LHC/ILC Synergy for Exploring Extended Higgs Sectors

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Collaboration with

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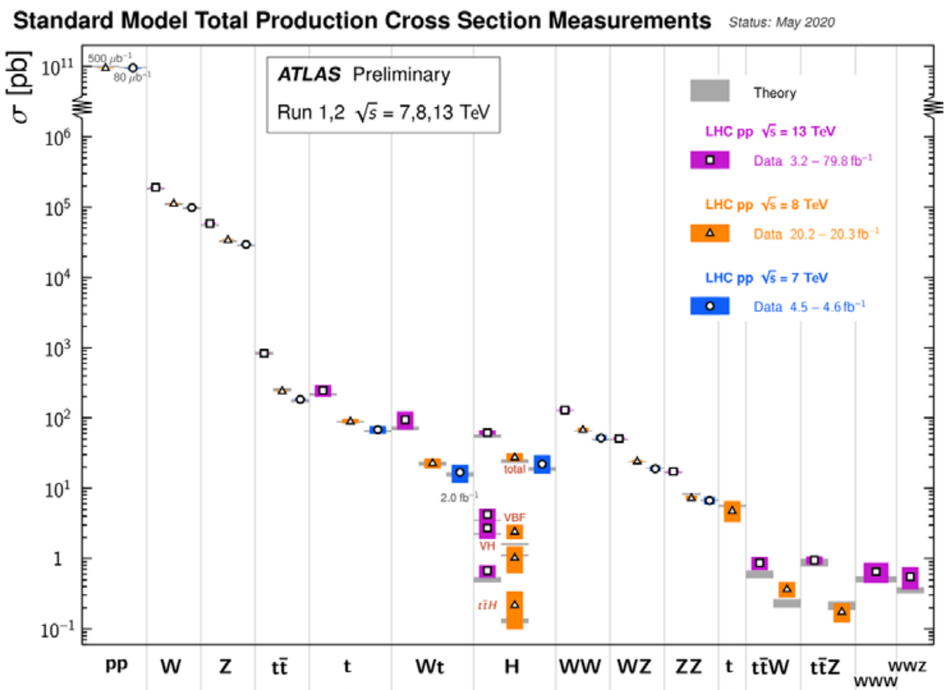
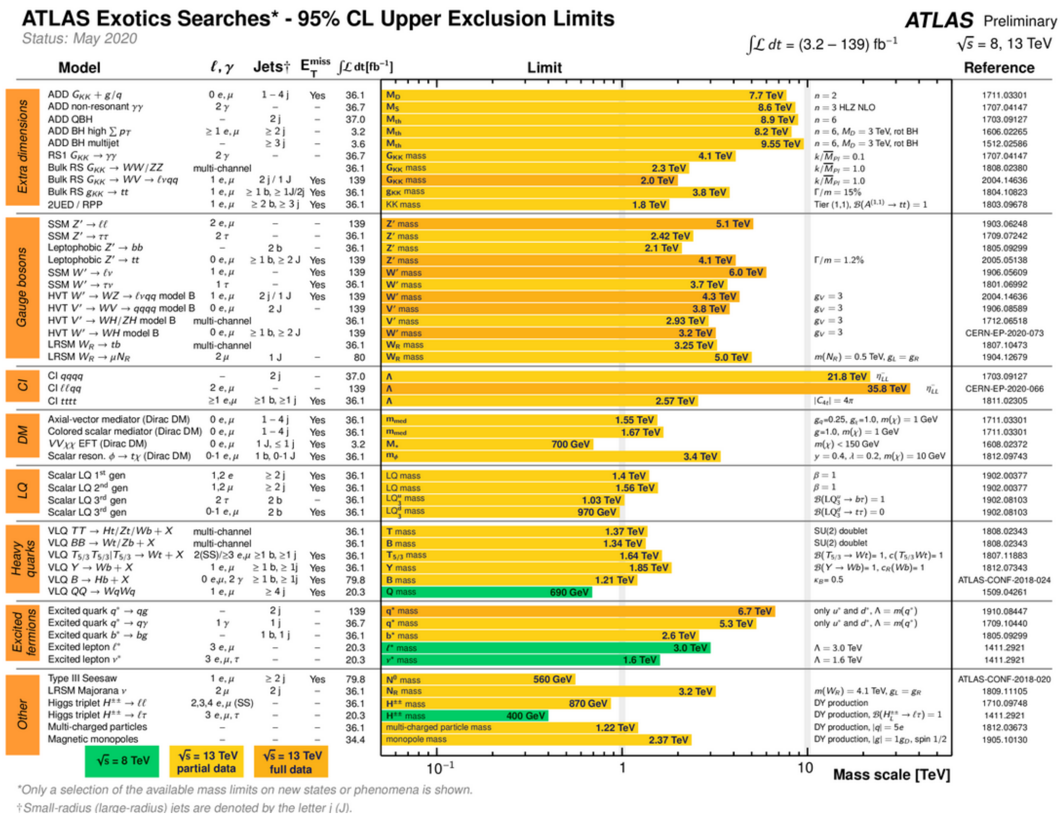
High Energy Frontier in Particle Physics: LHC and Future Colliders

2020, Oct. 5th, NTU

2 Figs well describing the current status



SM predictions are good agreement.



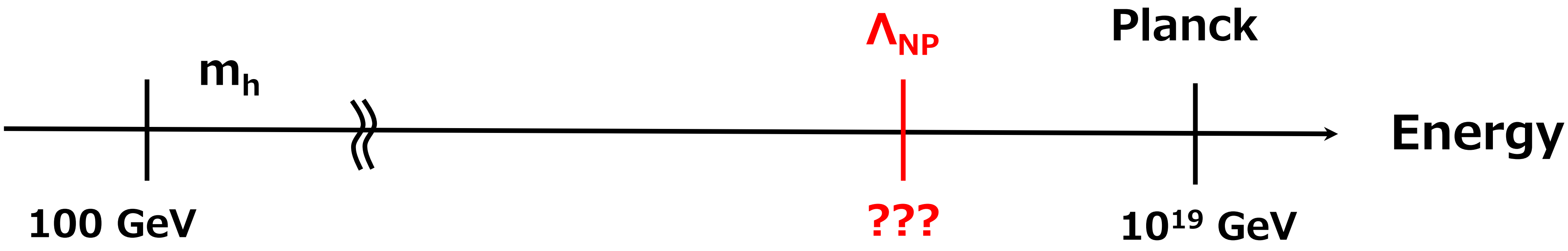
New particles have not been observed.

