

LHC/ILC Synergy for Exploring Extended Higgs Sectors

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Collaboration with

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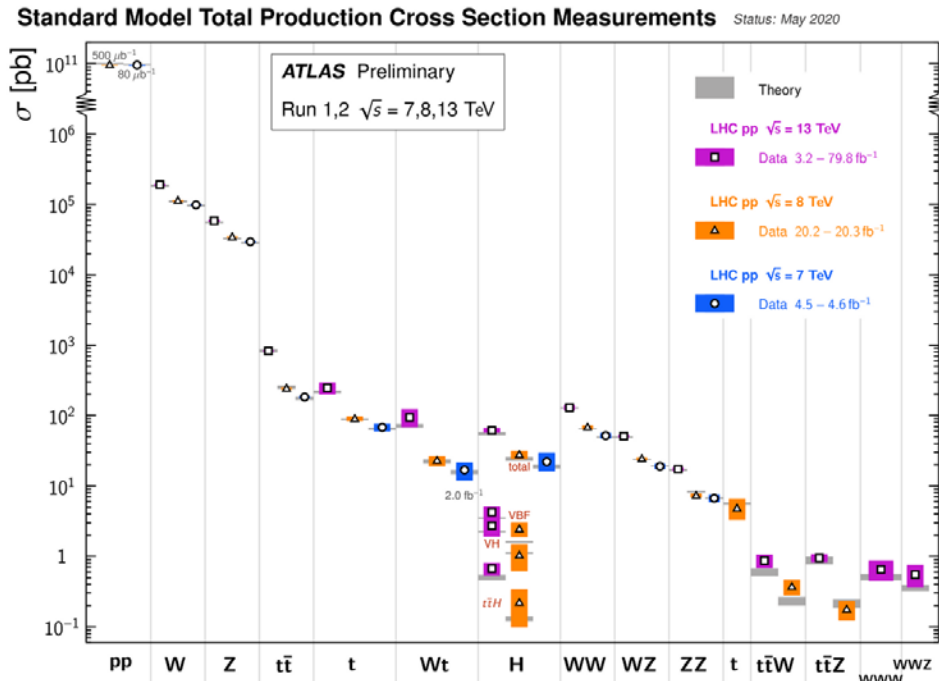
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High Energy Frontier in Particle Physics: LHC and Future Colliders

2020, Oct. 5th, NTU

2 Figs well describing the current status



SM predictions are good agreement.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 8, 13$ TeV

Model	ℓ, γ	Jets †	$E_{\text{T}}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0, e, \mu$	$1 - 4 \text{ J}$	Yes	M_{Pl}	$n = 2$ 1711.02301
	ADD non-resonant $\gamma\gamma$	2γ	-	-	M_{Pl}	$n = 3 \text{ HLZ NLO}$ 1707.04147
	ADD QBH	-	2 J	-	M_{Pl}	$n = 6$ 1703.09127
	ADD BH high Σp_T	$\geq 1, e, \mu$	$\geq 2 \text{ J}$	-	M_{Pl}	$n = 6, M_{\text{Pl}} = 3 \text{ TeV, rot BH}$ 1606.02265
	ADD BH multiplet	-	$\geq 3 \text{ J}$	-	M_{Pl}	$n = 6, M_{\text{Pl}} = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	$G_{KK} \text{ mass}$	$k/M_{\text{Pl}} = 0.1$ 1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	$G_{KK} \text{ mass}$	$k/M_{\text{Pl}} = 1.0$ 1606.02280
	Bulk RS $G_{KK} \rightarrow WV/l\nu q\bar{q}$	$1, e, \mu$	$2 \text{ J} / 1 \text{ J}$	Yes	$G_{KK} \text{ mass}$	$k/M_{\text{Pl}} = 1.0$ 2004.14636
	Bulk RS $G_{KK} \rightarrow tt$	$1, e, \mu$	$\geq 1 \text{ b}, \geq 1 \text{ J} / 2 \text{ J}$	Yes	$G_{KK} \text{ mass}$	$l'/m = 15\%$ 1804.10823
	ZUED / RPP	$1, e, \mu$	$\geq 2 \text{ b}, \geq 3 \text{ J}$	Yes	$KK \text{ mass}$	Tier (1,1), $2\ell(A^{(1,1)} \rightarrow tt) = 1$ 1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2, e, \mu$	-	-	$Z' \text{ mass}$	$n = 2$ 1903.06248
	SSM $Z' \rightarrow \tau\tau$	$2, \tau$	-	-	$Z' \text{ mass}$	$n = 3 \text{ HLZ NLO}$ 1709.07242
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	$Z' \text{ mass}$	$n = 6$ 1805.08299
	Leptophobic $Z' \rightarrow \tau\tau$	$0, e, \mu$	$\geq 1 \text{ b}, \geq 2 \text{ J}$	Yes	$Z' \text{ mass}$	$n = 6$ 2005.05138
	SSM $W' \rightarrow \ell\nu$	$1, e, \mu$	-	Yes	$W' \text{ mass}$	$l'/m = 1.2\%$ 1906.05609
	SSM $W' \rightarrow \tau\nu$	$1, \tau$	-	Yes	$W' \text{ mass}$	$n = 6, M_{\text{Pl}} = 3 \text{ TeV, rot BH}$ 1801.06992
	HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	$1, e, \mu$	$2 \text{ J} / 1 \text{ J}$	Yes	$W' \text{ mass}$	$k/M_{\text{Pl}} = 1.0$ 2004.14636
	HVT $V' \rightarrow WV \rightarrow qq\bar{q}\bar{q}$ model B	$0, e, \mu$	2 J	-	$V' \text{ mass}$	$k/M_{\text{Pl}} = 1.0$ 1906.08589
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	$V' \text{ mass}$	$l'/m = 15\%$ 1712.06518
	HVT $W' \rightarrow WH$ model B	$0, e, \mu$	$\geq 1 \text{ b}, \geq 2 \text{ J}$	Yes	$V' \text{ mass}$	$n = 6, M_{\text{Pl}} = 3 \text{ TeV, rot BH}$ 1801.06992
CI	CI $qq\bar{q}\bar{q}$	-	2 J	-	A	$m(N_{\text{H}}) = 0.5 \text{ TeV, } g_L = g_R$ 1703.09127
	CI $\ell\ell q\bar{q}$	$2, e, \mu$	-	-	A	$n = 2$ 1711.02301
	CI $t\bar{t}t\bar{t}$	$\geq 1, e, \mu$	$\geq 1 \text{ b}, \geq 1 \text{ J}$	Yes	A	$n = 6$ 1811.02305
DM	Axial-vector mediator (Dirac DM)	$0, e, \mu$	$1 - 4 \text{ J}$	Yes	m_{DM}	$g_{\text{DM}} = 0.25, g_{\text{H}} = 1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	Colored scalar mediator (Dirac DM)	$0, e, \mu$	$1 - 4 \text{ J}$	Yes	m_{DM}	$g = 1.0, m(\chi) = 1 \text{ GeV}$ 1711.03301
	VV $_{\text{UV}}$ EFT (Dirac DM)	$0, e, \mu$	$1 \text{ J}, \leq 1 \text{ J}$	Yes	M_{Pl}	$m(\chi) < 150 \text{ GeV}$ 1606.02272
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	$0 - 1, e, \mu$	$1 \text{ b}, 0 - 1 \text{ J}$	Yes	m_{DM}	$y = 0.4, i = 0.2, m(\chi) = 10 \text{ GeV}$ 1812.08743
LQ	Scalar LQ 1 st gen	$1, 2, e, \mu$	$\geq 2 \text{ J}$	Yes	$LQ \text{ mass}$	$\beta = 1$ 1902.00377
	Scalar LQ 2 nd gen	$1, 2, e, \mu$	$\geq 2 \text{ J}$	Yes	$LQ \text{ mass}$	$\beta = 1$ 1902.00377
	Scalar LQ 3 rd gen	$2, \tau$	2 b	-	$LQ \text{ mass}$	$2\ell(LQ_{\text{S}}^* \rightarrow b\bar{r}) = 1$ 1902.08103
	Scalar LQ 3 rd gen	$0 - 1, e, \mu$	2 b	Yes	$LQ \text{ mass}$	$2\ell(LQ_{\text{S}}^* \rightarrow \tau\bar{r}) = 0$ 1902.08103
Heavy quarks	VLO $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	$T \text{ mass}$	SU(2) doublet 1808.02343
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	$B \text{ mass}$	SU(2) doublet 1807.11883
	VLO $T_{3/2} T_{3/2} \rightarrow Wt + X$	$2(SS) \geq 3, e, \mu \geq 1 \text{ b}, \geq 1 \text{ J}$	Yes	Yes	$T_{3/2} \text{ mass}$	$2\ell(T_{3/2} \rightarrow Wt) = 1, c(T_{3/2} W) = 1$ 1812.07343
	VLO $Y \rightarrow Wb + X$	$1, e, \mu$	$\geq 1 \text{ b}, \geq 1 \text{ J}$	Yes	$Y \text{ mass}$	$2\ell(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$ 1812.07343
	VLO $B \rightarrow Hb + X$	$0, e, \mu, 2 \gamma$	$\geq 1 \text{ b}, \geq 1 \text{ J}$	Yes	$B \text{ mass}$	$x_{\text{DM}} = 0.5$ 1509.04261
	VLO $QQ \rightarrow WqWq$	$1, e, \mu$	$\geq 4 \text{ J}$	Yes	$Q \text{ mass}$	$x_{\text{DM}} = 0.5$ 1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 J	-	$q^* \text{ mass}$	only u^* and d^* , $A = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	1 J	-	$q^* \text{ mass}$	only u^* and d^* , $A = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow b\gamma$	$3, e, \mu$	$1 \text{ b}, 1 \text{ J}$	-	$b^* \text{ mass}$	$2\ell(T_{3/2} \rightarrow Wt) = 1, c(T_{3/2} W) = 1$ 1805.02929
	Excited lepton ℓ^*	-	-	-	$\ell^* \text{ mass}$	$2\ell(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$ 1411.2921
	Excited lepton ν^*	$3, e, \mu, \tau$	-	-	$\nu^* \text{ mass}$	$A = 1.6 \text{ TeV}$ 1411.2921
Other	Type III Seesaw	$1, e, \mu$	$\geq 2 \text{ J}$	Yes	$N \text{ mass}$	$m(W_{\text{H}}) = 4.1 \text{ TeV, } g_L = g_R$ 1809.11105
	LRSM Majorana ν	$2, \mu$	2 J	-	$N \text{ mass}$	$n = 6$ 1710.09748
	Higgs triplet $H^{1,2,3} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	$H^{1,2,3} \text{ mass}$	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\ell) = 1$ 1411.2921
	Higgs triplet $H^{1,2,3} \rightarrow \ell\tau$	$3, e, \mu, \tau$	-	-	$H^{1,2,3} \text{ mass}$	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\tau) = 1$ 1411.2921
	Multi-charged particles	-	-	-	multi-charged particle mass	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\tau) = 1$ 1812.07343
	Magnetic monopoles	-	-	-	monopole mass	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\tau) = 1$ 1905.10130
Other	Excited quark $q^* \rightarrow qg$	-	2 J	-	$q^* \text{ mass}$	only u^* and d^* , $A = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	1 J	-	$q^* \text{ mass}$	only u^* and d^* , $A = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow b\gamma$	$3, e, \mu$	$1 \text{ b}, 1 \text{ J}$	-	$b^* \text{ mass}$	$2\ell(T_{3/2} \rightarrow Wt) = 1, c(T_{3/2} W) = 1$ 1805.02929
	Excited lepton ℓ^*	-	-	-	$\ell^* \text{ mass}$	$2\ell(Y \rightarrow Wb) = 1, c_Y(Wb) = 1$ 1411.2921
	Excited lepton ν^*	$3, e, \mu, \tau$	-	-	$\nu^* \text{ mass}$	$A = 1.6 \text{ TeV}$ 1411.2921
	Type III Seesaw	$1, e, \mu$	$\geq 2 \text{ J}$	Yes	$N \text{ mass}$	$m(W_{\text{H}}) = 4.1 \text{ TeV, } g_L = g_R$ 1809.11105
	LRSM Majorana ν	$2, \mu$	2 J	-	$N \text{ mass}$	$n = 6$ 1710.09748
	Higgs triplet $H^{1,2,3} \rightarrow \ell\ell$	$2, 3, 4, e, \mu$ (SS)	-	-	$H^{1,2,3} \text{ mass}$	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\ell) = 1$ 1411.2921
	Higgs triplet $H^{1,2,3} \rightarrow \ell\tau$	$3, e, \mu, \tau$	-	-	$H^{1,2,3} \text{ mass}$	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\tau) = 1$ 1411.2921
	Multi-charged particles	-	-	-	multi-charged particle mass	DY production, $2\ell(H^{1,2,3} \rightarrow \ell\tau) = 1$ 1812.07343

*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter J (J).

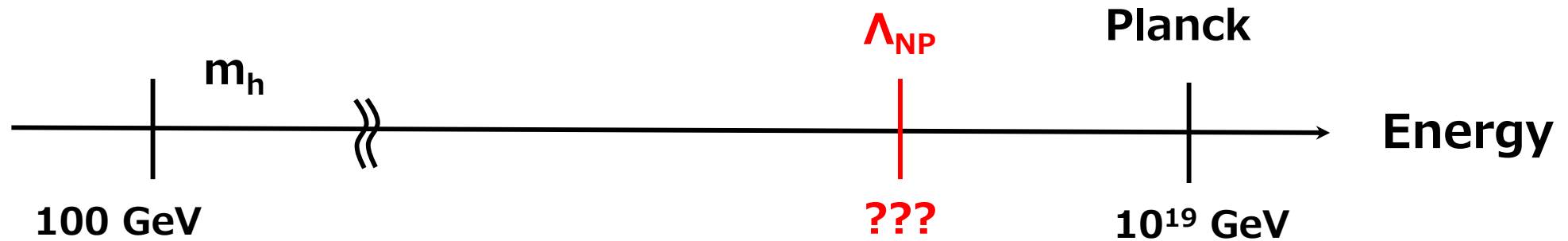
New particles have not been observed.

Q. Is the SM enough?

A. Of course, **No!**

Higgs as a problematic sector

- We expect that a **new scale** appears at high energies.



Λ_{NP} = grand unification, seesaw, inflation scale, etc.

$$m_h^2 \sim \frac{\Lambda_{NP}^2}{16\pi^2} \sim \frac{M_{NP}^2}{16\pi^2} \gg (125 \text{ GeV})^2$$

- We need a new symmetry to stabilize the Higgs mass to be 125 GeV.

