LHC/ILC Synergy for Exploring Extended Higgs Sectors

Kei Yagyu（Osaka U.）

大阪大学
OSAKA UNIVERSITY

Collaboration with

Masashi Aiko, Shinya Kanemura (Osaka U.),

Kentarou Mawatari (Iwate U.)

Snowmass (Energy Frontier)

2020, Jul. 8th, Online

Introduction

- BSM must exist, because of unsolved phenomena such as

  Neutrino masses, DM and Baryon asymmetry of Universe.

- New paradigm for the EWSB is necessary, such as

  Supersymmetry, Composite Higgs and Gauge Higgs Unification.

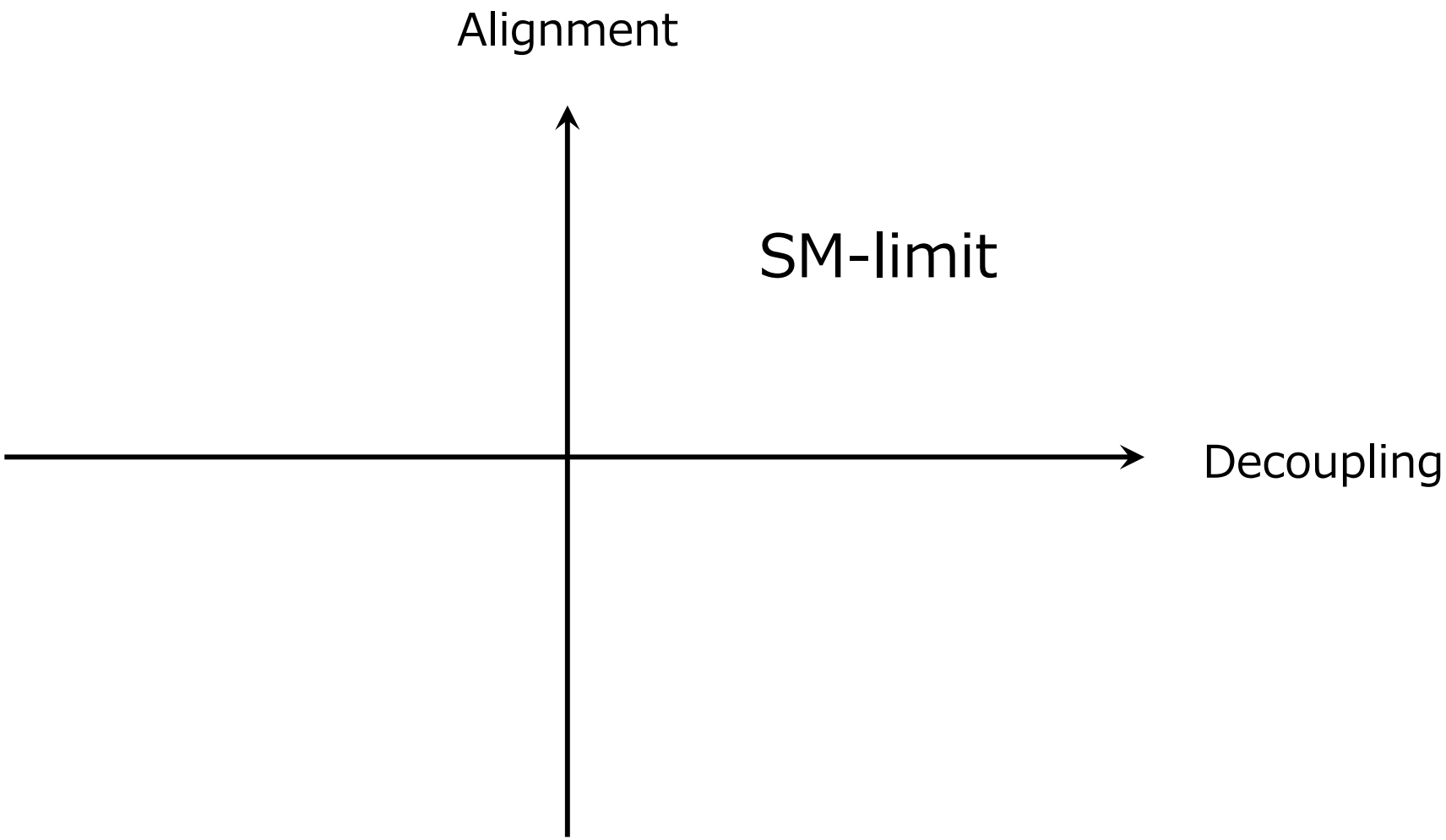
- Exploring the Higgs sector is a key to probe these BSM/NP!

- How can we clarify the property of the Higgs sector?

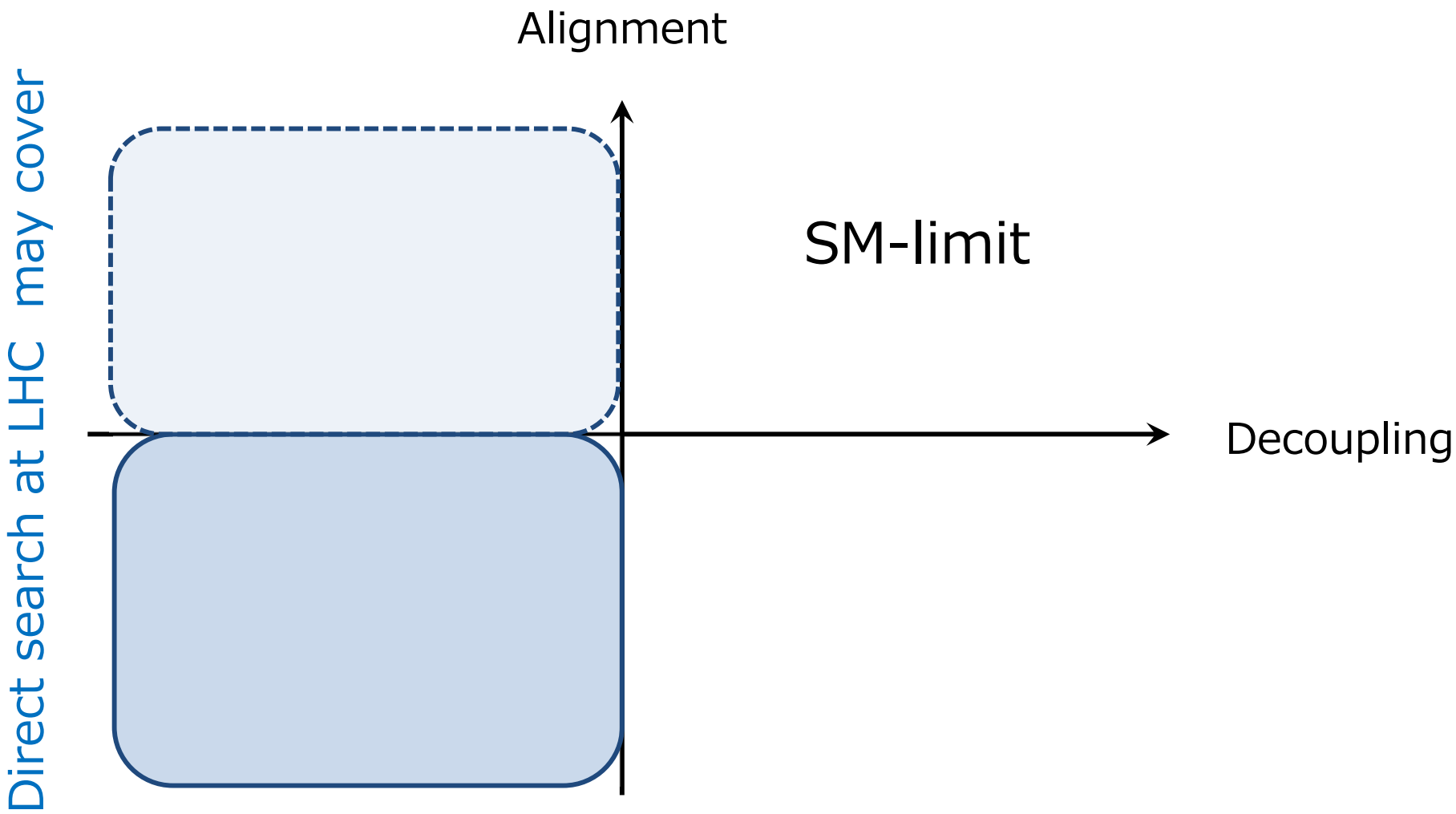
Direct searches for additional Higgs bosons and indirect searches via

Higgs precise measurements can probe the Higgs sector.