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.

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

- 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)

Higgs as a problematic sector

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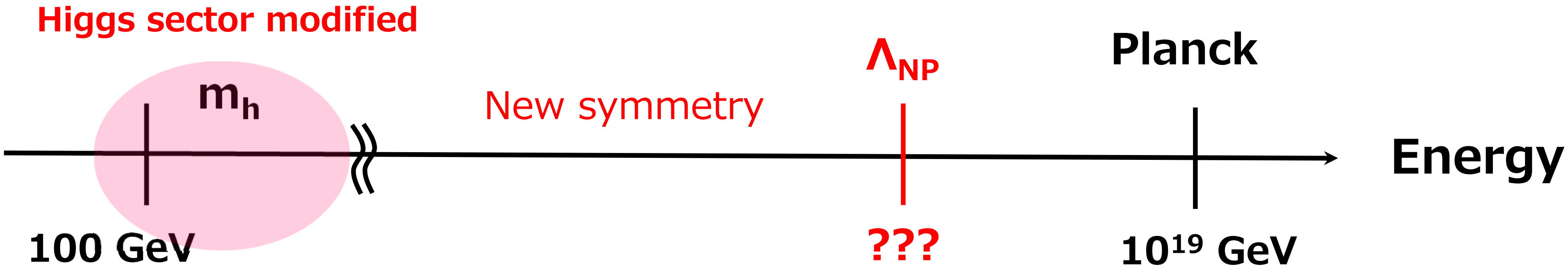

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E.g., Supersymmetry

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Gauge symmetry (Gauge Higgs unification)

Higgs as a portal to BSM

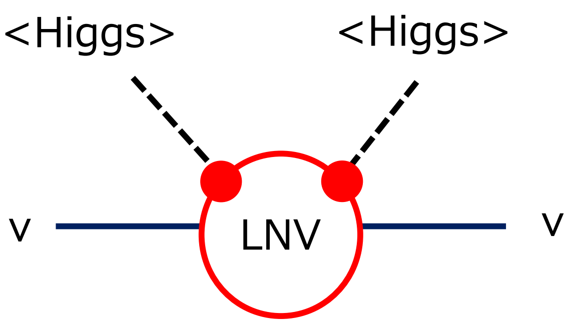
- The Higgs sector can be a portal to a BSM sector.

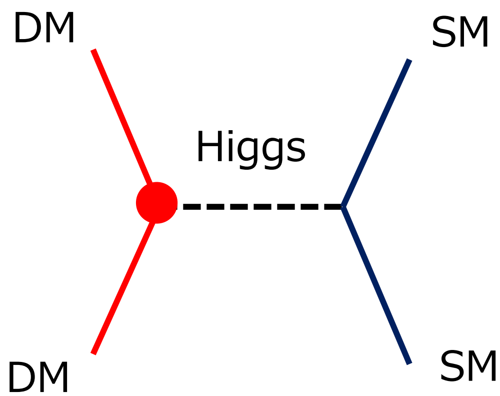
Standard Model

Higgs sector

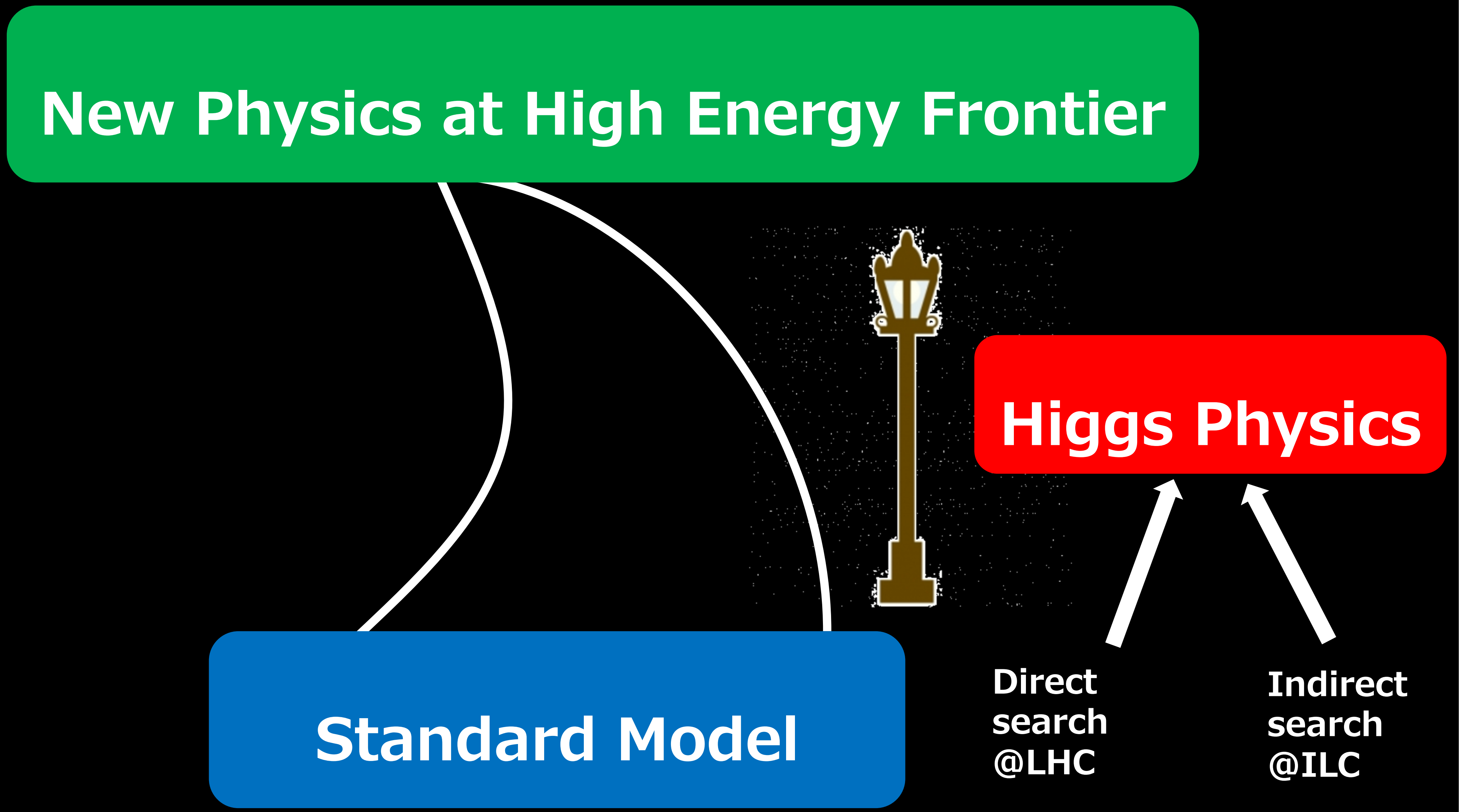
Beyond the SM

- Neutrino mass (type-II, rad. seesaw)
- Dark matter (inert Higgs)
- Baryon asymmetry (EWBG)
- Inflation (Higgs inflation)