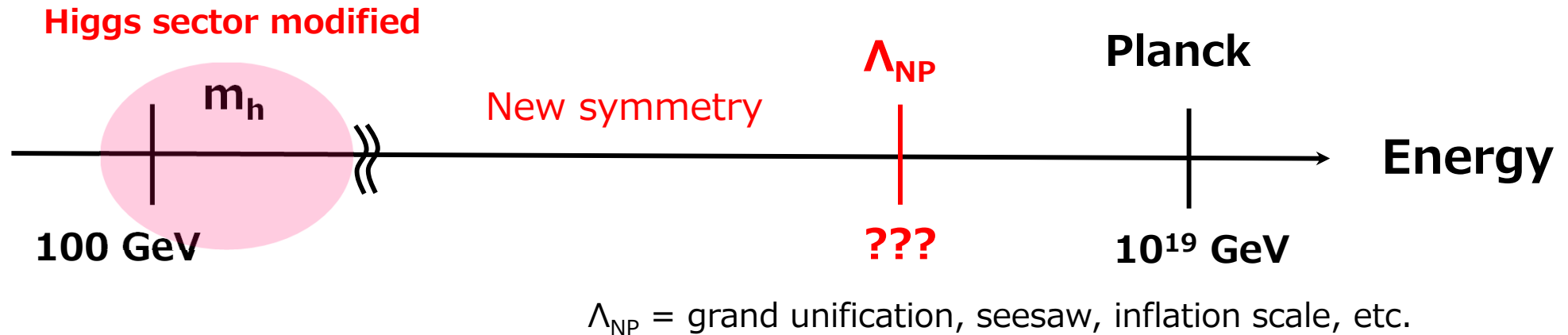
E.g., Supersymmetry

Chiral symmetry (Composite Higgs)

Gauge symmetry (Gauge Higgs unification)

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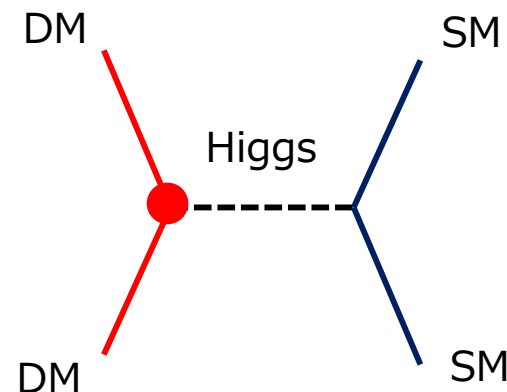
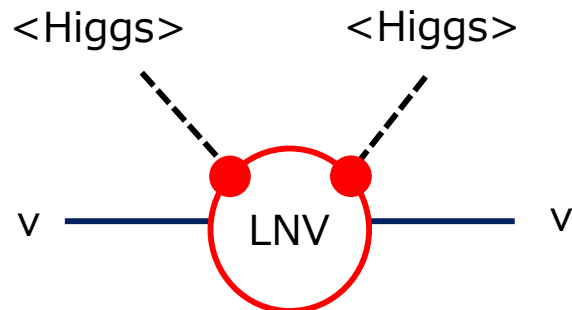
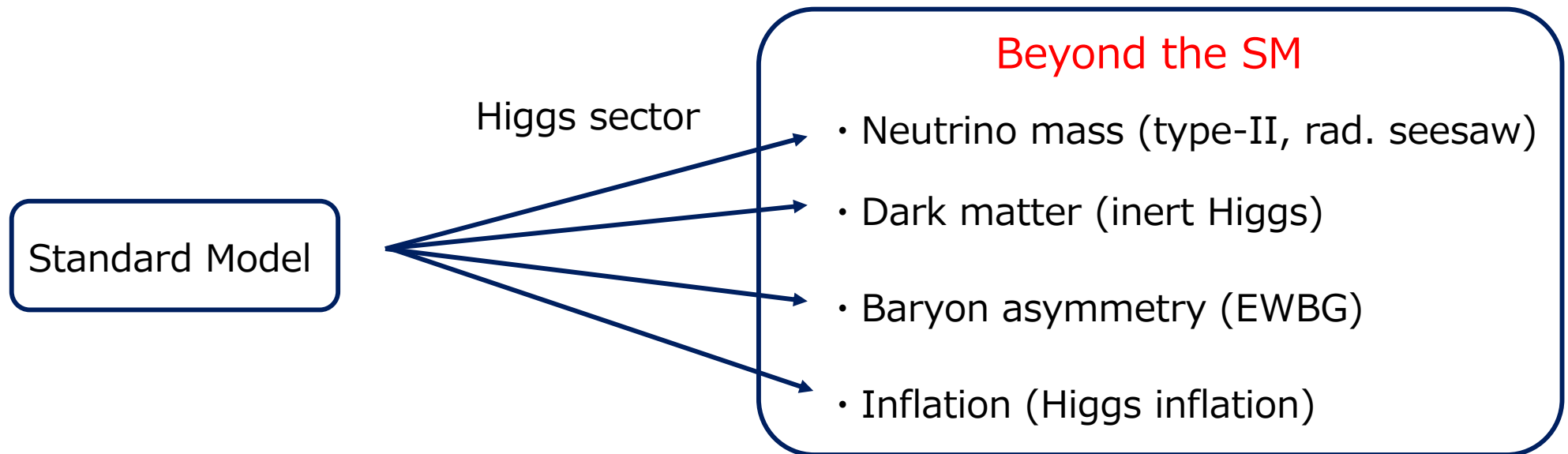
E.g., Supersymmetry

Chiral symmetry (Composite Higgs)

Gauge symmetry (Gauge Higgs unification)

Higgs as a portal to BSM

- The Higgs sector can be a **portal** to a BSM sector.