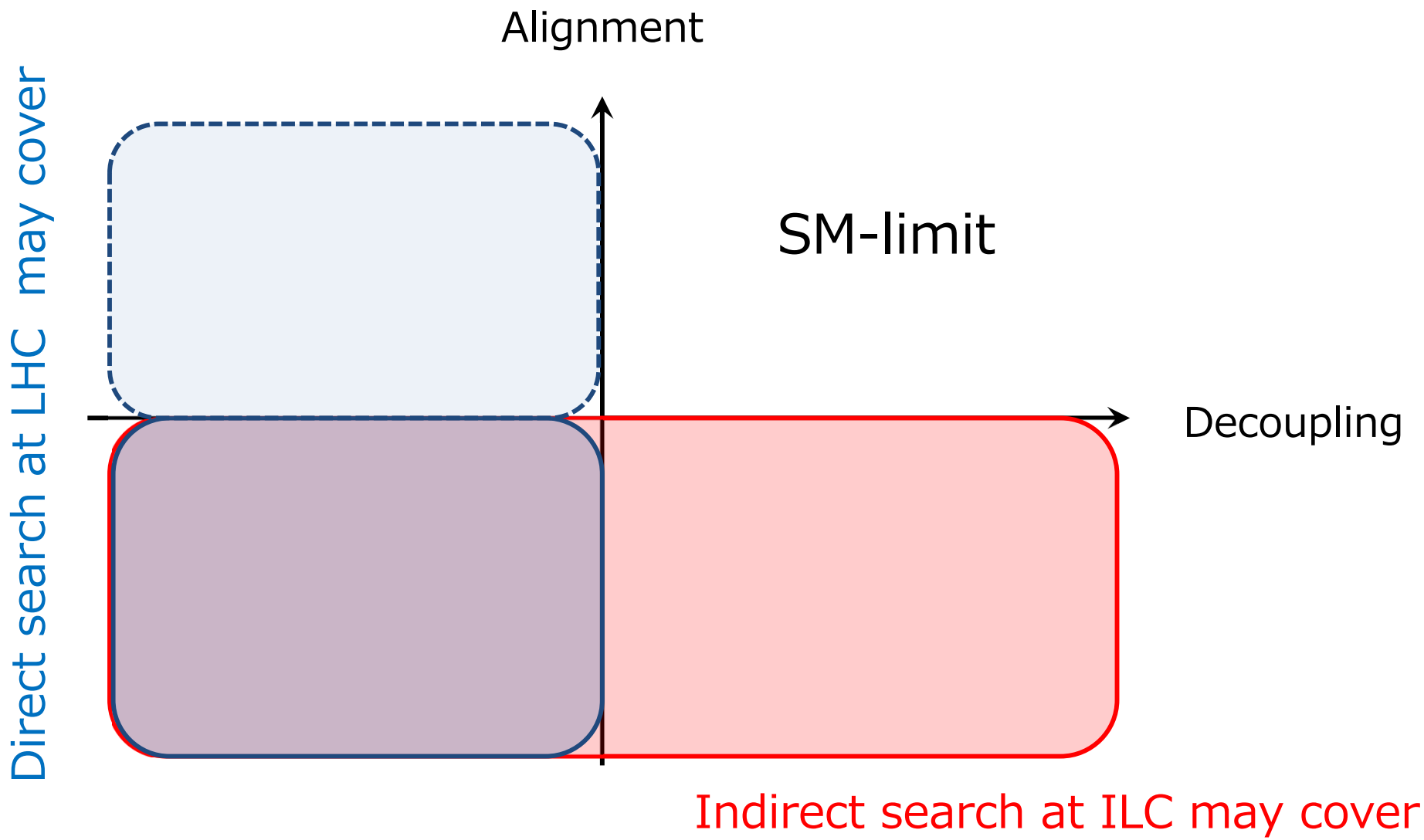
Keywords: Alignment/Decoupling



Keywords: Alignment/Decoupling



Keywords: Alignment/Decoupling



Synergy b/w LHC and ILC searches is important!

2 Higgs doublet models

- Simple extension of the Higgs sector:

$$\Phi_{\rm SM} \to \Phi_1,\ \Phi_2$$

$$h_{\rm SM} \to h,\ H,\ A,\ H^{\pm}$$

- Variations of the 2HDM

CP
- CP-conserving 2HDM
- CP-violating 2HDM
  (See, talk by M. Kubota)

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

Z_2
- Hardly-broken (General 2HDM)
- Softly-broken (Type-I, Type-II, Type-X, Type-Y)
- Unbroken (Inert doublet model)

$$M^2 = m_3^2/(\sin\beta\cos\beta)$$

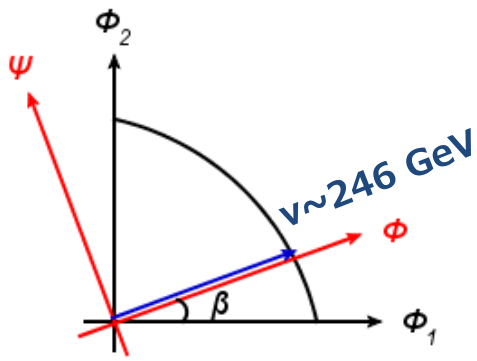
- 8 parameters v, m_h, m_H, m_A, m_{H+}, $\sin(\beta-\alpha)$, $\tan\beta$, and M^2

Alignment/Decoupling in the 2HDM

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

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

$\tan\beta = v_2/v_1$



NG boson

Charged Higgs

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

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

CP-even Higgs

CP-odd Higgs

125 GeV Higgs

- Masses of the Higgs boson at $\sin(\beta-\alpha) \sim 1$

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

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

-Masses of H, A, $H^\pm$ become infinity.

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

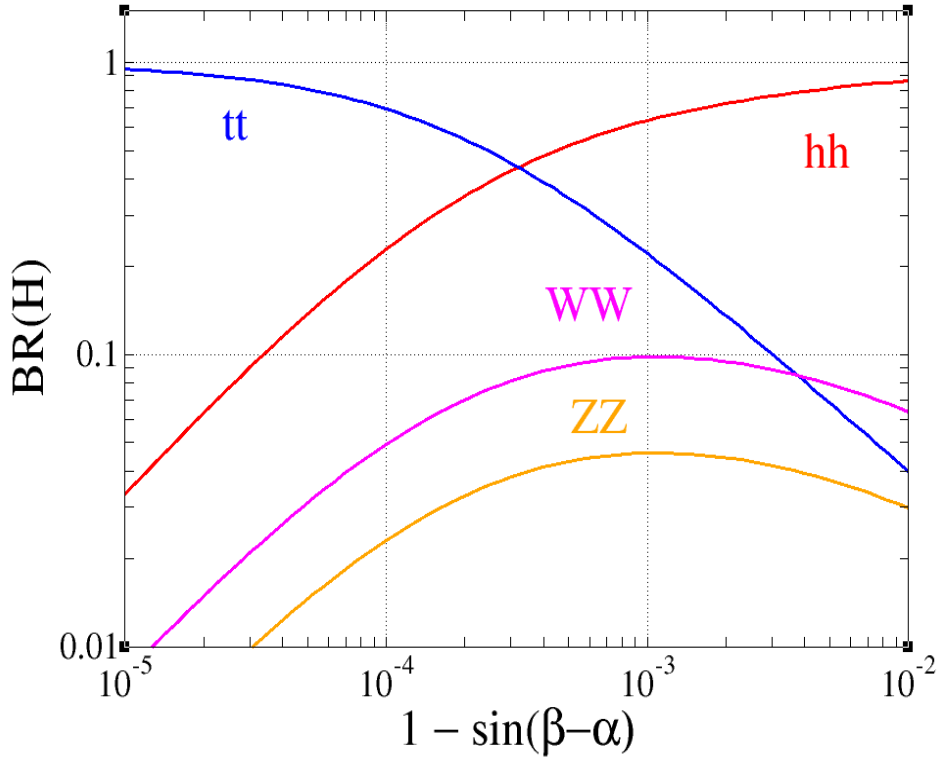
-h plays a role of the Higgs boson.