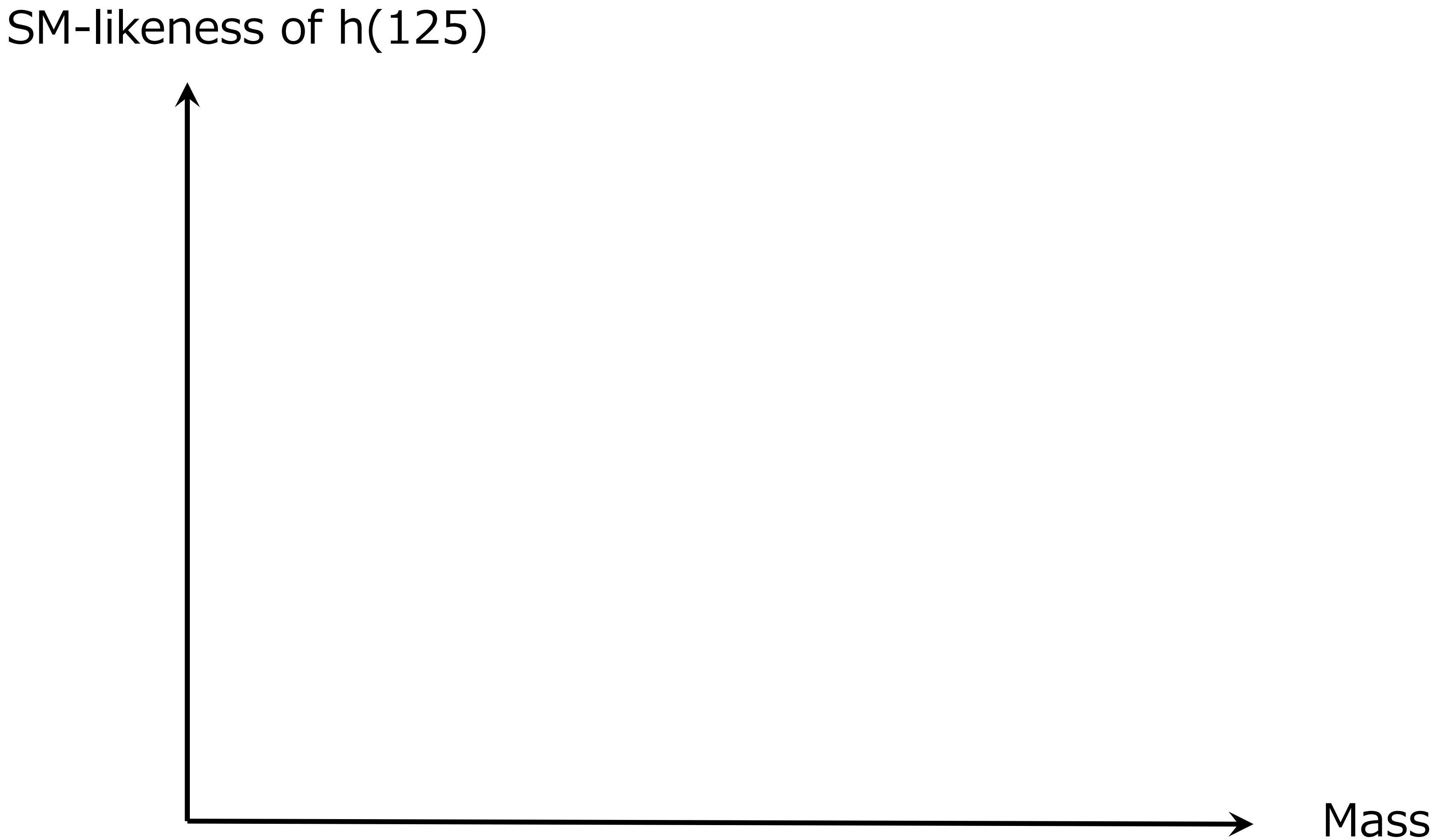




Higgs as a probe of New Physics



Keywords: Alignment/Decoupling



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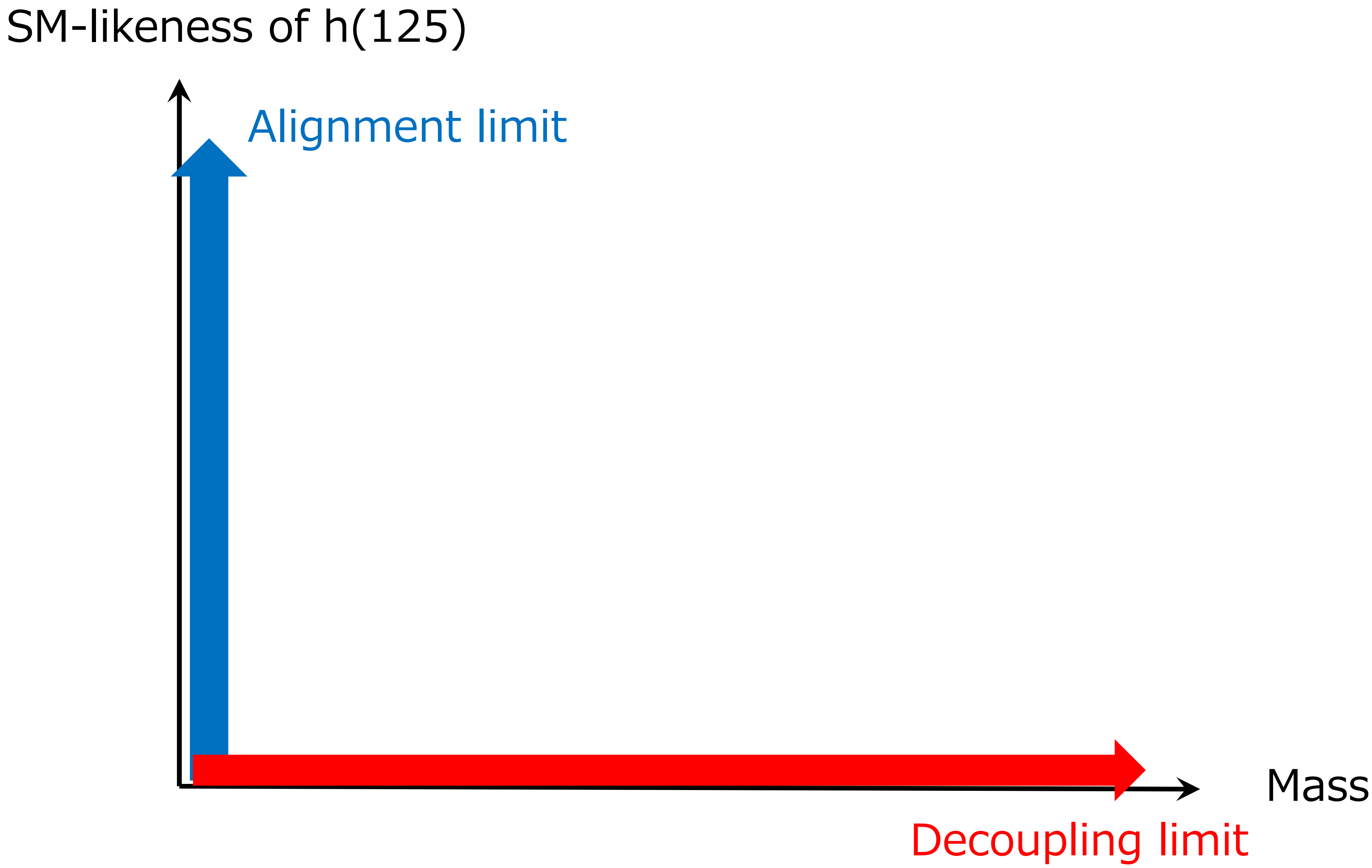