Higgs as a probe of New Physics

New Physics at High Energy Frontier

Standard Model

Higgs Physics

Direct
search
@LHC

Indirect
search
@ILC



Keywords: Alignment/Decoupling

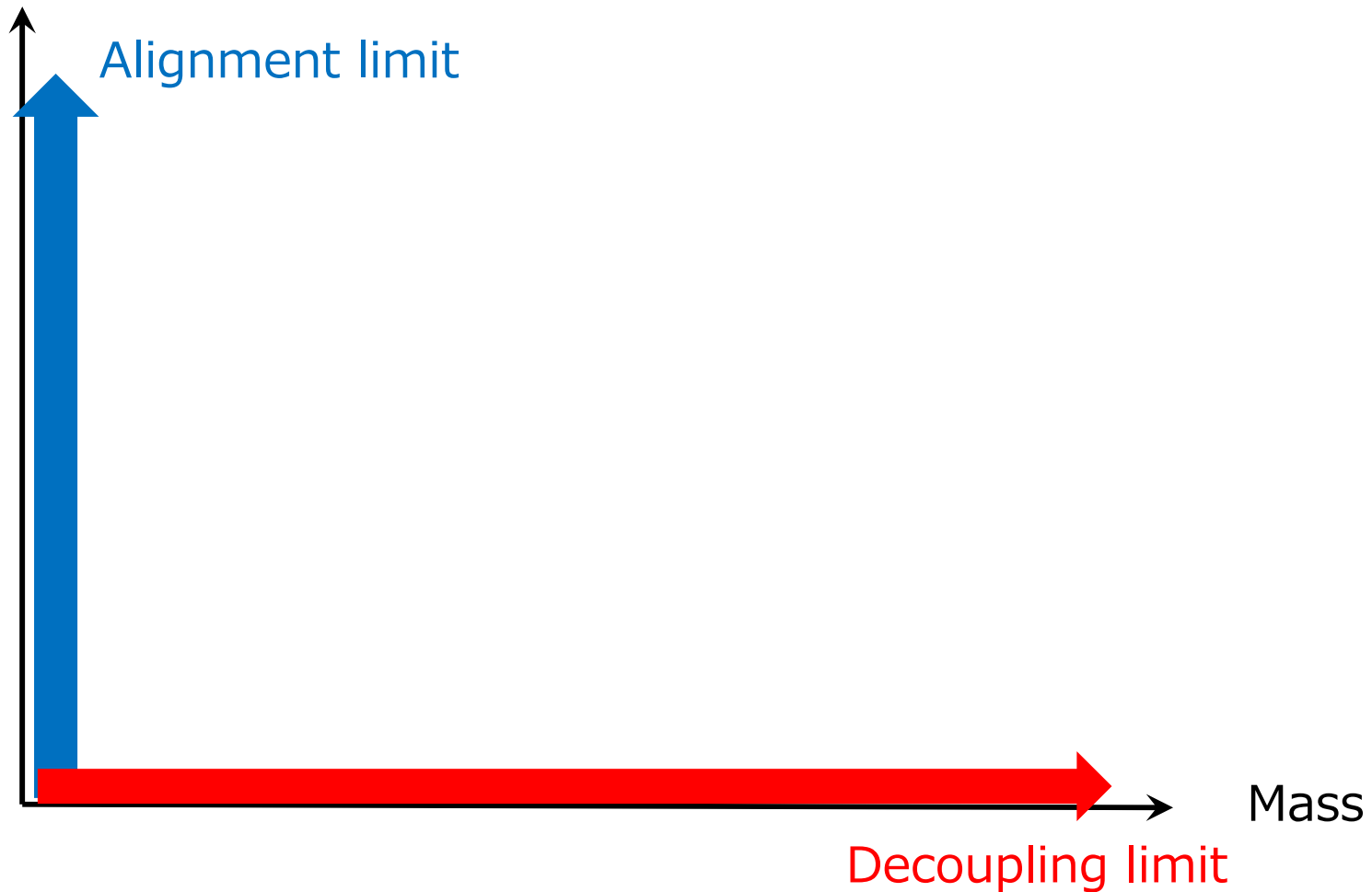
SM-likeness of $h(125)$



Mass

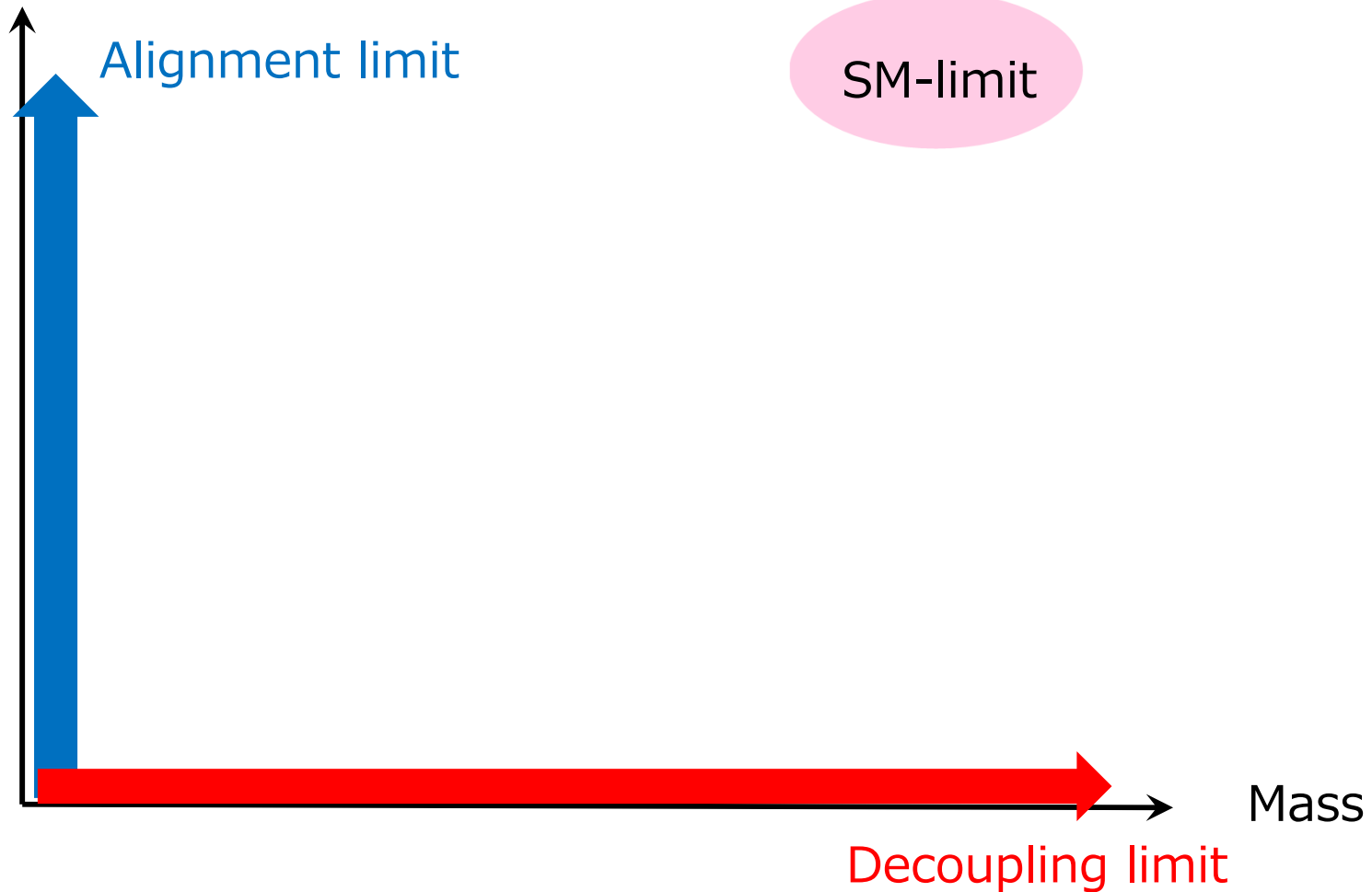
Keywords: Alignment/Decoupling

SM-likeness of $h(125)$



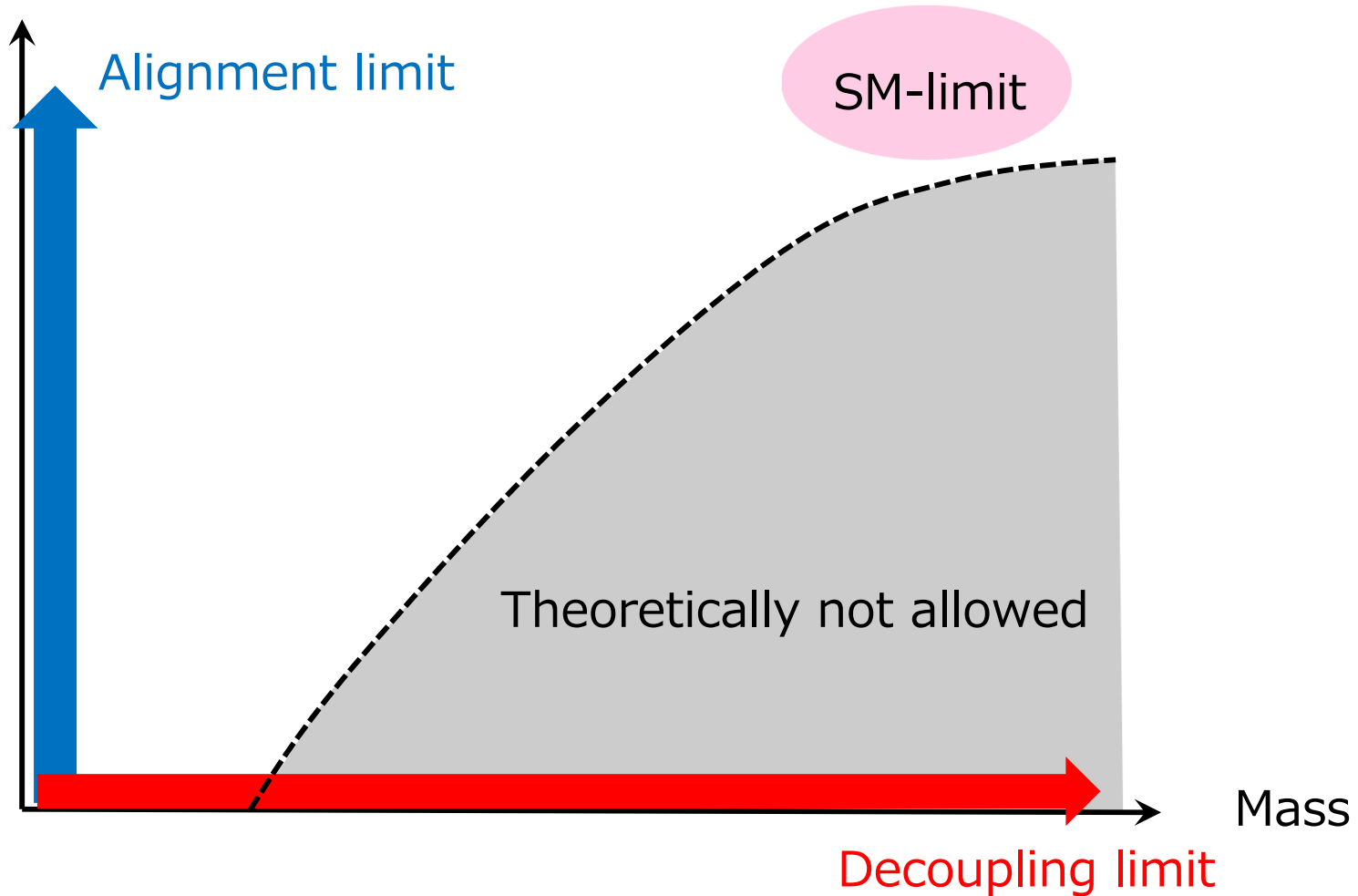
Keywords: Alignment/Decoupling

SM-likeness of $h(125)$



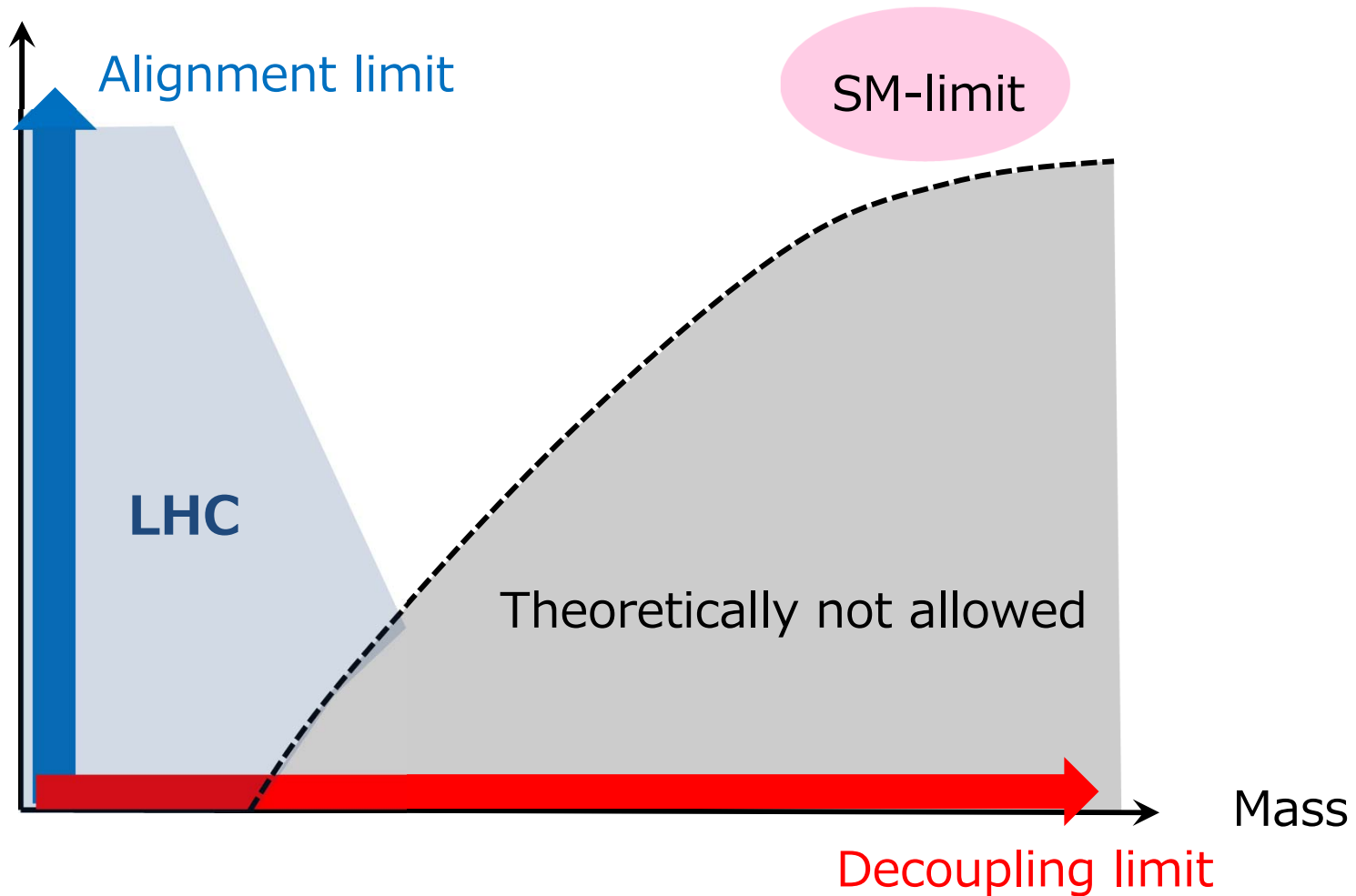
Keywords: Alignment/Decoupling

SM-likeness of $h(125)$



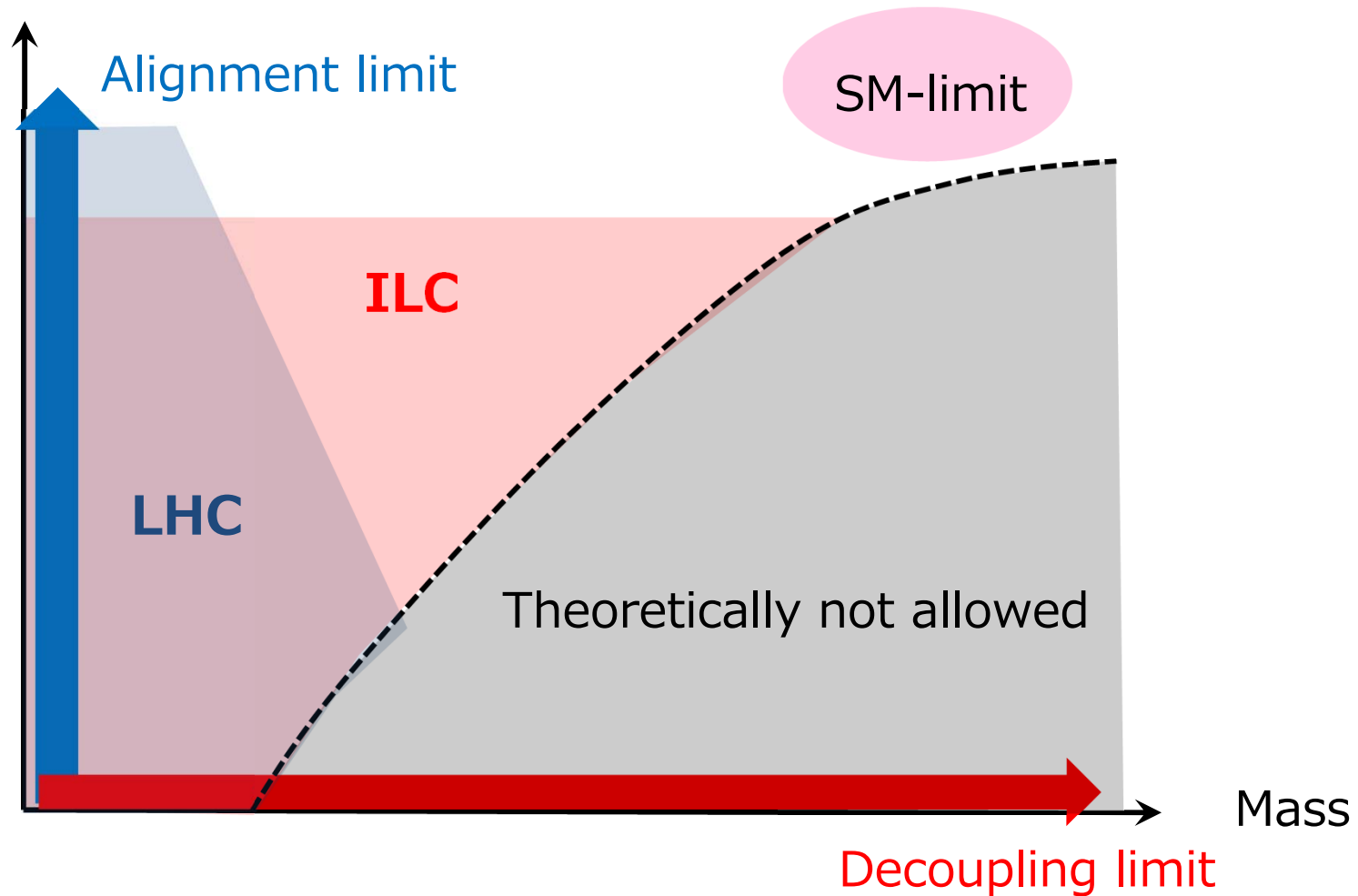
Keywords: Alignment/Decoupling

SM-likeness of $h(125)$



Keywords: Alignment/Decoupling

SM-likeness of $h(125)$



Synergy b/w LHC and ILC searches is important!

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I. Introduction

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2 Higgs doublet models

□ Simple extension of the Higgs sector:

$$\Phi_{\text{SM}} \rightarrow \Phi_1, \Phi_2$$

□ Variations of the 2HDM

$$h_{\text{SM}} \rightarrow h, H, A, H^\pm$$

CP { CP-conserving 2HDM
CP-violating 2HDM

Z₂ { Hardly-broken (General 2HDM)
Softly-broken (Type-I, Type-II, Type-X, Type-Y)
Unbroken (Inert doublet model)

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

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

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

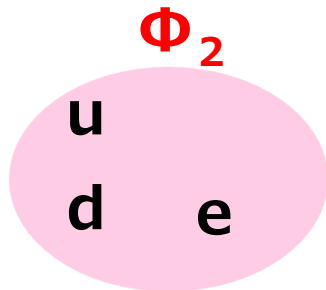
4 types of Yukawa interactions

In general, four independent types of Yukawa interactions are allowed in this setup.

Barger, Hewett, Phillips, PRD41 (1990)

Grossman, NPB426 (1994)

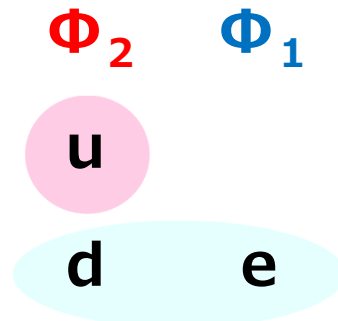
Type-I



- ν 2HDM

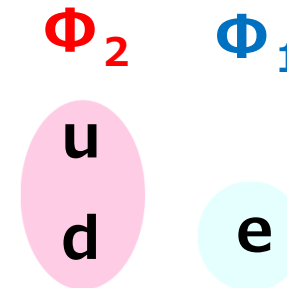
Ma, PRL86 (2001)

Type-II



-MSSM

**Type-X
(Leptophilic)**

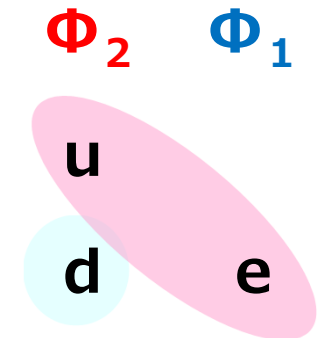


-Muon $g-2$

Broggio et al. JHEP1411 (2014)

Abe, Sato, KY, JHEP1507 (2015)

**Type-Y
(Flipped)**



Alignment/Decoupling in the 2HDM

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

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

NG boson

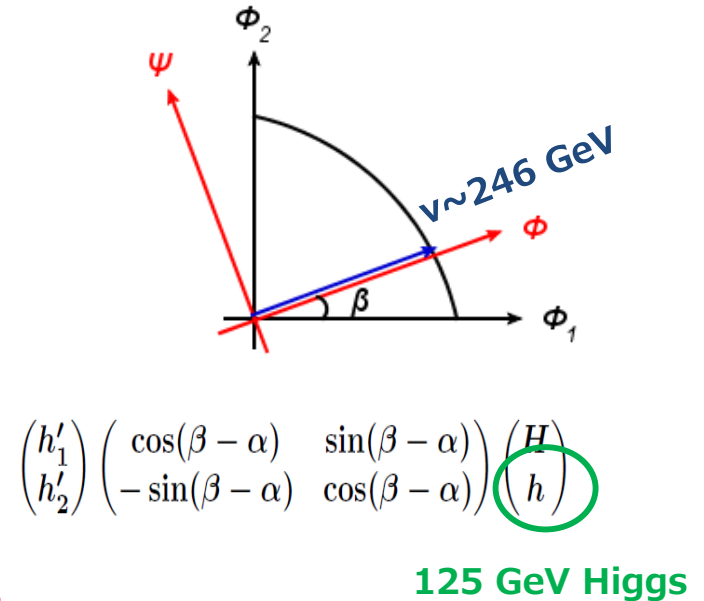
$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h'_1 + v + iG^0) \end{bmatrix}$

CP-even Higgs

Charged Higgs

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

CP-odd 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: $M^2 \rightarrow \infty$

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

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

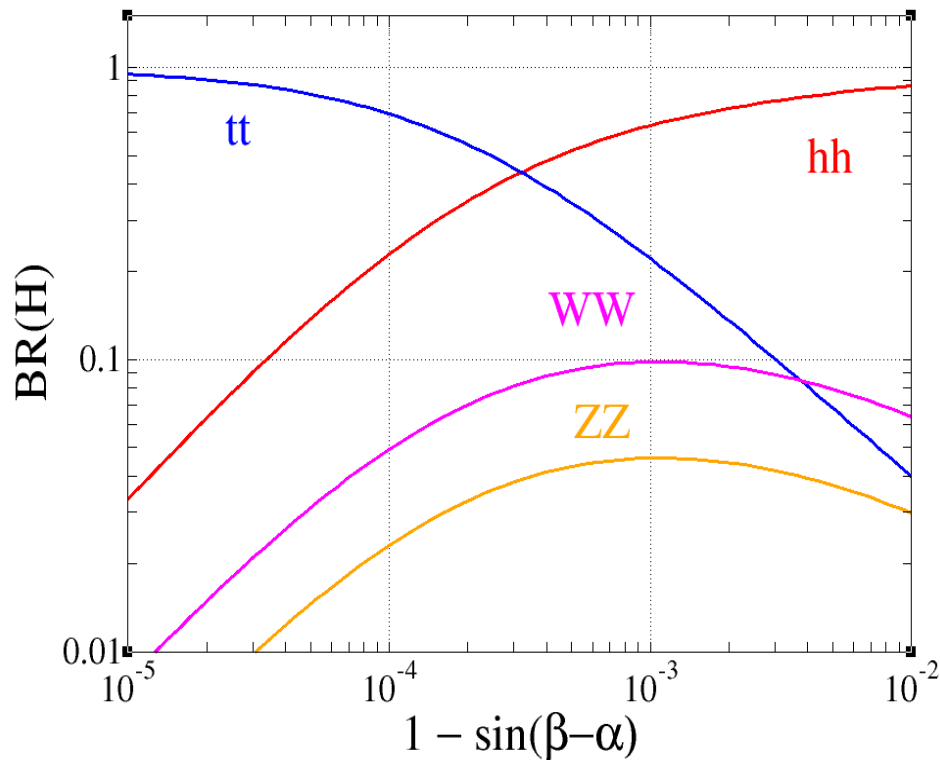
-h behaves like the SM Higgs boson.

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

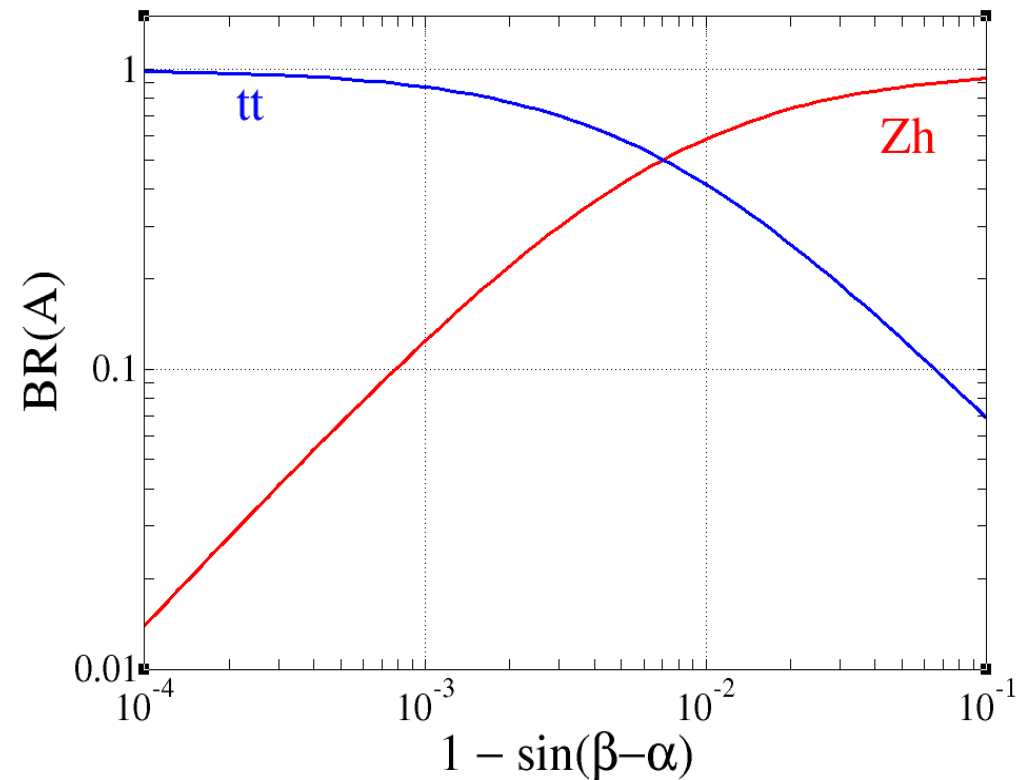
(Non) alignment in the 2HDM

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

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



Alignment limit



NLO EW corr. to $H \rightarrow hh$:

Krause, Muhlleitner, Santos, Ziesche (2016)

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

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Decoupling without alignment?