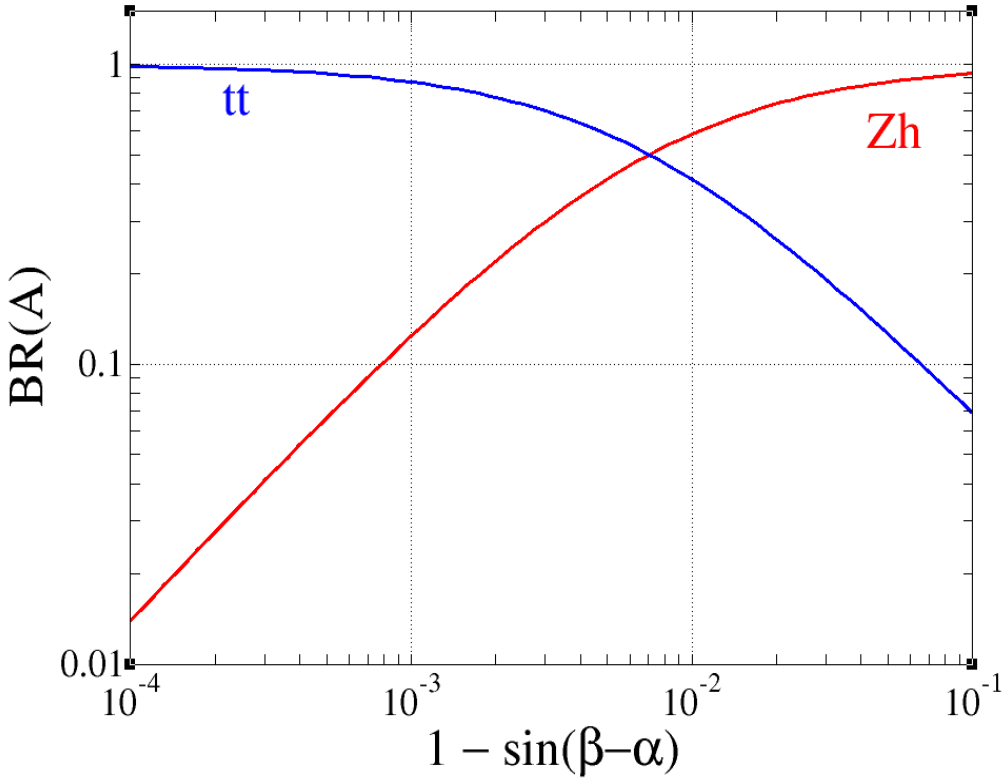
-H, A, $H^\pm$ behave fermio-philic scalars.

(Non) alignment in the 2HDM

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

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





Alignment limit

NLO EW corr. to H → hh:

Krause, Muhlleitner, Santos, Ziesche (2016)

Higgs to Higgs decays become important for the non-alignment case.

Decoupling without alignment?

Q. Can we take M → ∞ with sin(β-α) ≠ 1?

A. No.

$$m_h^2 = \lambda v^2 + \underline{\cos^2(\beta - \alpha) M^2} = (125\ \mathrm{GeV})^2$$

This term becomes huge when M » v and sin(β-α) ≠ 1

This term should also be huge to keep 125 GeV → unitarity violation

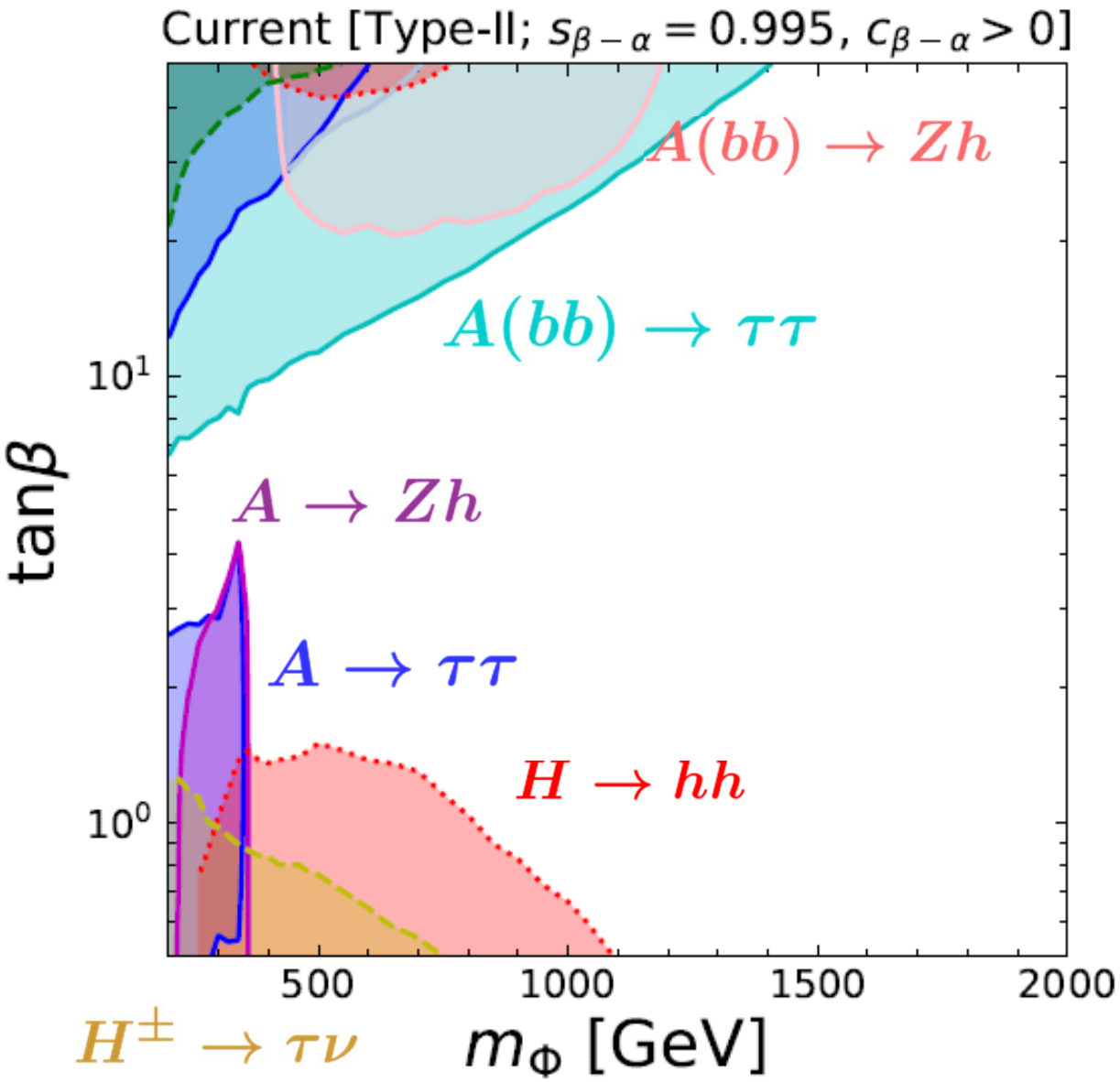
The upper limit on M (~2nd Higgs scale) appears when sin(β-α) ≠ 1.

ILC can extract it from precise measurements of h couplings

ILC can set the upper limit on the second Higgs mass scale.