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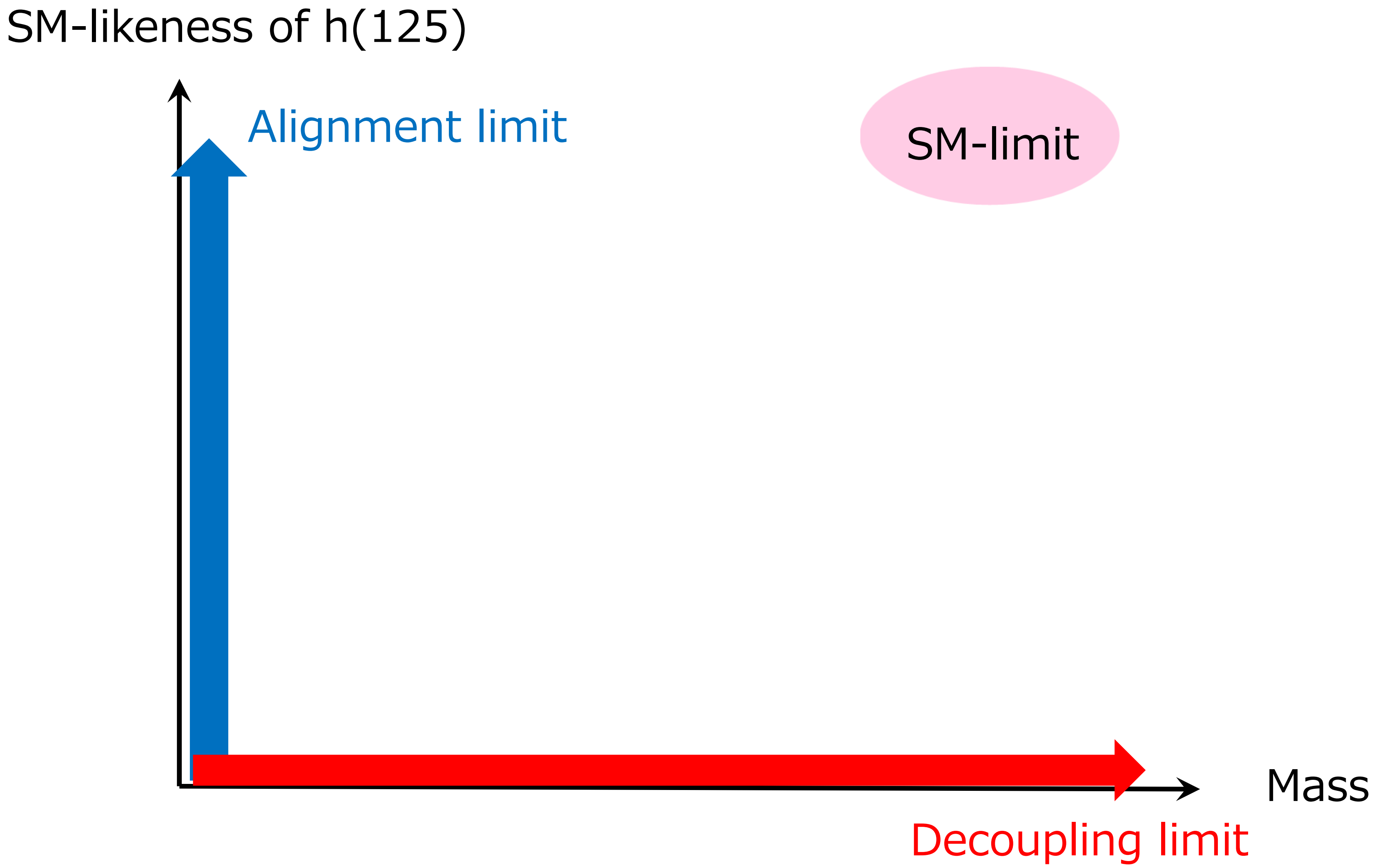