Q. Can we take $M \rightarrow \infty$ with $\sin(\beta-\alpha) \neq 1$?

A. No.

$$m_h^2 = \lambda v^2 + \underbrace{\cos^2(\beta - \alpha) M^2}_{\text{This term becomes huge when } M \gg v \text{ and } \sin(\beta-\alpha) \neq 1} = (125 \text{ GeV})^2$$



This term becomes huge when $M \gg v$ and $\sin(\beta-\alpha) \neq 1$

This term should also be huge to keep 125 GeV $\rightarrow$ unitarity violation

The upper limit on M ($\sim 2^{\text{nd}}$ Higgs scale) appears when $\sin(\beta-\alpha) \neq 1$.



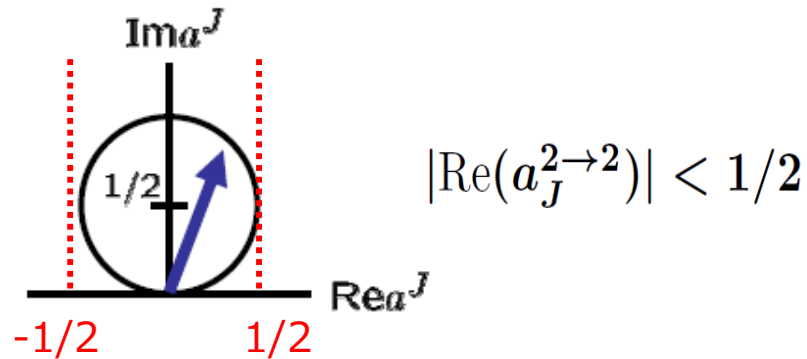
ILC can extract it from precise measurements of h couplings

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

Unitarity & vacuum stability bounds

Lee, Quigg, Thacker (1977)

□ Perturbative unitarity



In the 2HDM, there are 12 a_0 .

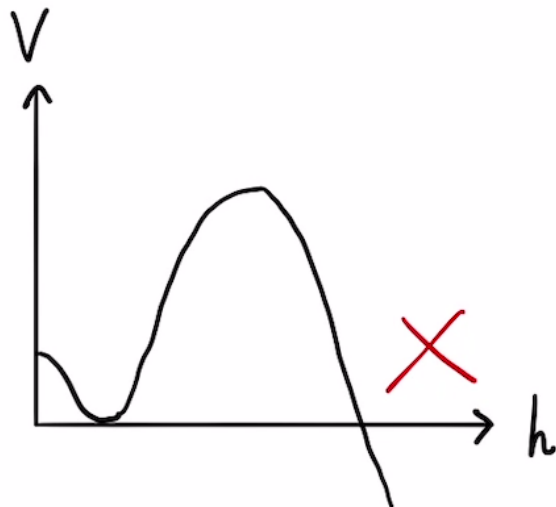


$M \gg m_\phi$ or $M \ll$ is disfavored.

Cf. $m_\phi^2 \sim M^2 + \lambda' v^2$

$$a_0 = \begin{array}{c} w_l^+ \quad w_l^+ \\ \diagdown \quad \diagup \\ \text{---} \text{---} \text{---} \\ \diagup \quad \diagdown \\ w_l^- \quad w_l^- \end{array} \Rightarrow_{E \rightarrow \infty} \begin{array}{c} \zeta^+ \quad \zeta^+ \\ \diagdown \quad \diagup \\ \text{---} \text{---} \text{---} \\ \diagup \quad \diagdown \\ \zeta^- \quad \zeta^- \end{array} = \frac{m_h^2}{8\pi v^2} \quad (\text{SM})$$

□ Vacuum stability (bounded from below)



Deshpande, Ma (1978)

Nie, Sher (1999)

Kanemura, Kasai, Okada (1999)

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \min(0, \lambda_4 \pm \lambda_5) > 0$$



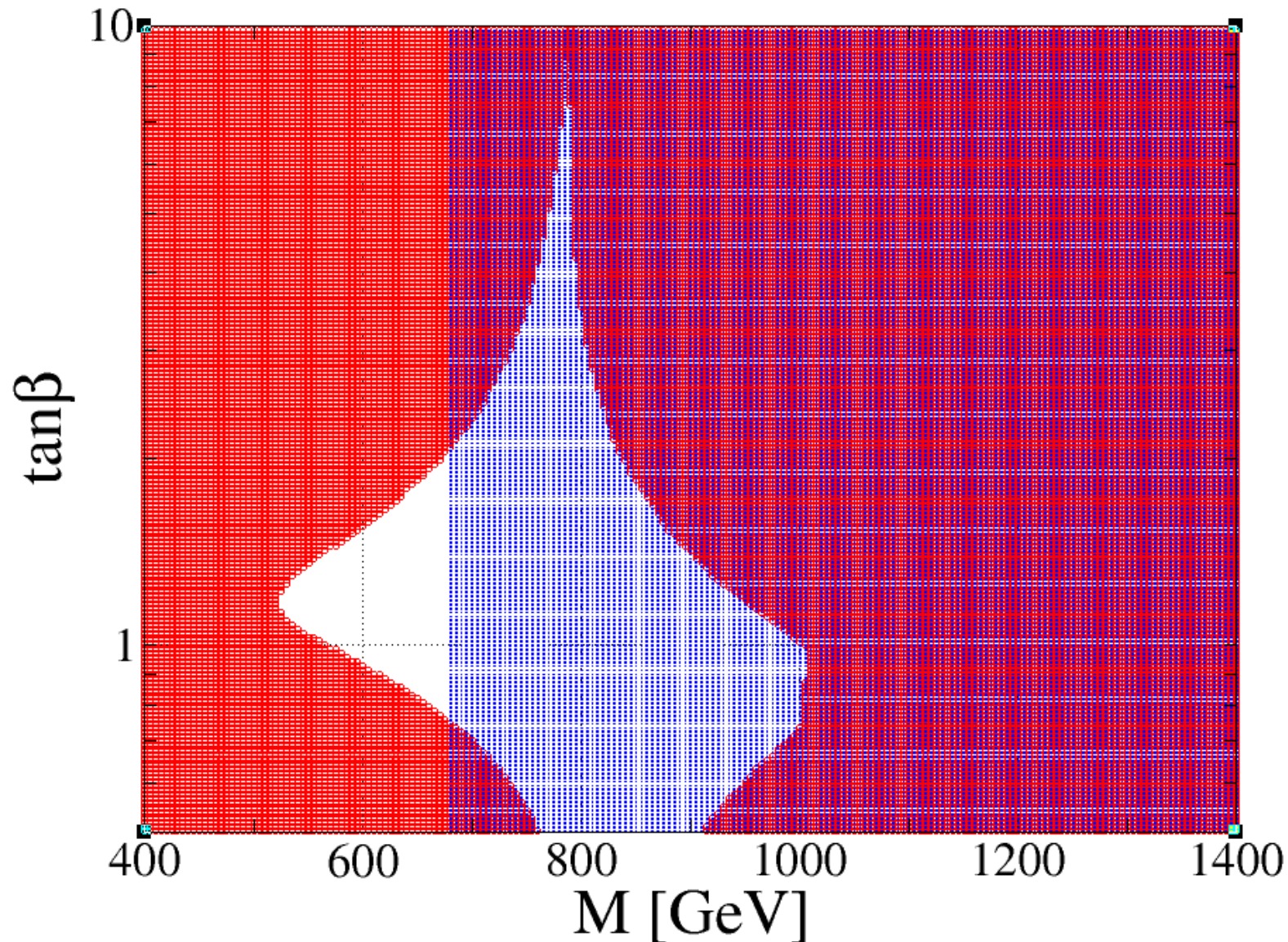
$M > m_\phi$ is disfavored.