Current Exclusion Limits @ LHC Run-II

Aiko, Kanemura, Mawatari, Yagyu (in preparation)



Cross section: SusHi v1-7-0

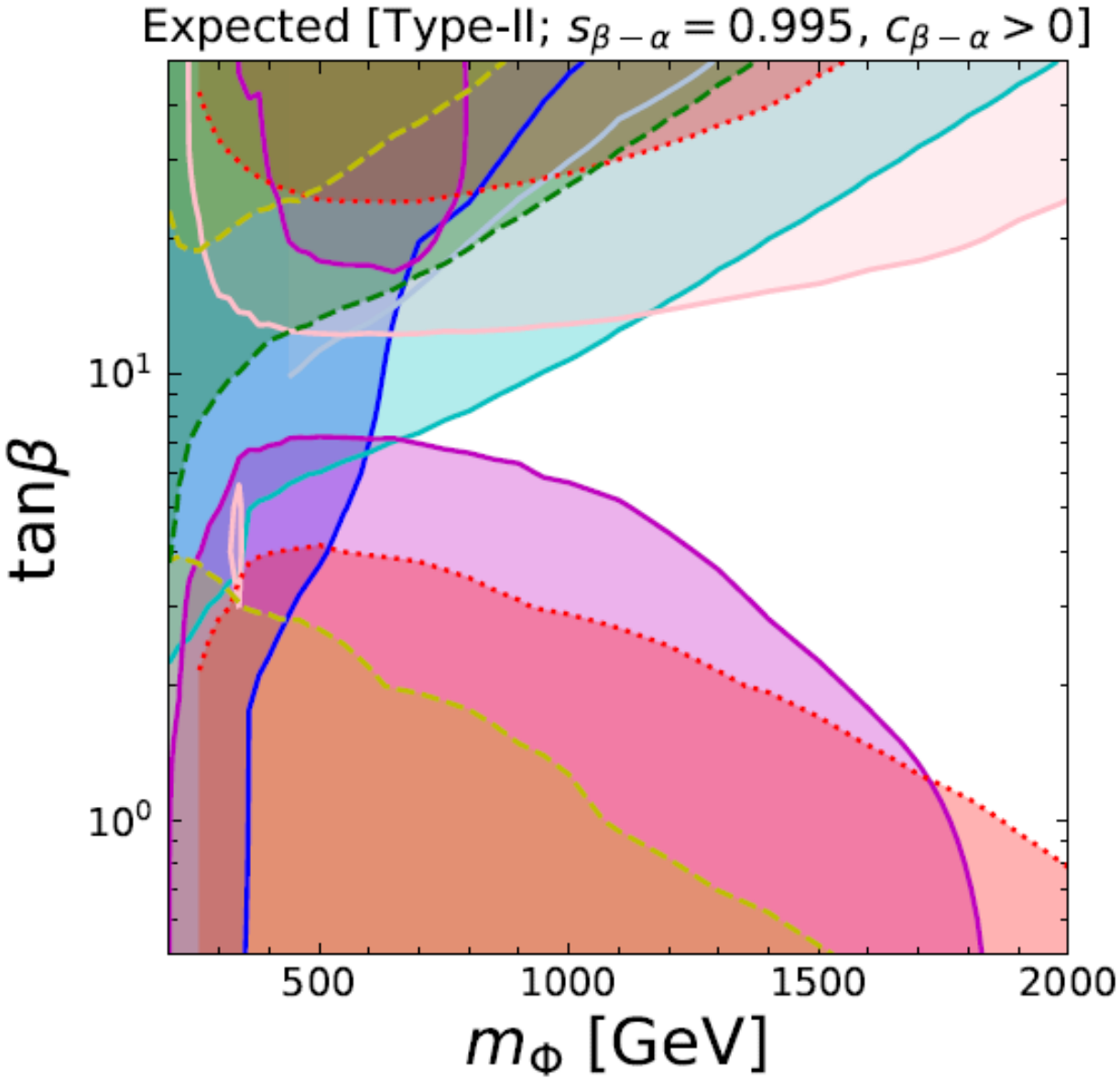
Harlander, Liebler, Mantler

BR:H-COUP v3-β

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Expected Exclusion Limits @ HL-LHC

Aiko, Kanemura, Mawatari, Yagyu (in preparation)



Cross section: SusHi v1-7-0

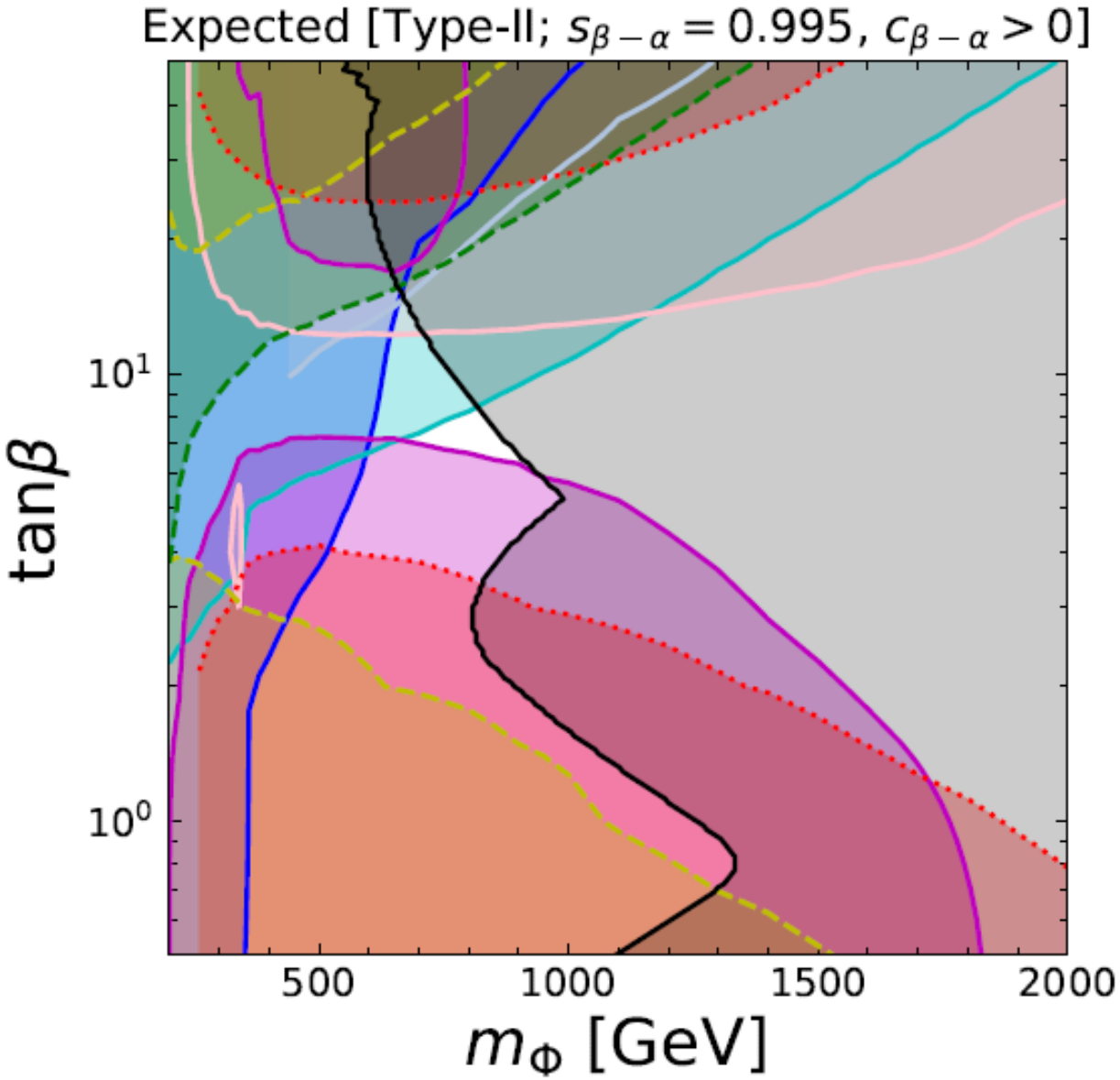
Harlander, Liebler, Mantler

BR:H-COUP v3-β

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Combined Limits from LHC/ILC

Aiko, Kanemura, Mawatari, Yagyu (in preparation)



Cross section: SusHi v1-7-0

Harlander, Liebler, Mantler

BR:H-COUP v3-β

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Indirect:H-COUP v3-β

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

$$\kappa_V = 0.995 \pm 0.0038$$

Aiko, Kanemura, Mawatari, Yagyu (in preparation)