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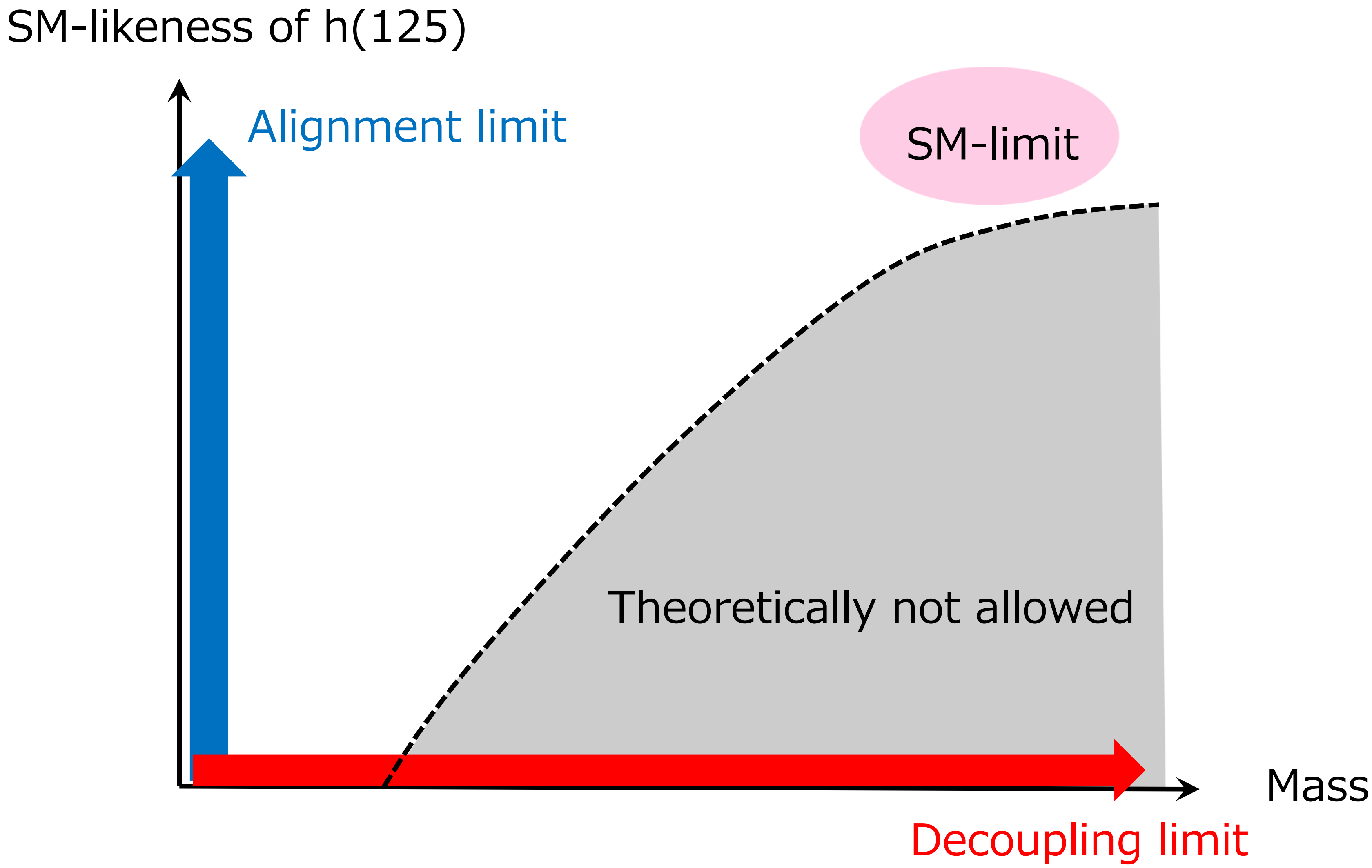

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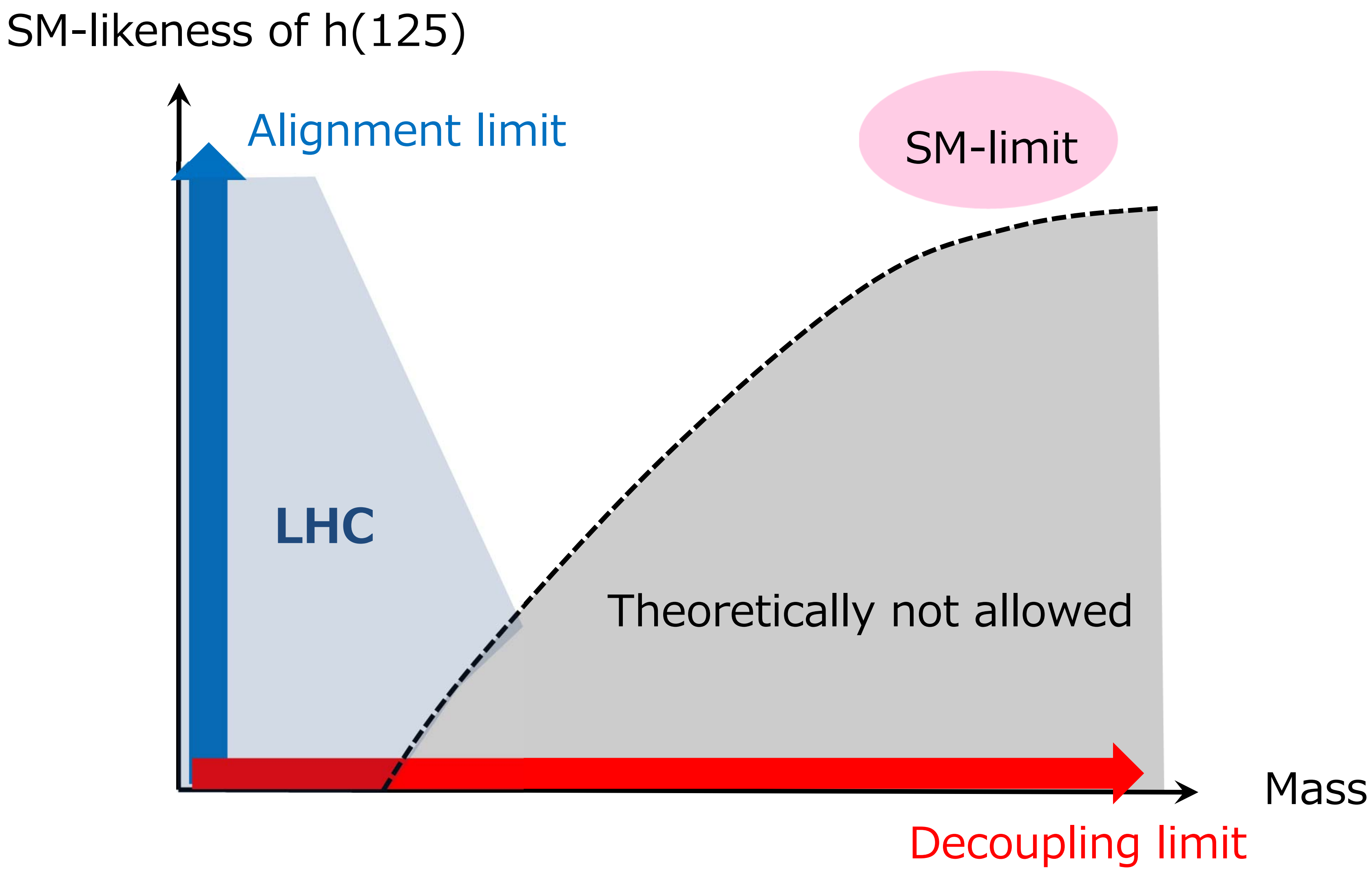