Cf. $m_\phi^2 \sim M^2 + \lambda' v^2$

$$m_\phi = 800 \text{ GeV}, \sin(\beta-\alpha) = 0.995$$

Excluded by the unitary bound

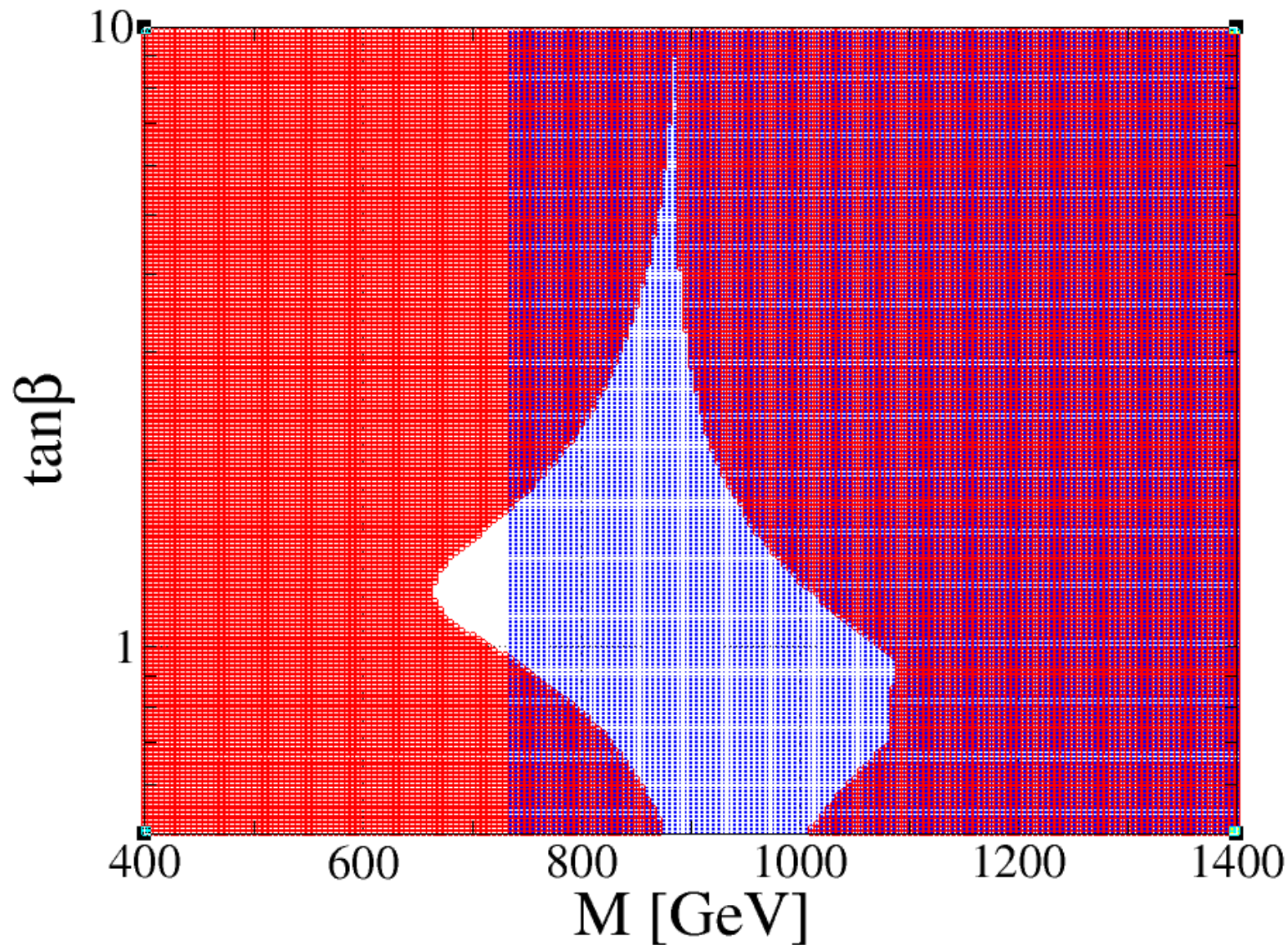
Excluded by the vacuum stability bound



$$m_\phi = 900 \text{ GeV}, \sin(\beta-\alpha) = 0.995$$

Excluded by the unitary bound

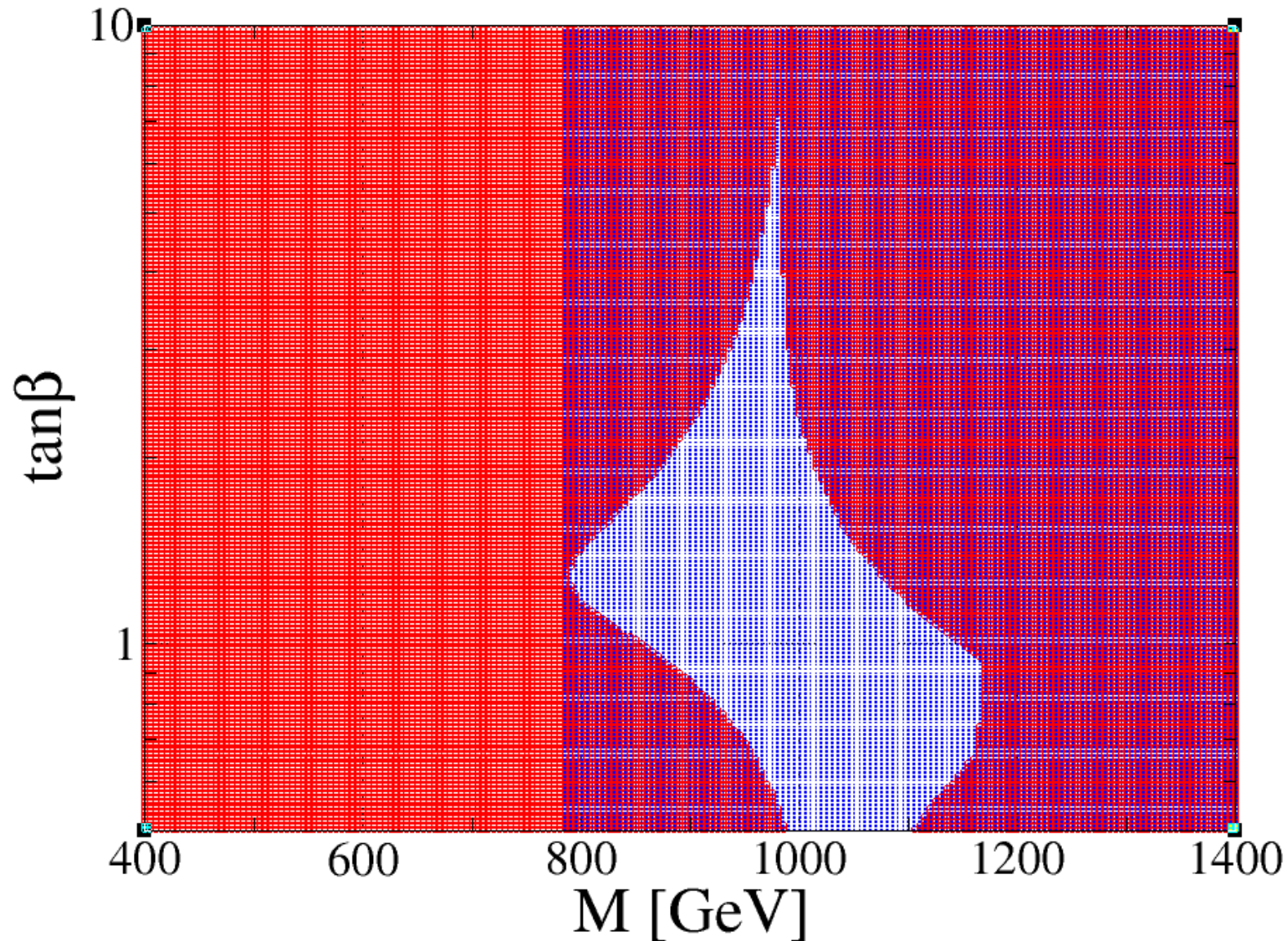
Excluded by the vacuum stability bound



$$m_\phi = 1000 \text{ GeV}, \sin(\beta-\alpha) = 0.995$$

Excluded by the unitary bound

Excluded by the vacuum stability bound



Contents

I. Introduction

II. 2HDMs and their alignment/decoupling limit

III. Theory constraints

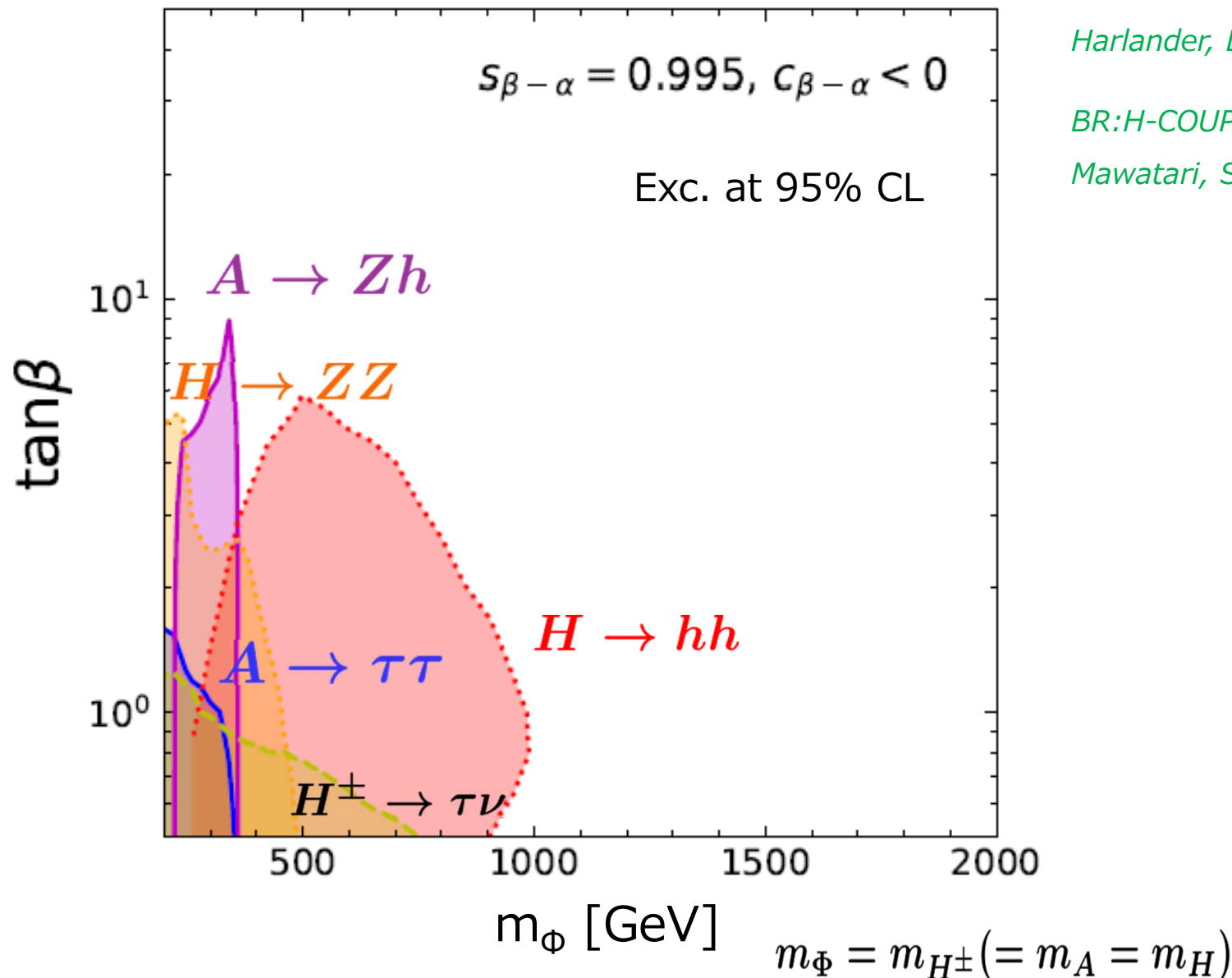
IV. Results

V. Summary

Excluded region by current LHC data

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY (in preparation)

Type-I



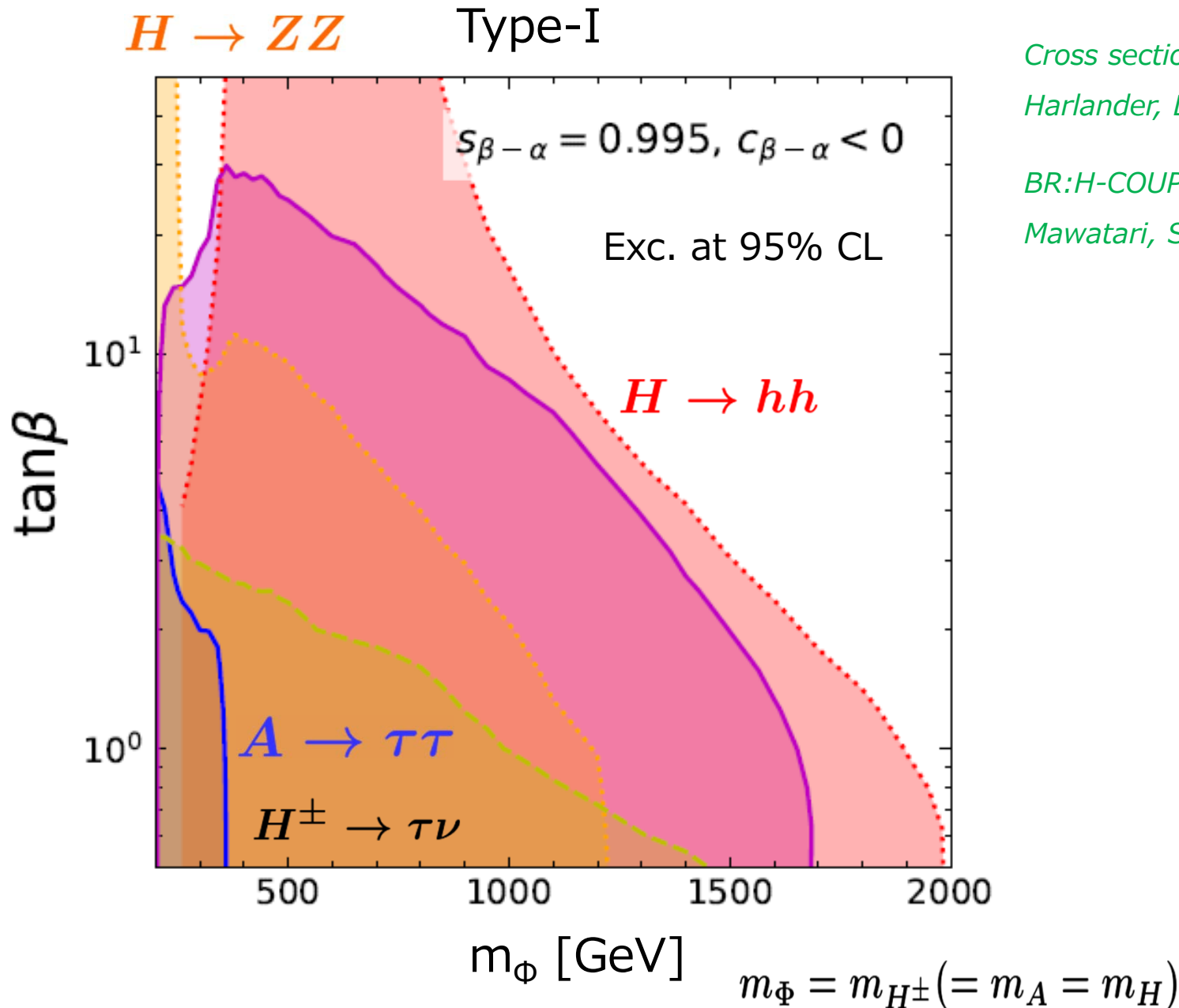
Cross section: SusHi v1-7-0

Harlander, Liebler, Mantler

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

Expected exclusion at HL-LHC

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY (in preparation)



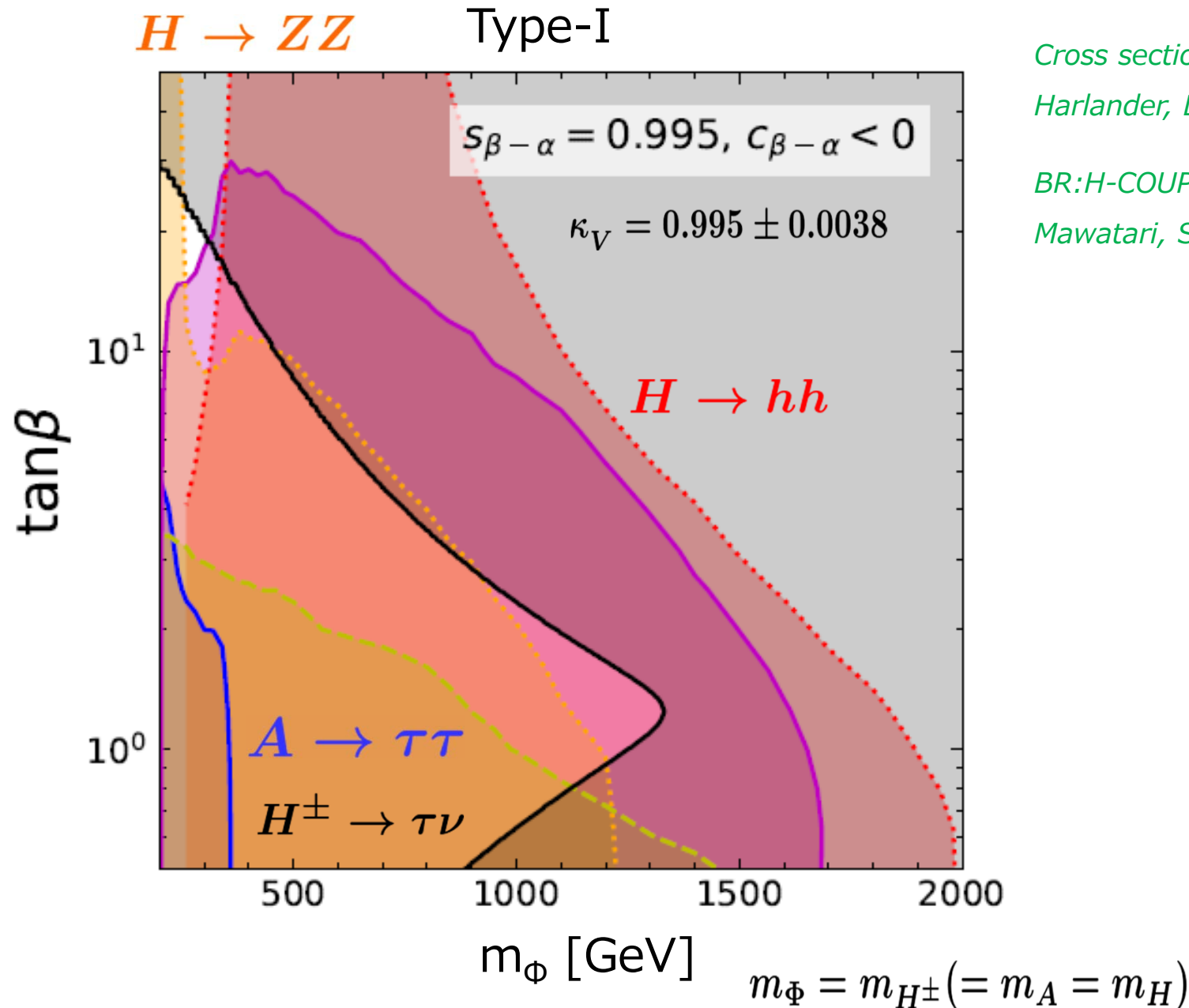
Cross section: SusHi v1-7-0

Harlander, Liebler, Mantler

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

Expected exclusion at HL-LHC and ILC

Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY (in preparation)



Cross section: SushI v1-7-0

Harlander, Liebler, Mantler

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

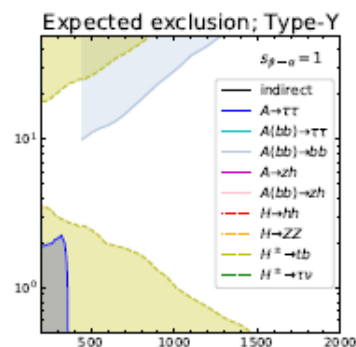
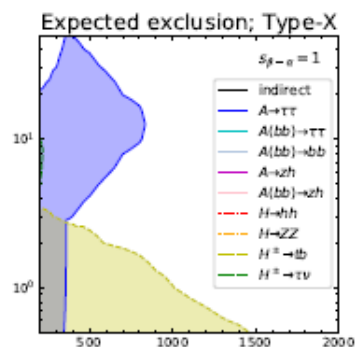
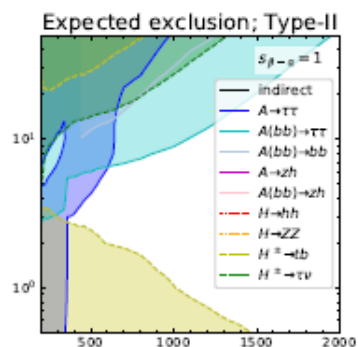
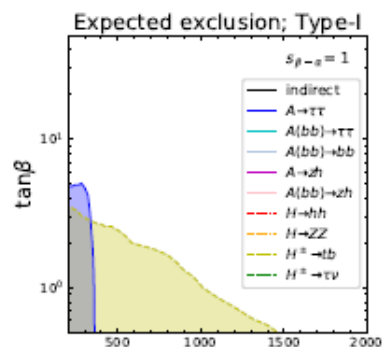
Type-I

Type-II

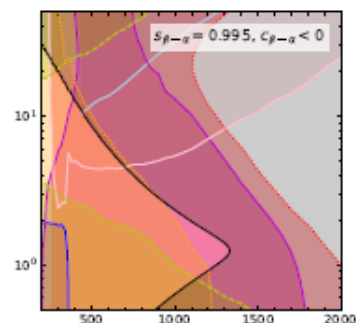
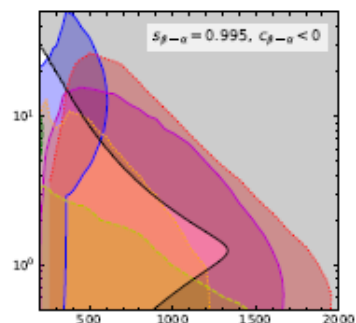
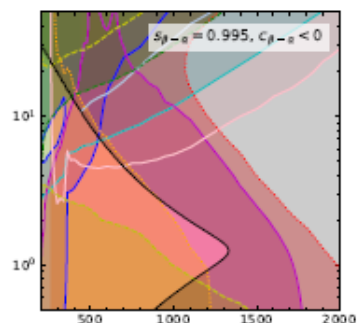
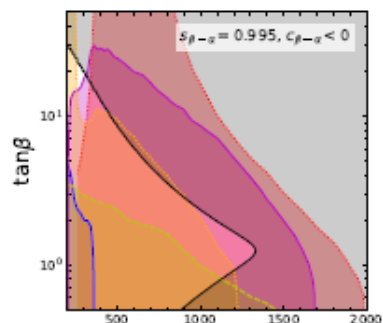
Type-X

Type-Y

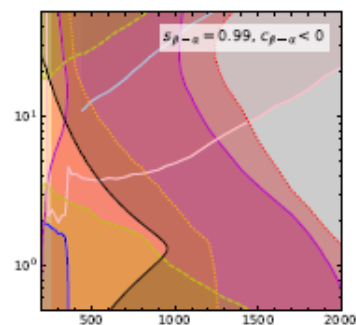
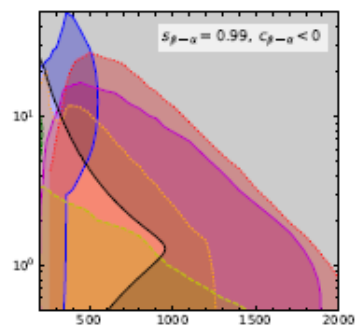
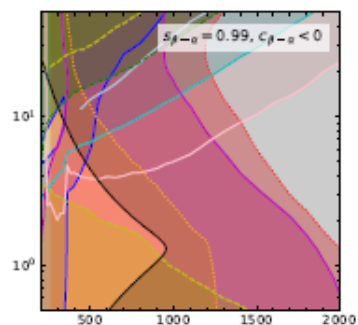
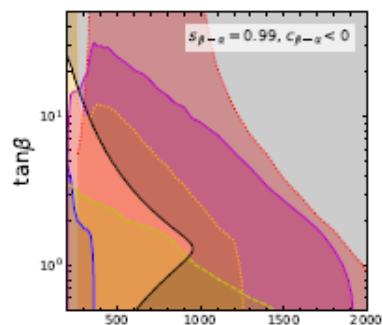
$$\sin(\beta-\alpha) = 1$$



