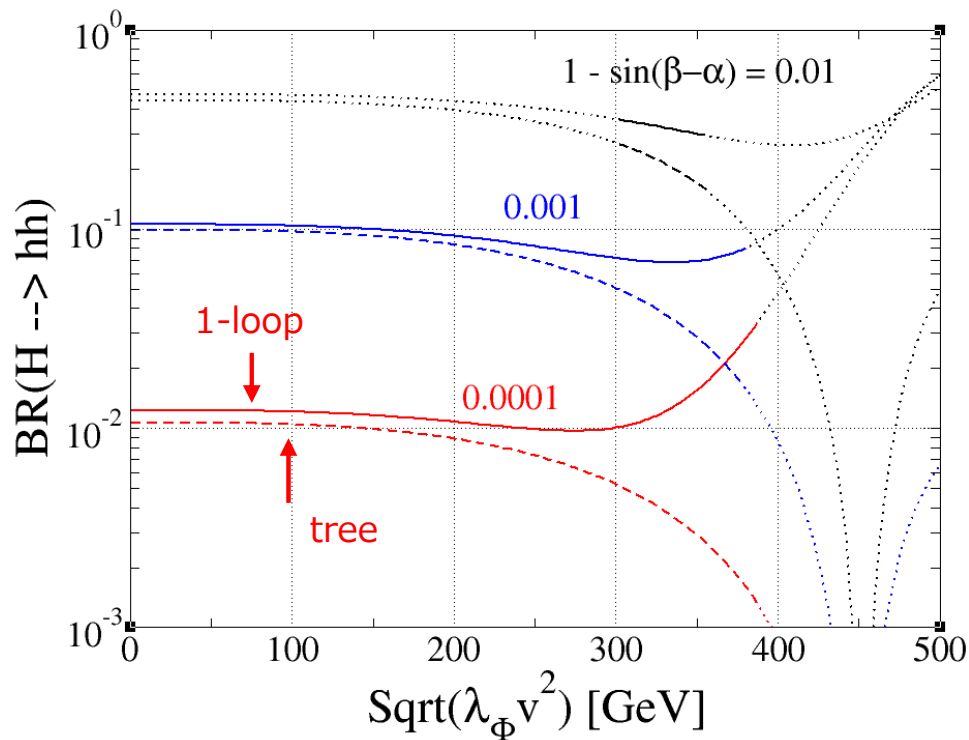
Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY: HCOUP Ver. 3, Preliminary

▣ Decay BR of $H \rightarrow hh$ at one-loop level.

• 2HDM type-I, $\tan\beta = 2$, $m_H = m_A = m_{H^+} = 500$ GeV, $\cos(\beta-\alpha) > 0$

$\Phi = H, A$ 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**.

Summary

- ❑ (Near) **alignment without decoupling** region is getting important.
- ❑ In the near alignment region, **Higgs to Higgs decays** become important, and the **new no loose theorem** gives upper limit on the mass of extra Higgs bosons.
- ❑ From **synergy** between LHC direct searches and ILC precise measurements, wide region of the parameter space can be explored.
- ❑ **1-loop corrections** to $H \rightarrow hh$ can be sizable, so that it should be included.