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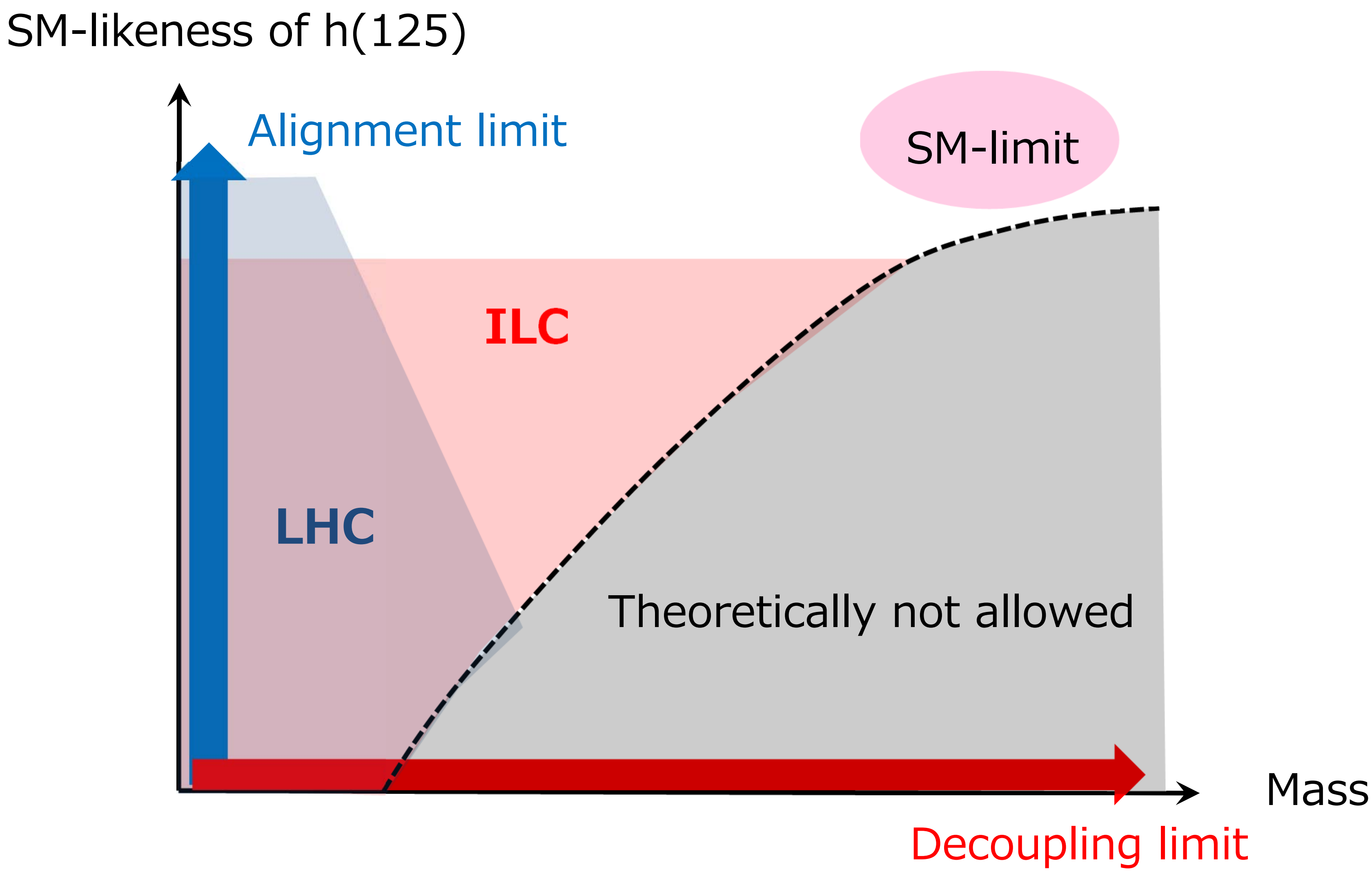


Synergy b/w LHC and ILC searches is important!

Contents

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

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

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

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

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

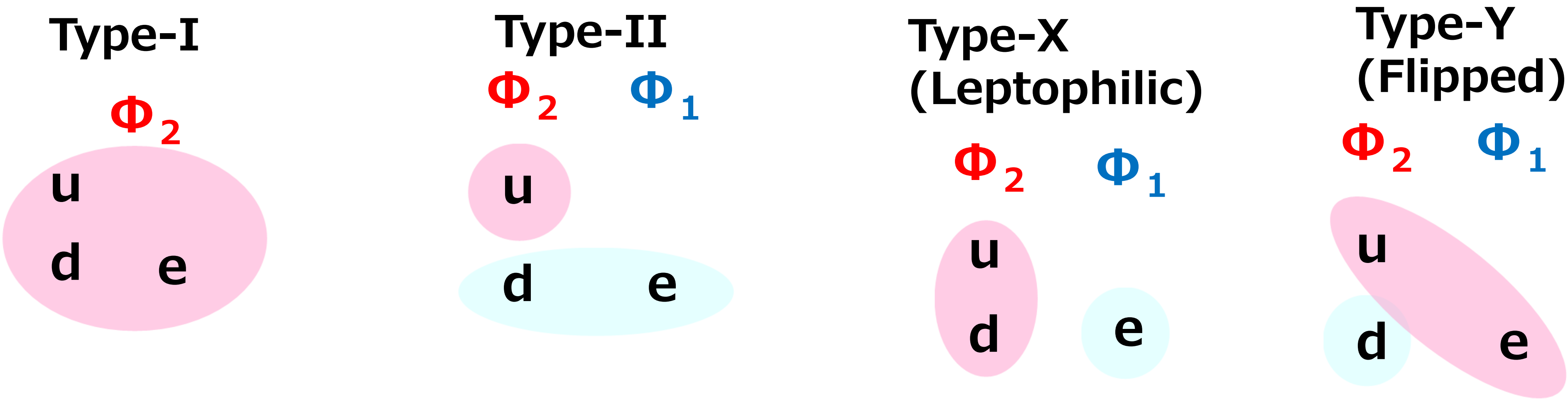
- 8 parameters v, m_h, m_H, m_A, m_{H+}, sin(β-α), tanβ, and M^2

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)