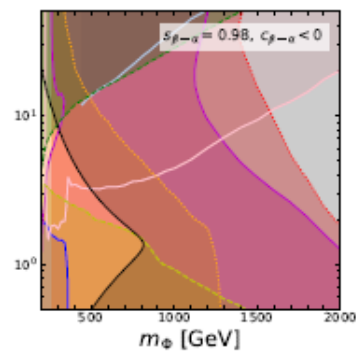
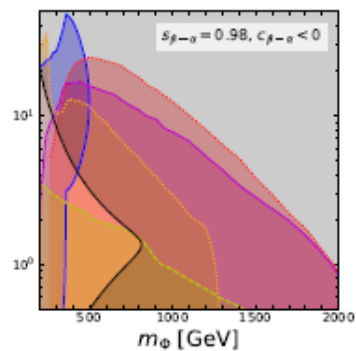
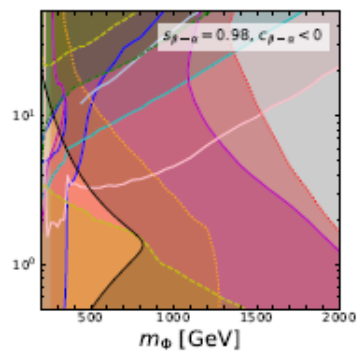
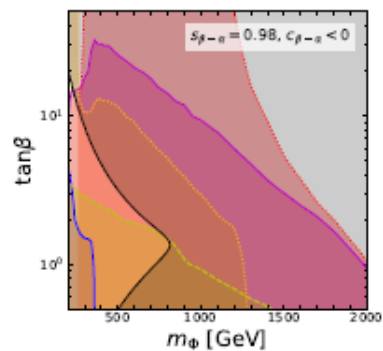
$$\sin(\beta-\alpha) = 0.995$$



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



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



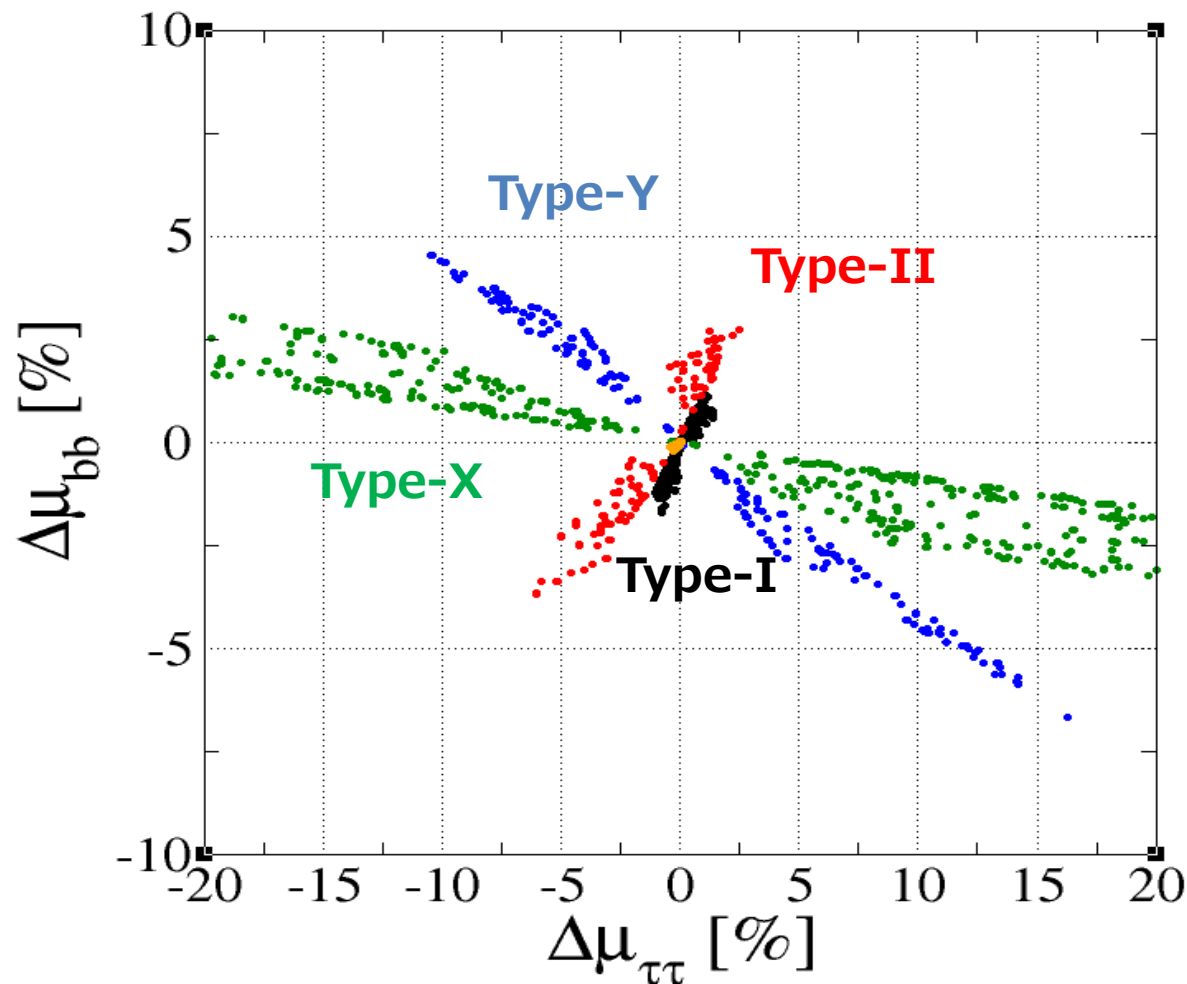
Fingerprinting the Higgs sector

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

$$\Delta\mu_{WW} = 0 \pm 4\%$$

$$\Delta\mu_X \equiv \text{BR}(h \rightarrow XX)_{\text{NP}} / \text{BR}(h \rightarrow XX)_{\text{SM}} - 1$$

$m_\phi > 600 \text{ GeV}$



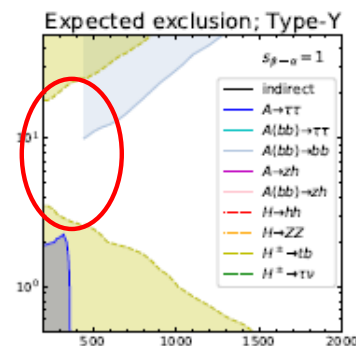
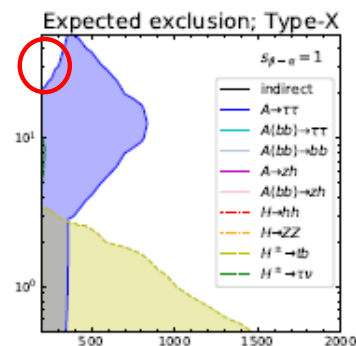
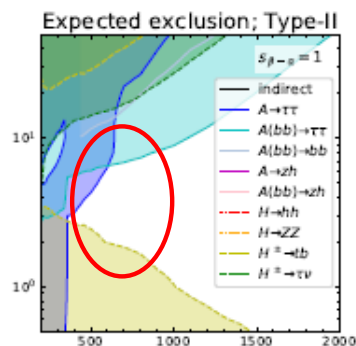
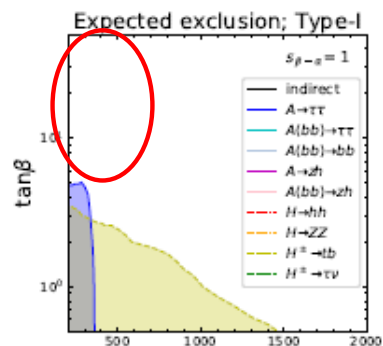
Type-I

Type-II

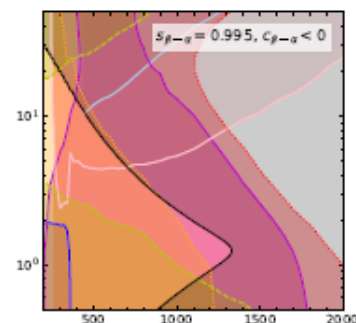
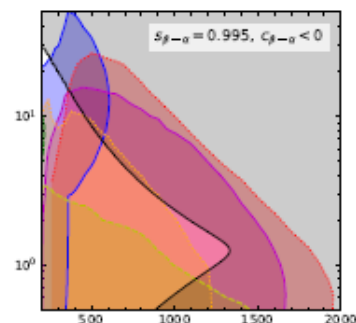
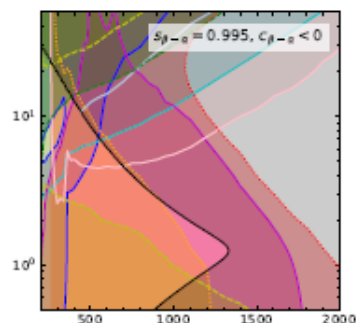
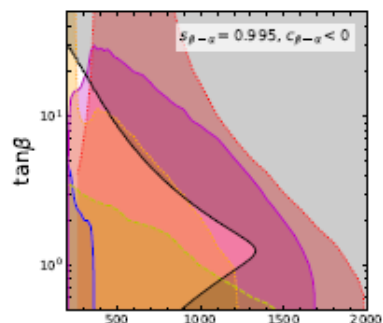
Type-X

Type-Y

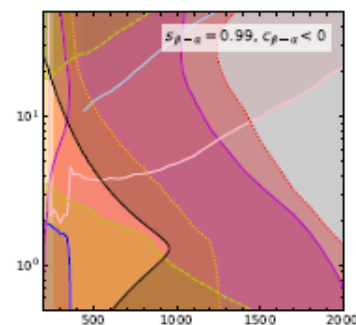
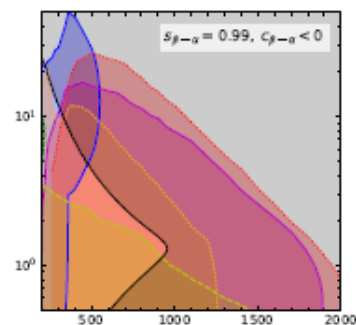
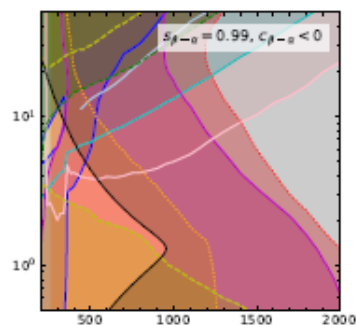
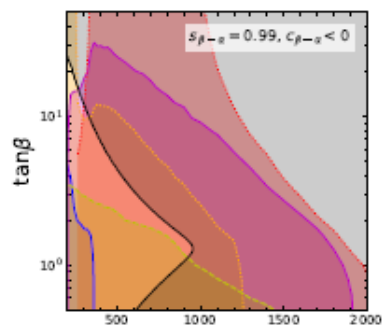
$$\sin(\beta-\alpha) = 1$$



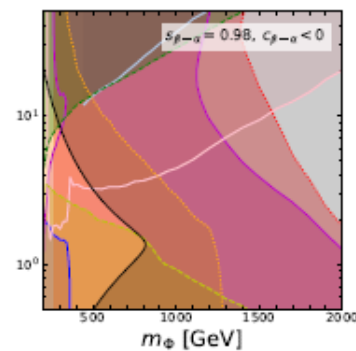
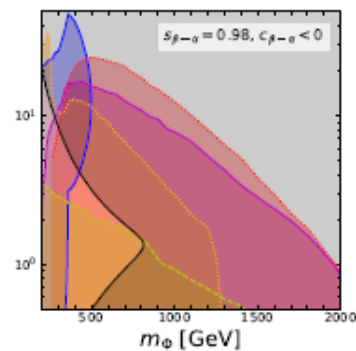
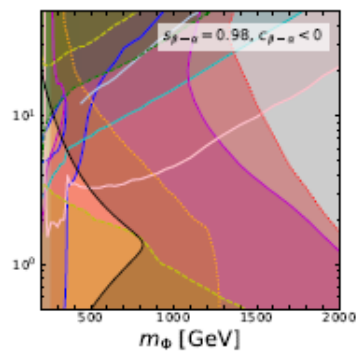
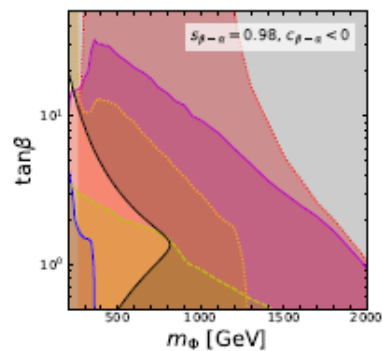
$$\sin(\beta-\alpha) = 0.995$$



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



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



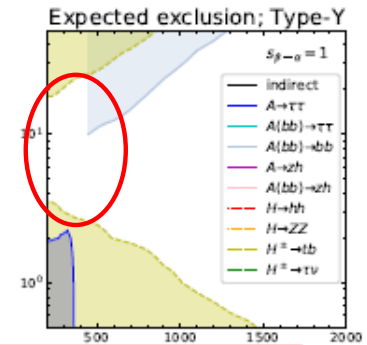
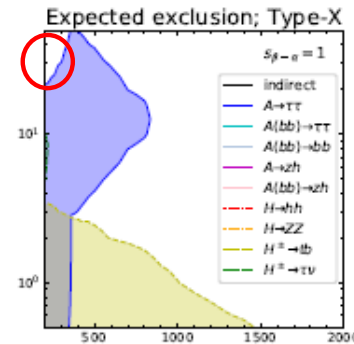
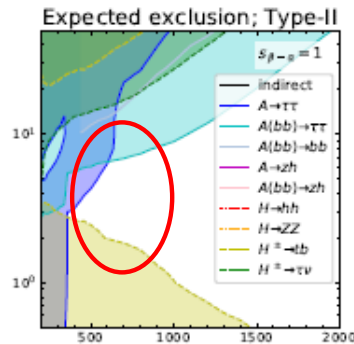
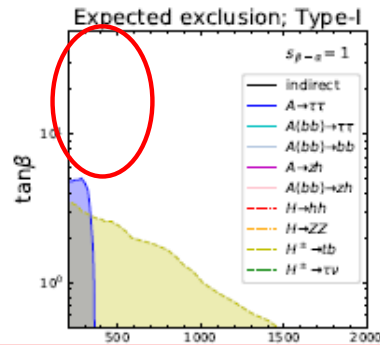
Type-I

Type-II

Type-X

Type-Y

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



Alignment without decoupling region can still remain.

- Electroweak baryogenesis

- Inert dark matter

Barbieri, Hall, Rychkov (2003), etc

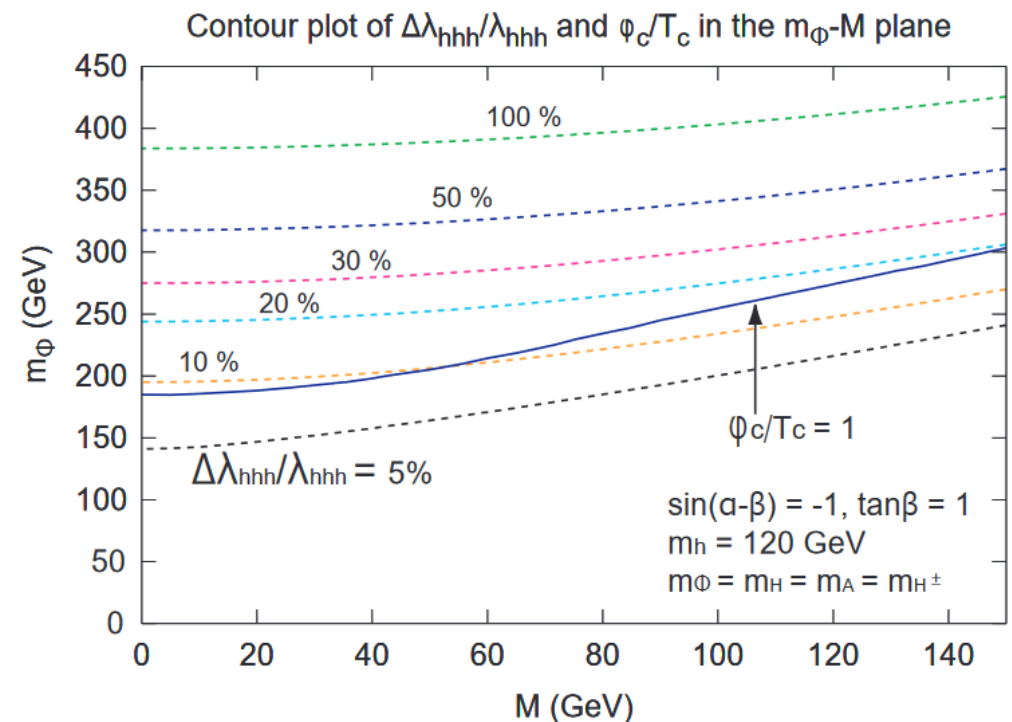
- $\mu(g-2)$ anomaly

Chun et. al, (2014)

Abe, Sato, Yagyu (2015), etc.

etc.