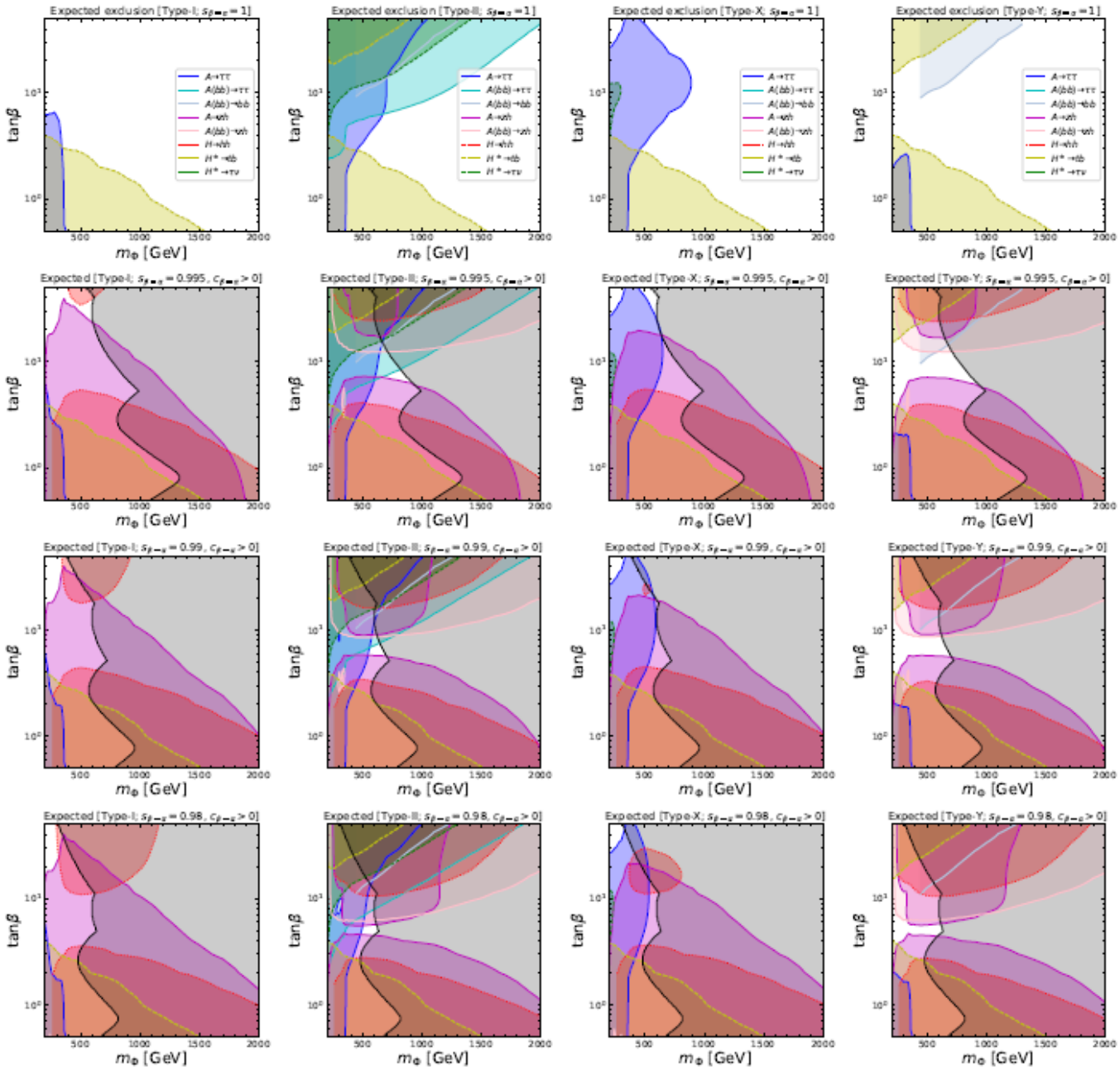
Type-I Type-II Type-X Type-Y

sin(β-α) = 1

sin(β-α) = 0.995

sin(β-α) = 0.99

sin(β-α) = 0.98



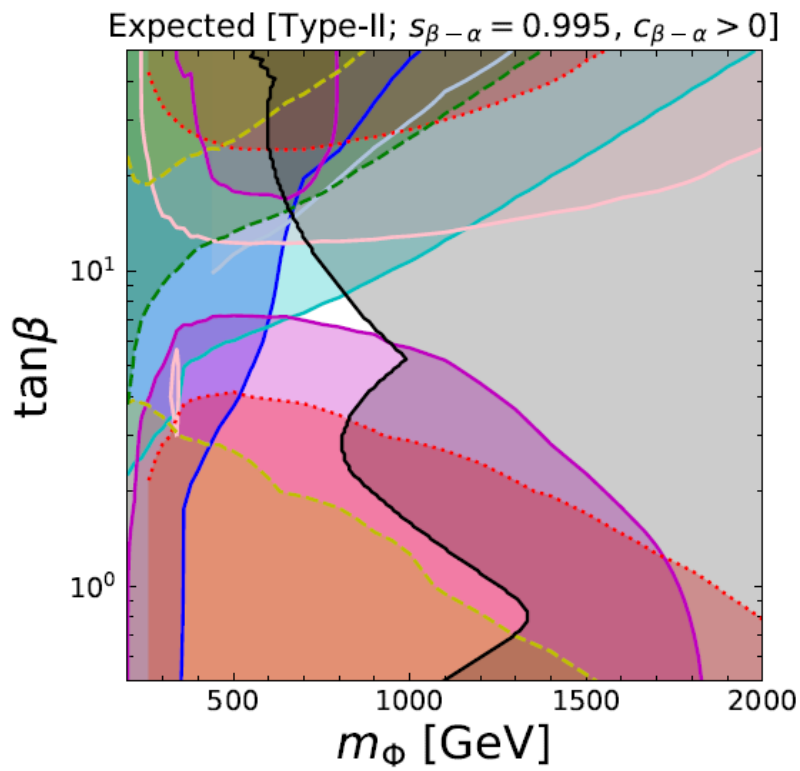
Summary

- Higgs physics is the window of New Physics.

- Scenario of extended Higgs sectors can be classified by alignment and decoupling.

- Wide region of the parameter space can be excluded by the synergy of LHC direct and ILC indirect searches.

- Alignment without decoupling region can be survived, which can be explored by measuring other observables e.g., the triple h coupling.