-ν2HDM

-MSSM

-Muon g-2

Ma, PRL86 (2001)

Broggio et al. JHEP1411 (2014)

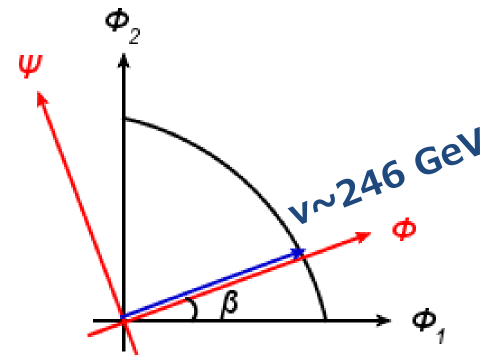
Abe, Sato, KY, JHEP1507 (2015)

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

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

CP-even Higgs

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

- Masses of the Higgs boson at sin(β-α) ~ 1

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

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

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

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

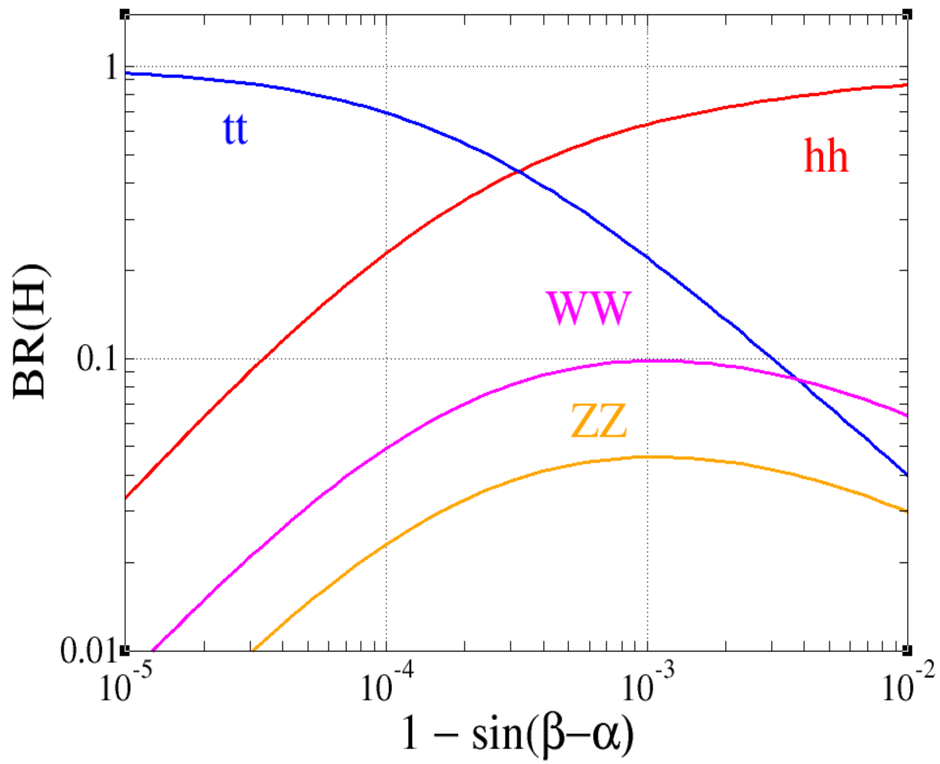
-h behaves like the SM Higgs boson.

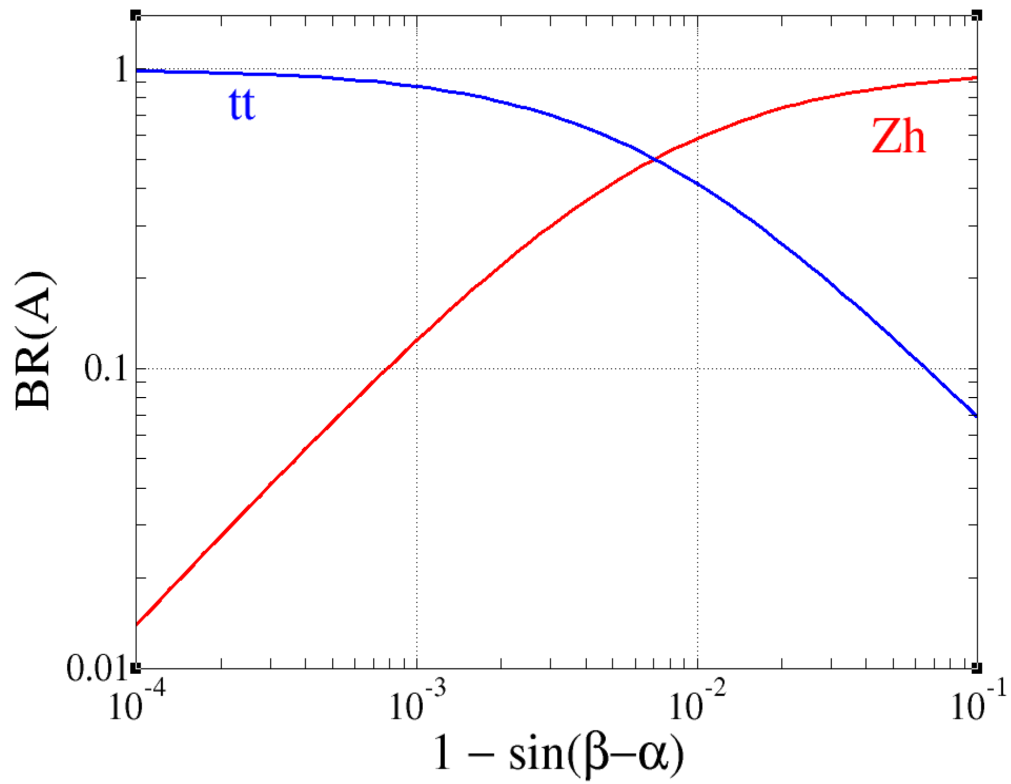
-H, A, $H^\pm$ behave fermio-philic scalars.

(Non) alignment in the 2HDM

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

Type-I 2HDM with 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.

Contents

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

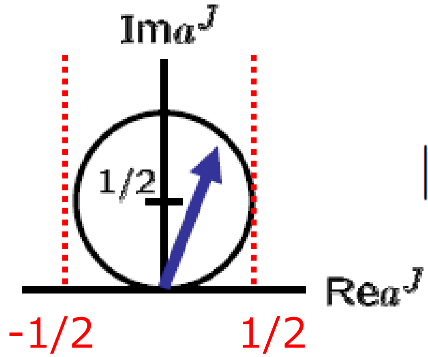
ILC can set the upper limit on the second Higgs mass scale.