Kanemura, Okada, Senaha (2004)



Summary

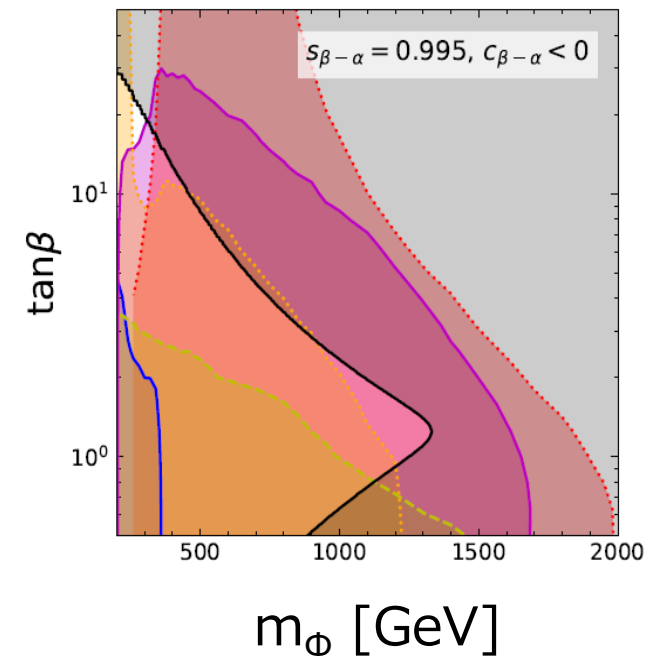
- We can explore wide region of the parameter space by using the **synergy** between direct search at the LHC and indirect search at the ILC.

- If we find signatures → Possible new physics can be further narrowed down by the **fingerprinting** of the Higgs sector.

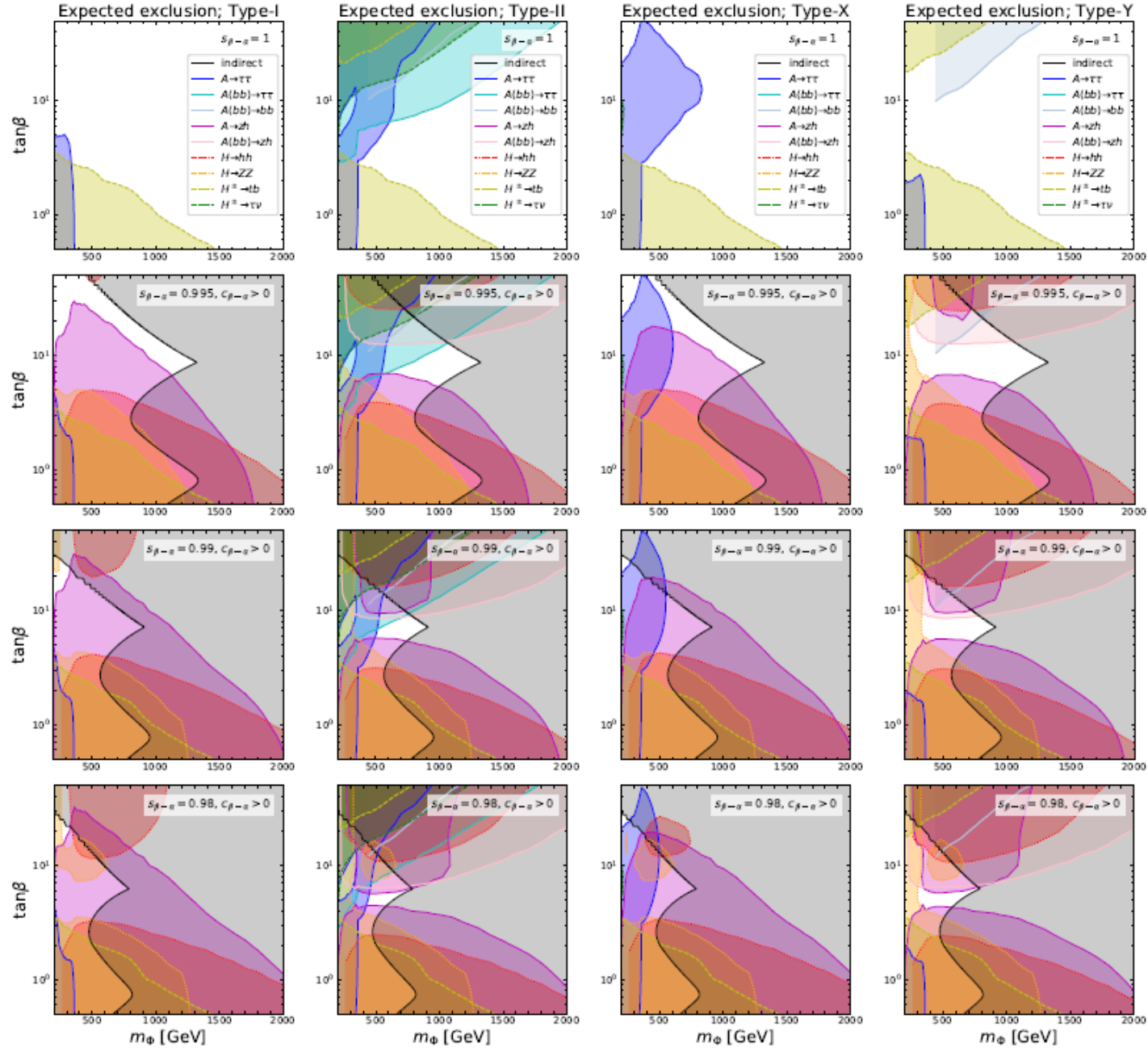
- If we do not find signatures → **alignment w/o decoupling** scenario can still remain.

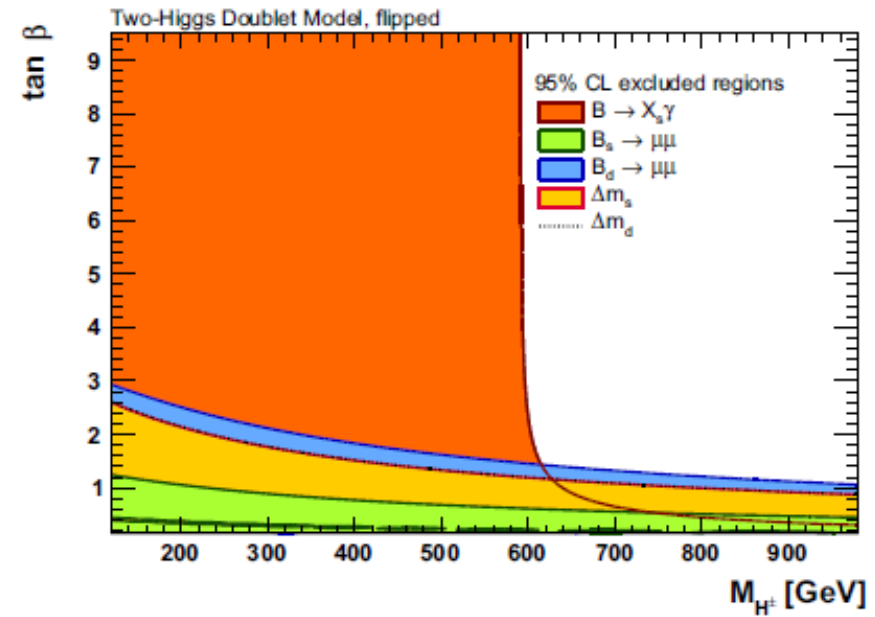
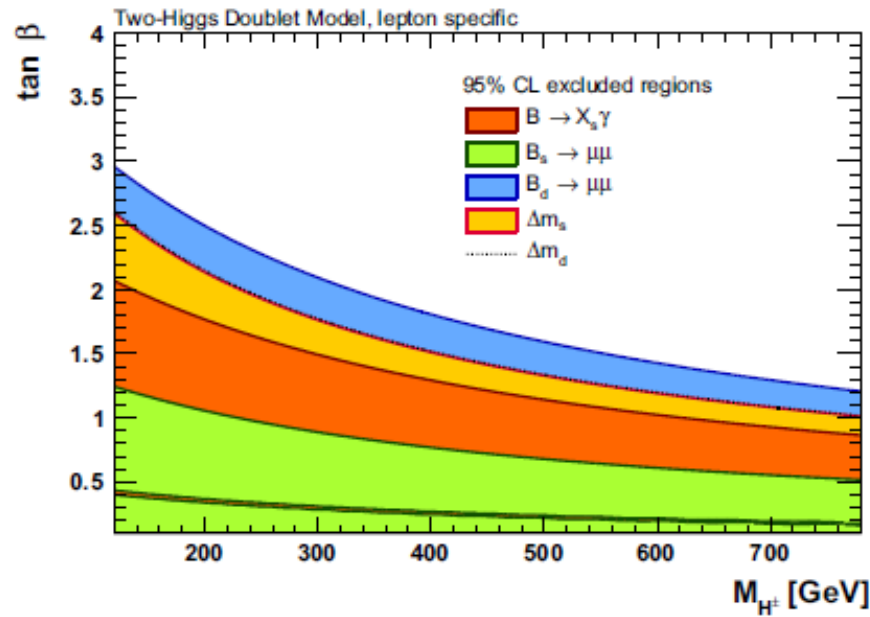
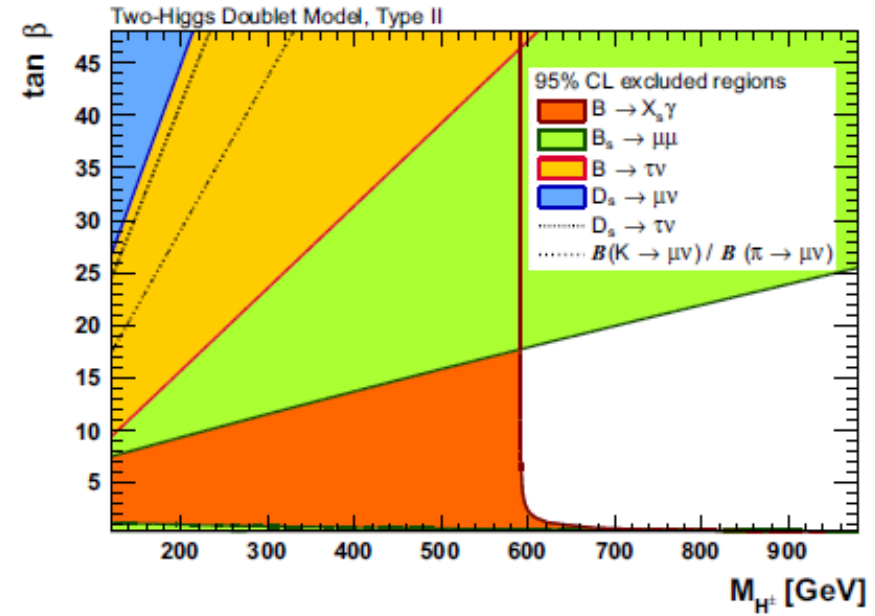
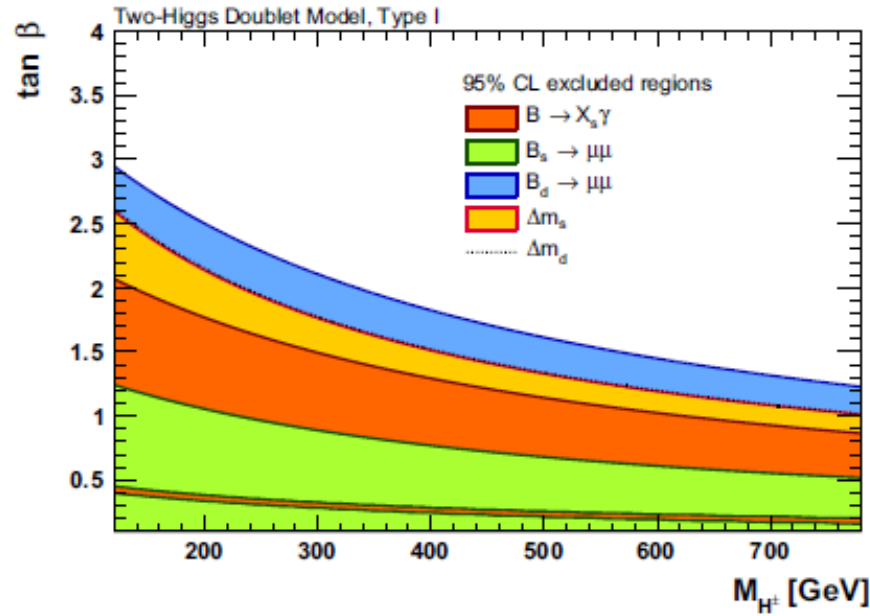
- Motivations: EWBG, Inert dark matter, muon $g - 2$, etc.

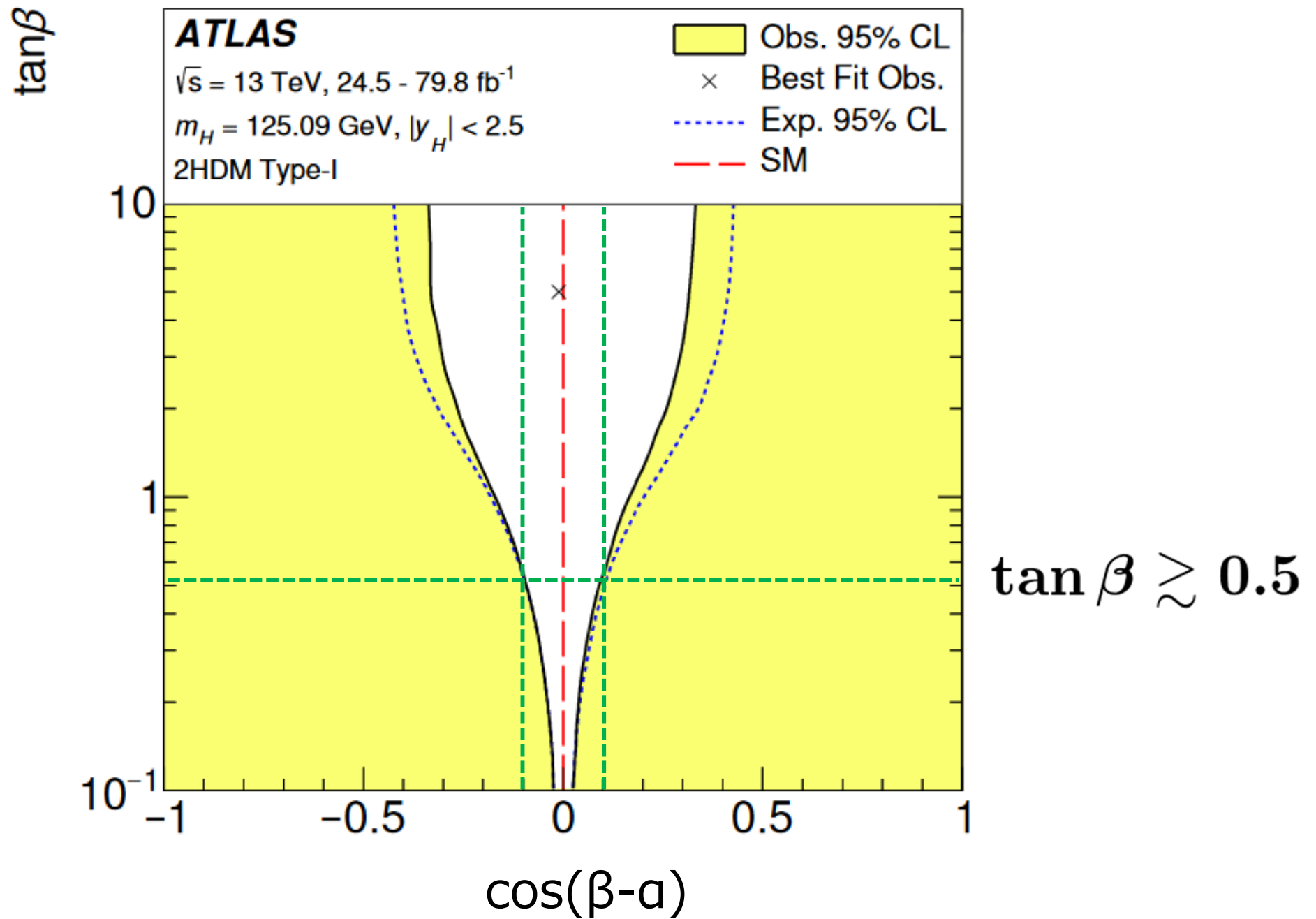
Non-decoupling effects of additional Higgs bosons on **hhh coupling** can be important → ILC500.