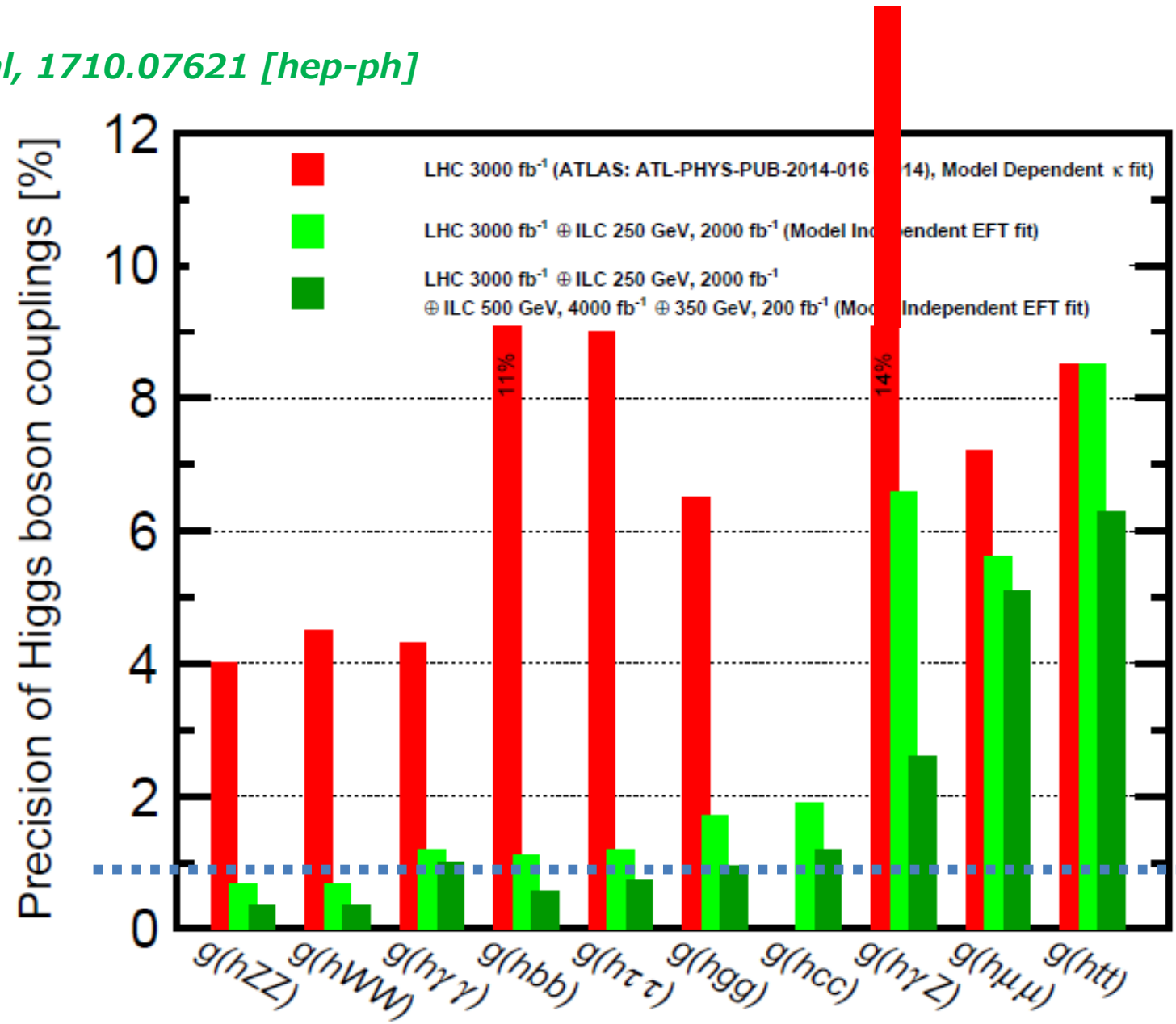


ATLAS-CONF-2018-31 (13 TeV, 80/fb)

Parameter	(a) no BSM
κ_Z	1.07 ± 0.10
κ_W	1.07 ± 0.11
κ_b	$0.97^{+0.24}_{-0.22}$
κ_t	$1.09^{+0.15}_{-0.14}$
κ_τ	$1.02^{+0.17}_{-0.16}$
κ_γ	$1.02^{+0.09}_{-0.12}$
κ_g	$1.00^{+0.12}_{-0.11}$
B_{BSM}	-

$$\kappa_X = \frac{g_{hXX}{}^{\mathrm{Exp}}}{g_{hXX}{}^{\mathrm{SM}}}$$

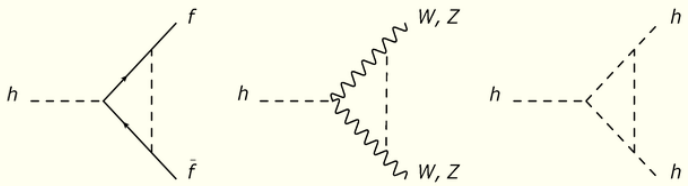
Fujii et al, 1710.07621 [hep-ph]



1%!!

H-COUP

H-COUP



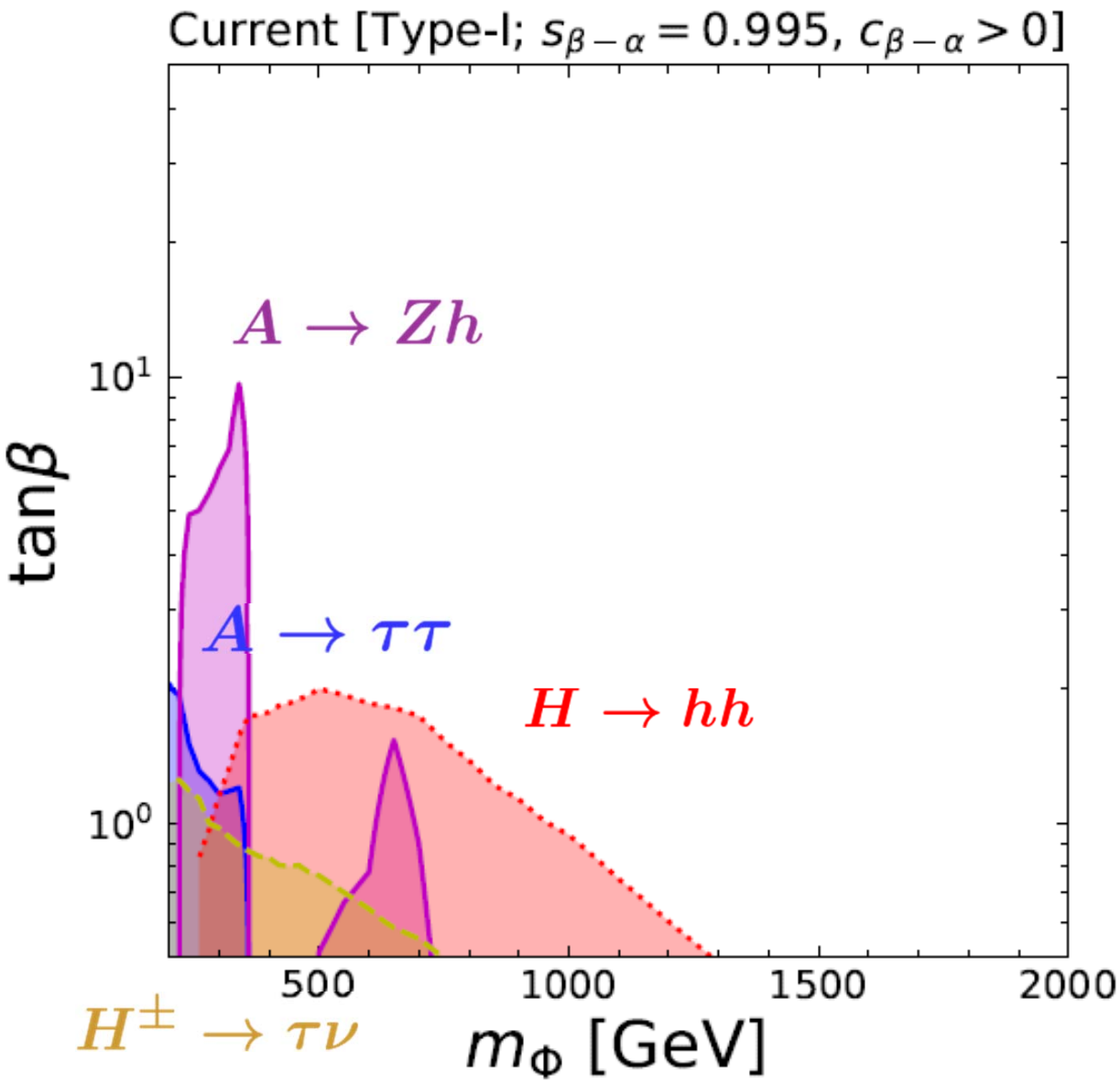
NEW!! H-COUP version 2.3 was released (30 Apr. 2020)