Case for $\cos(\beta-\alpha) > 0$



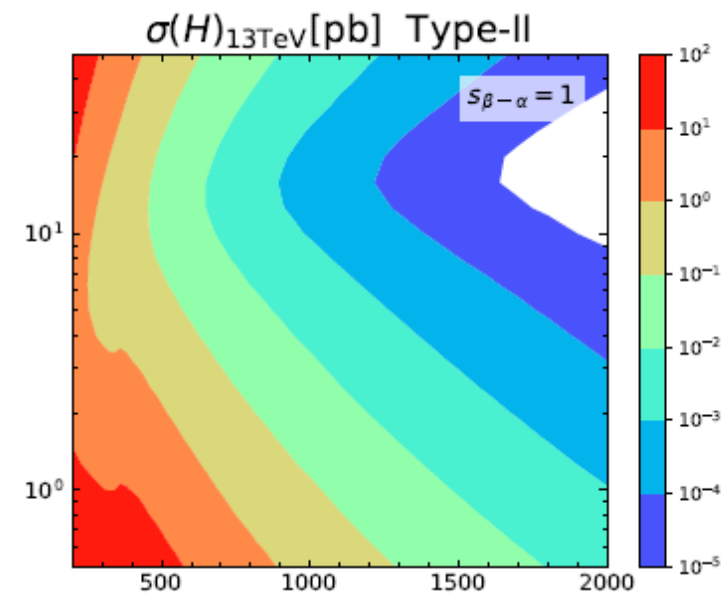
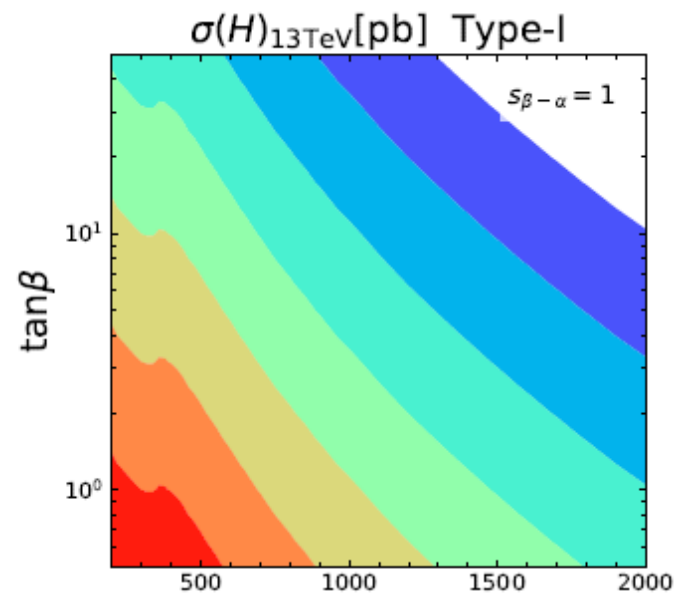




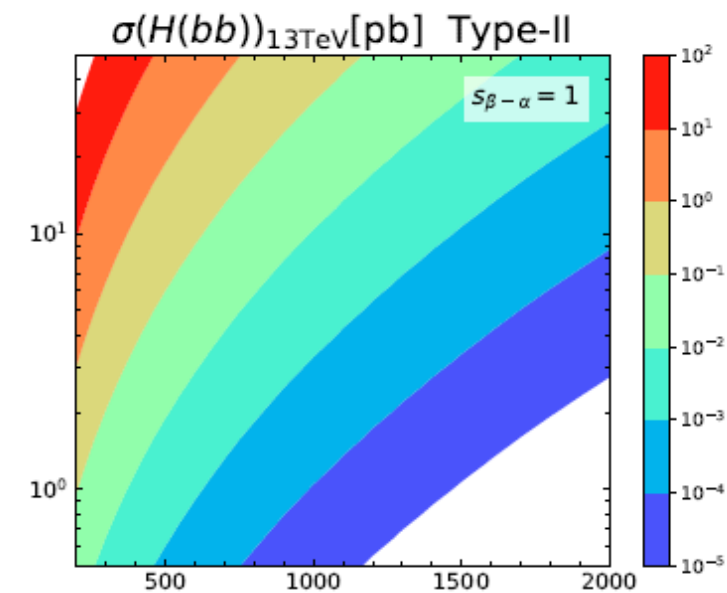
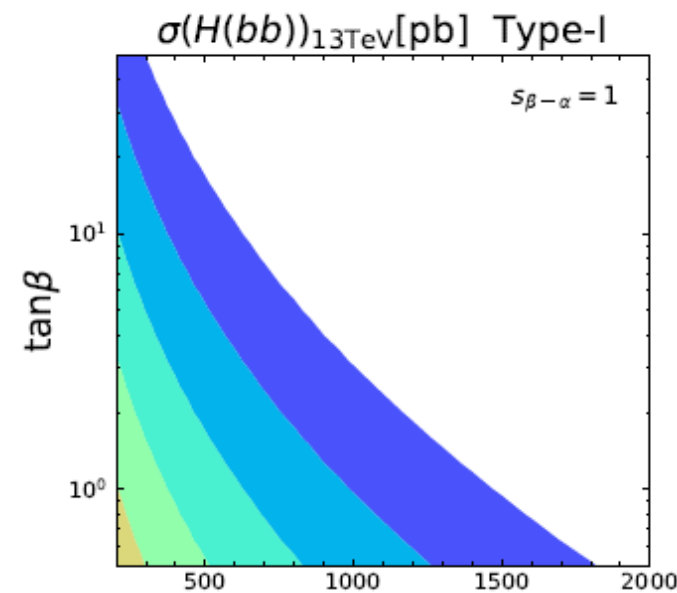
	Current (ATLAS,CMS)	HL-LHC (ATLAS,CMS) [%]	ILC250 [%]	ILC500 [%]
κ_Z	$(1.11 \pm 0.08, 1.00 \pm 0.11)$	(2.6,2.4)	0.38	0.30
κ_W	$(1.05 \pm 0.09, -1.13^{+0.16}_{-0.13})$	(3.1,2.6)	1.8	0.40
κ_b	$(1.03^{+0.19}_{-0.17}, 1.17^{+0.27}_{-0.31})$	(6.2, 6.0)	1.8	0.60
κ_t	$(1.09^{+0.15}_{-0.14}, 0.98 \pm 0.14)$	(6.3, 5.5)	—	6
κ_c	(—,—)	(—,—)	2.4	1.2
κ_τ	$(1.05^{+0.16}_{-0.15}, 1.02 \pm 0.17)$	(3.7,2.8)	1.9	0.80
κ_μ	$(-,0.80^{+0.59}_{-0.80})$	(7.7,6.7)	5.6	5.1
κ_g	$(0.99^{+0.11}_{-0.10}, 1.18^{+0.16}_{-0.14})$	(4.2,4.0)	2.2	0.97
κ_γ	$(1.05 \pm 0.09, 1.07^{+0.14}_{-0.15})$	(3.7,2.9)	1.1	1.0
$\kappa_{Z\gamma}$	(—,—)	(12.7,—)	16	16
κ_h	(—,—)	(—,—)	—	27

Constrained quantity	Applicable mass region	Reference
$\sigma(\phi) \times B(\phi \rightarrow \tau\tau)$	$200 < m_\Phi < 2000$ GeV	Fig. 7(a) in [1]
$\sigma(\phi(bb)) \times B(\phi \rightarrow \tau\tau)$	$200 < m_\Phi < 2000$ GeV	Fig. 7(b) in [1]
$\sigma(\phi(bb)) \times B(\phi \rightarrow bb)$	$450 < m_\Phi < 1400$ GeV	Fig. 8 in [2]
$\sigma(\phi) \times B(\phi \rightarrow tt)$	$400 < m_\Phi < 5000$ GeV	Fig. 14 in [3]
$\sigma(H) \times B(H \rightarrow hh) \times B(h \rightarrow bb)^2$	$260 < m_\Phi < 2000$ GeV	Fig. 9(a) in [4]
$\sigma(H) \times B(H \rightarrow WW)$	$200 < m_\Phi < 2000$ GeV	Fig. 5 in [5]
$\sigma(H) \times B(H \rightarrow ZZ)$	$200 < m_\Phi < 2000$ GeV	Fig. 6 in [6]
$\sigma(A) \times B(A \rightarrow Zh) \times B(h \rightarrow bb)$	$200 < m_\Phi < 2000$ GeV	Fig. 6(a) in [7]
$\sigma(A(bb)) \times B(A \rightarrow Zh) \times B(h \rightarrow bb)$	$200 < m_\Phi < 2000$ GeV	Fig. 6(b) in [7]
$\sigma(tH^\pm) \times B(H^\pm \rightarrow tb)$	$200 < m_\Phi < 2000$ GeV	Fig. 8 in [8]
$\sigma(tH^\pm) \times B(H^\pm \rightarrow \tau\nu)$	$200 < m_\Phi < 2000$ GeV	Fig. 8(a) in [9]

$gg \rightarrow H/A$



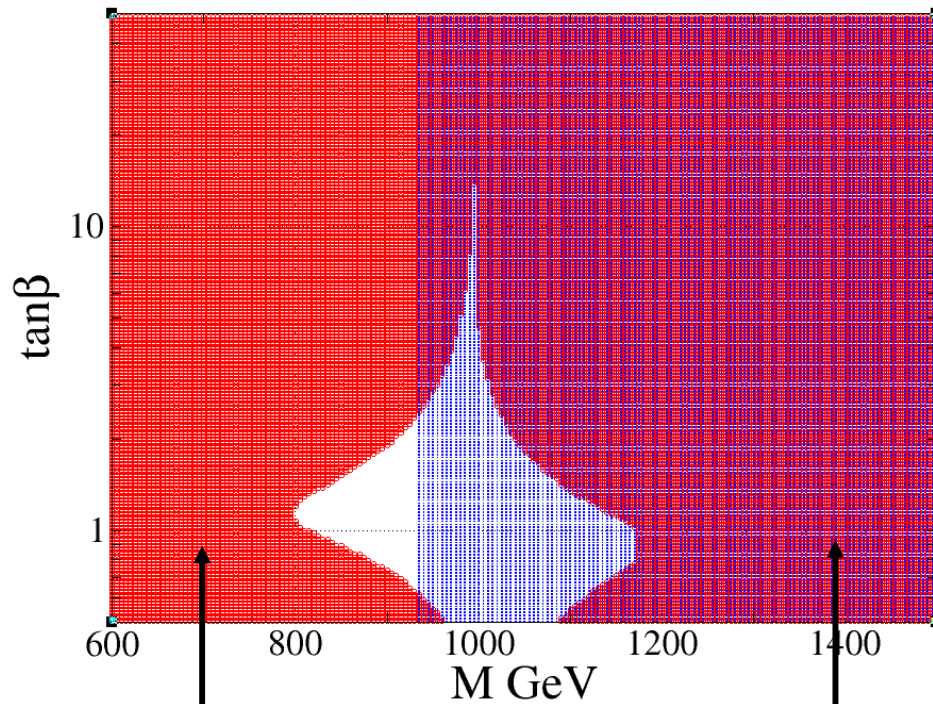
$gg \rightarrow bbH/bbA$



$$\sin(\beta-\alpha) = 0.995, \cos(\beta-\alpha) < 0$$

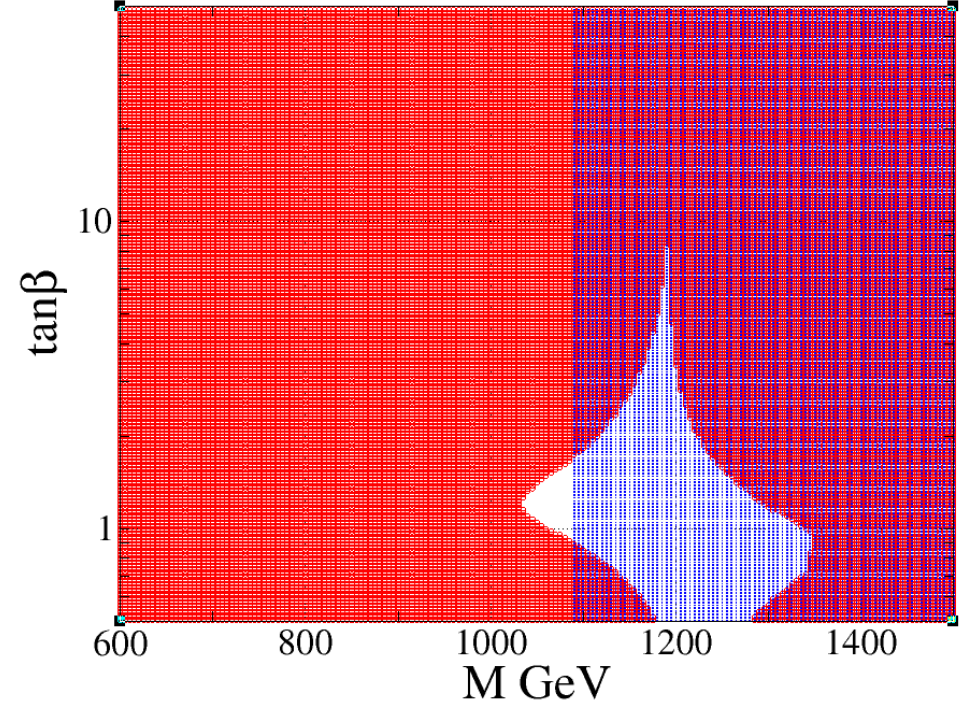
$$m_\phi = 1000 \text{ GeV}$$

$$m_\phi = 1200 \text{ GeV}$$



Excluded by unitarity

Excluded by vacuum stability



$$x = \pi/2 - (\beta - \alpha)$$

$$\lambda_1 v^2 = (m_\Phi^2 - M^2)t_\beta^2 - 2m_\Phi^2 t_\beta |x| + m_h^2 (1 + 2|x|t_\beta)$$

$$\lambda_2 v^2 = (m_\Phi^2 - M^2)\frac{1}{t_\beta^2} + 2m_\Phi^2 \frac{1}{t_\beta} |x| + m_h^2 (1 - 2|x|\frac{1}{t_\beta})$$

$s_{\beta-\alpha}$	Type-I	Type-II	Type-X	Type-Y
0.995	$t_\beta \geq 0.54$ ($t_\beta \geq 0.54$)	$0.57 \leq t_\beta \leq 1.63$ (-)	$0.42 \leq t_\beta \leq 4.2$ ($0.43 \leq t_\beta \leq 4.1$)	- (-)
0.990	$t_\beta \geq 0.86$ ($t_\beta \geq 0.86$)	- (-)	$0.72 \leq t_\beta \leq 2.5$ ($0.71 \leq t_\beta \leq 2.0$)	- (-)
0.980	$t_\beta \geq 1.3$ ($t_\beta \geq 1.3$)	- (-)	- (-)	- (-)

TABLE III. Allowed range of $\tan \beta$ for the case with $c_{\beta-\alpha} > 0$ ($c_{\beta-\alpha} < 0$) from the signal strength data of the discovered Higgs boson at the LHC [\[10\]](#). The hyphen denotes no allowed region.