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

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

Current Exclusion Limits @ LHC Run-II



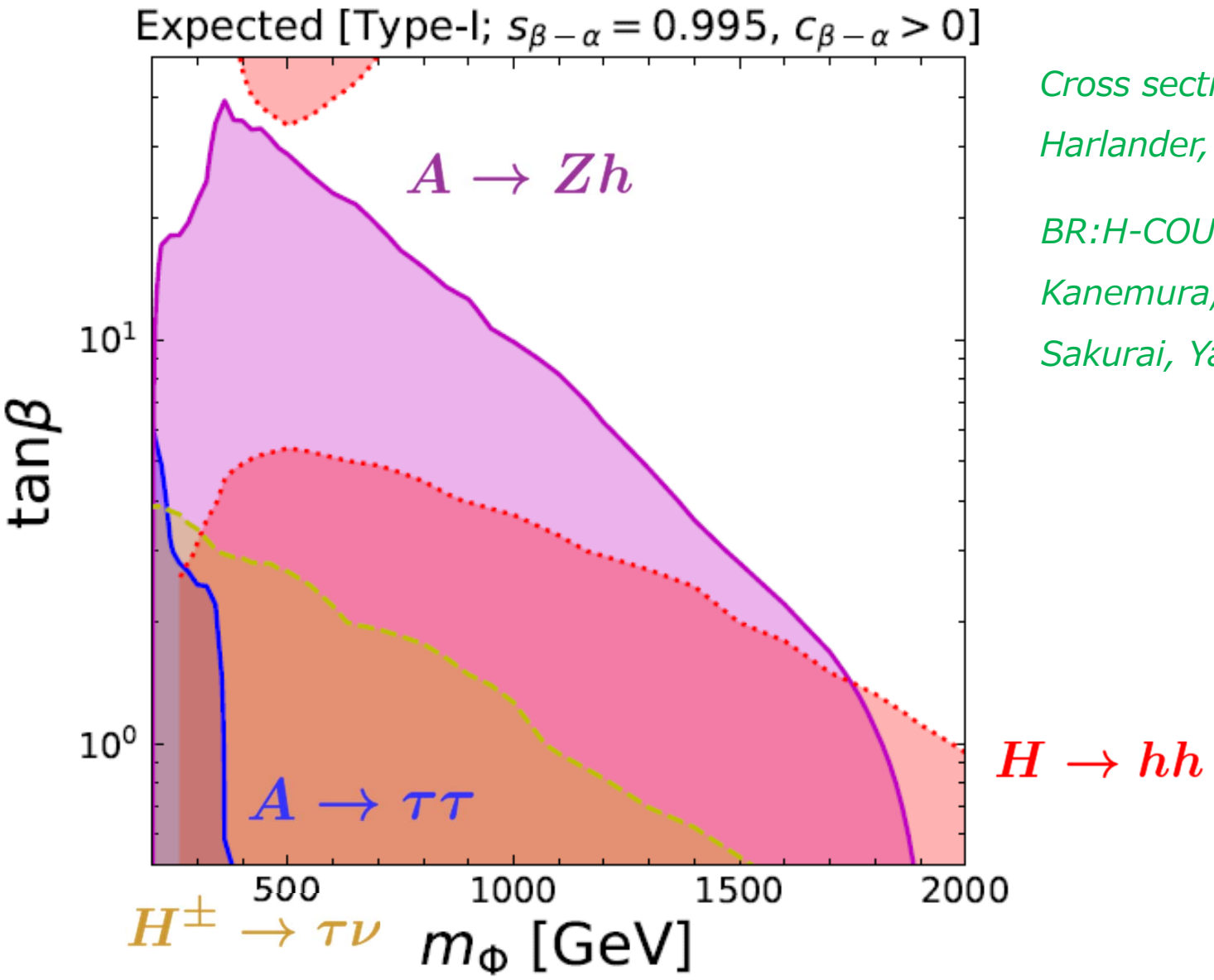
Cross section: SusHi

Harlander, Liebler, Mantler

BR:H-COUP v2

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Expected Exclusion Limits @ HL-LHC



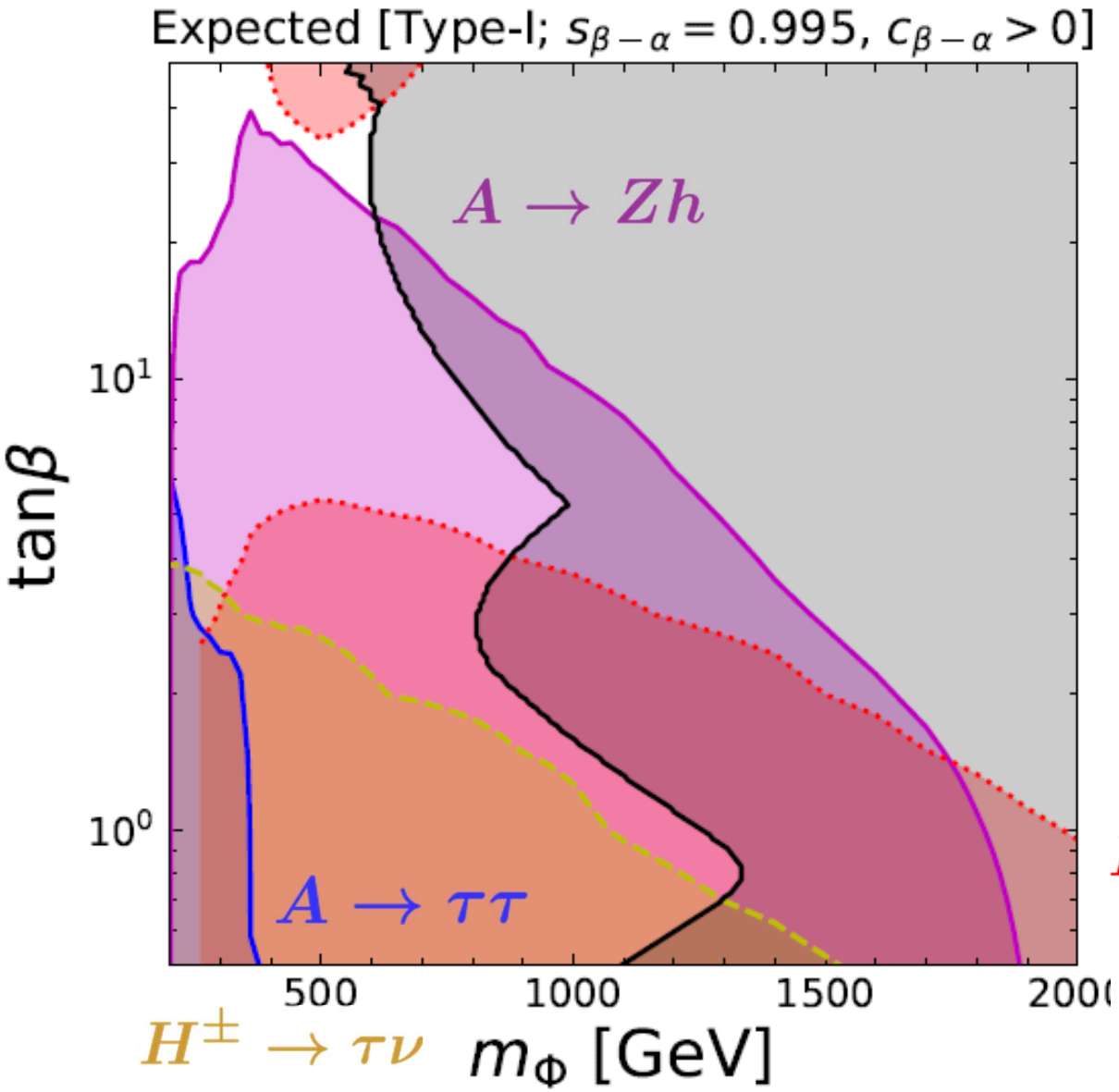
Cross section: SusHi

Harlander, Liebler, Mantler

BR:H-COUP v2

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Combined Limits from LHC/ILC



Cross section: SusHi

Harlander, Liebler, Mantler

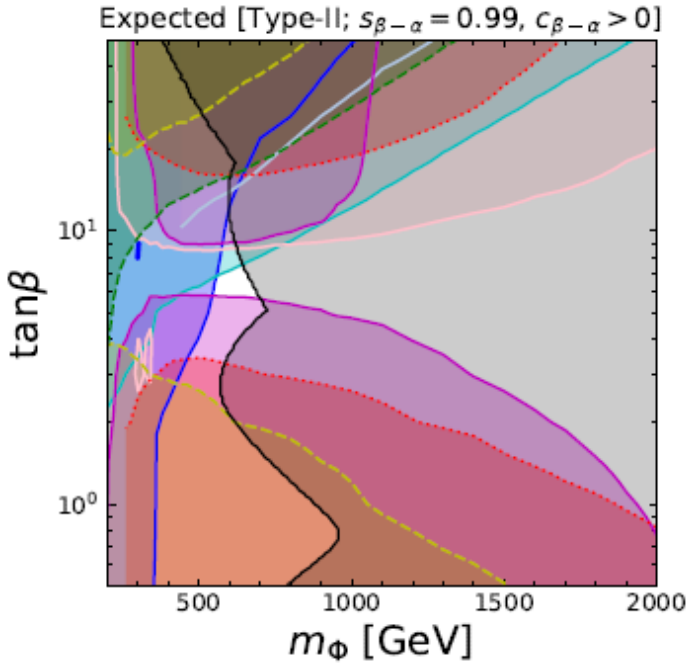
BR:H-COUP v2

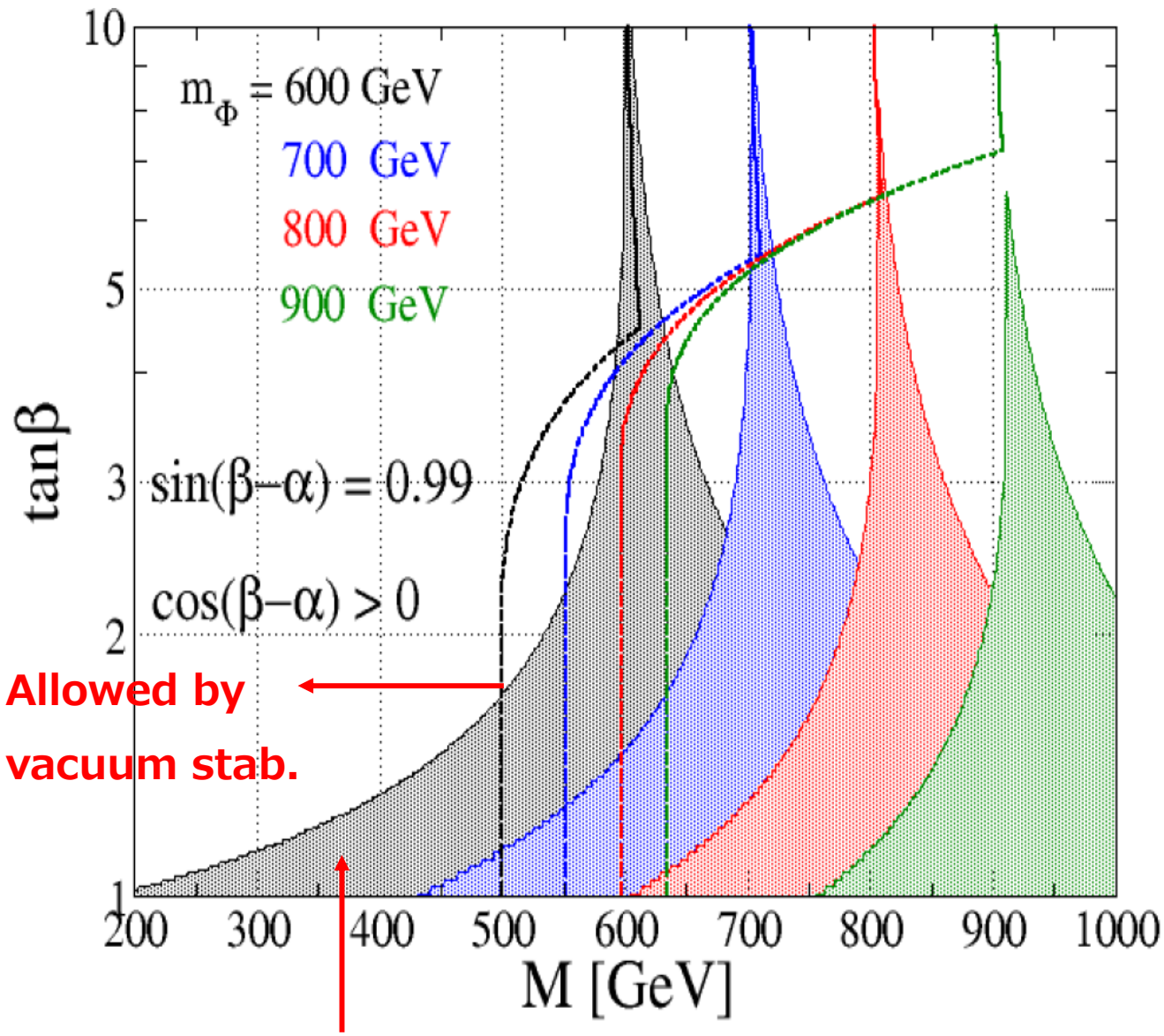
Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

Indirect:H-COUP v2

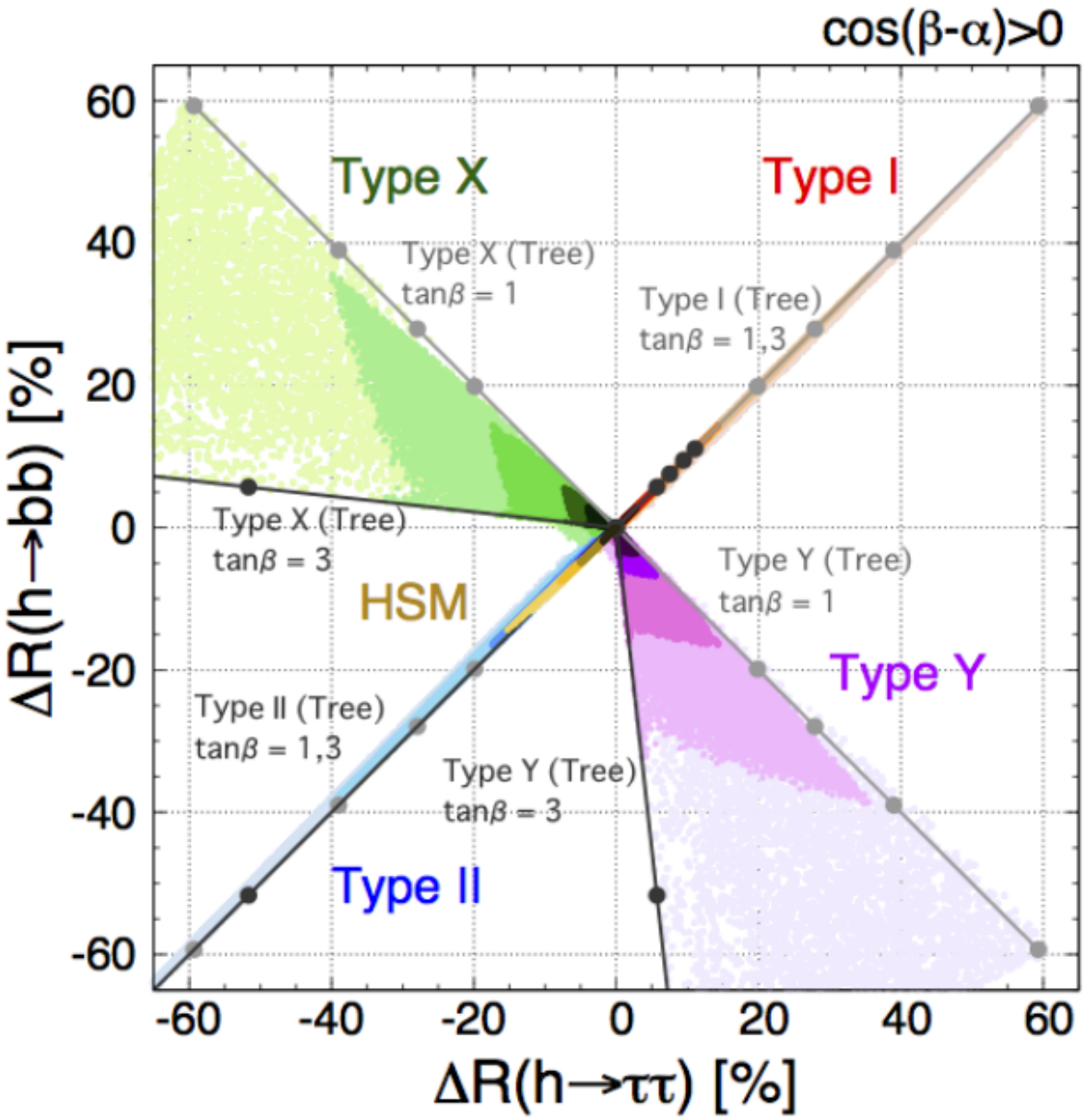
Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

$$\kappa_V = 0.995 \pm 0.0038$$


Expected [Type-II; $s_{\beta-\alpha} = 0.99$, $c_{\beta-\alpha} > 0$]
10^1
10^0
tanβ
500
1000
1500
2000
m_Φ [GeV]


m_Φ = 600 GeV
700 GeV
800 GeV
900 GeV
sin(β−α) = 0.99
cos(β−α) > 0
tanβ
10
5
3
2
1
200
300
400
500
600
700
800
900
1000
M [GeV]
Allowed by
vacuum stab.
Allowed by unitarity

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv: 1803.01456 (PLB)



- LHCWG (H+: NLO)
- SusHi (A, H: N3LO)