Unitarity & vacuum stability bounds

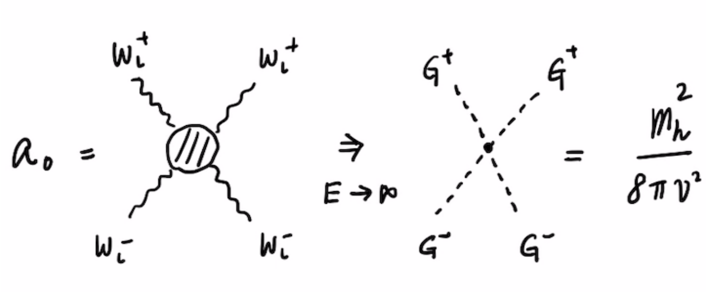
Lee, Quigg, Thacker (1977)

For 2HDM: Kanemura, Kubota, Takasugi (1993), Akeroyd, Arhrib, Naimi (2000), Ginzburg, Ivanov (2005)

- Perturbative unitarity



$$|\mathrm{Re}(a_J^{2\to 2})| < 1/2$$



(SM)

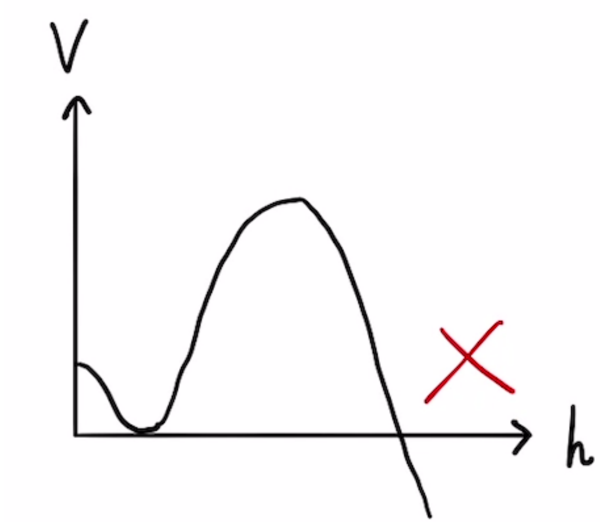
In the 2HDM, there are 12 a_0.

M » m_Φ or M « is disfavored.

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

- Vacuum stability (bounded from below)

Deshpande, Ma (1978)
Nie, Sher (1999)
Kanemura, Kasai, Okada (1999)



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

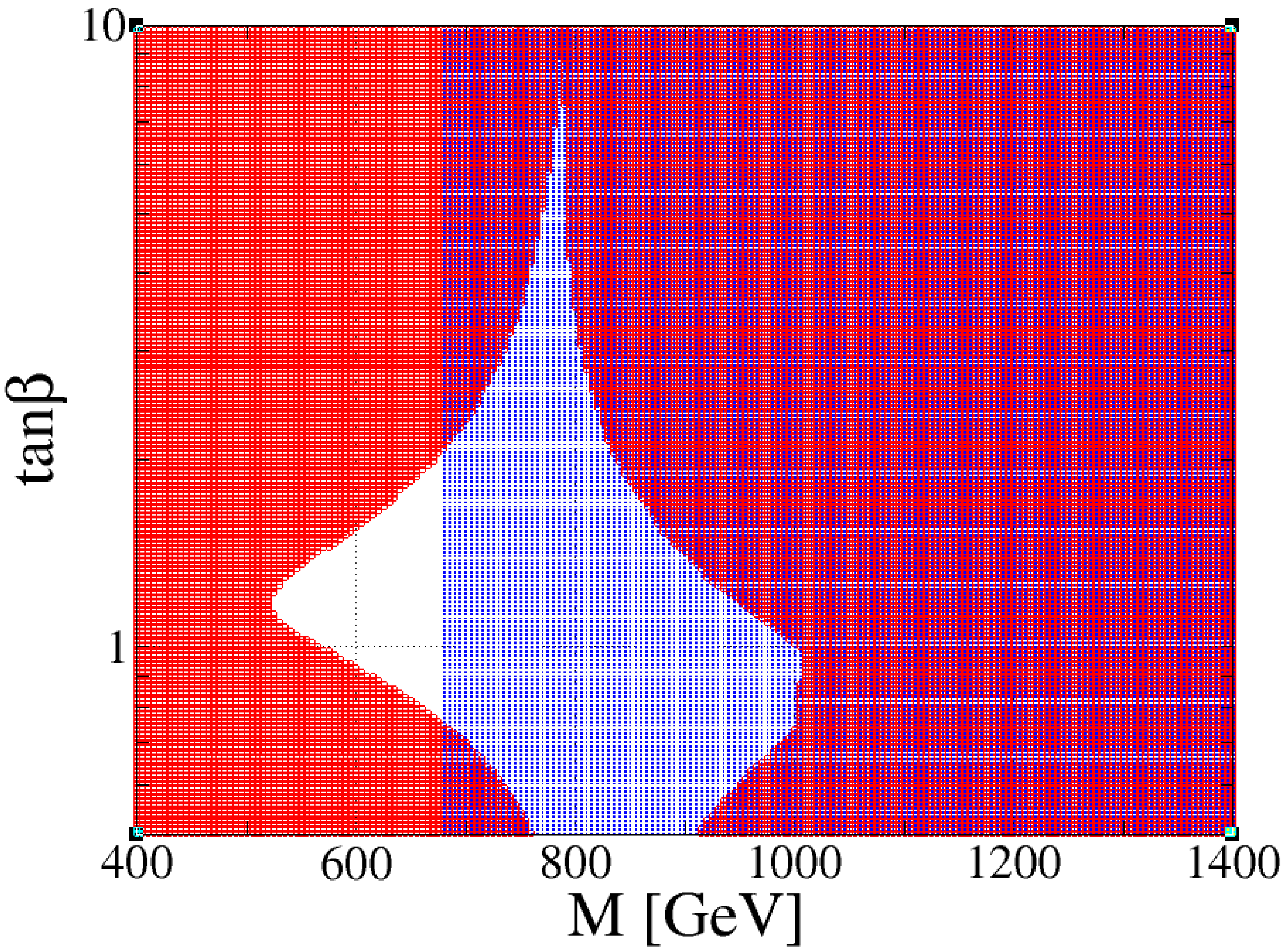
M > m_Φ is disfavored.

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

m_Φ = 800 GeV, sin(β-α) = 0.995

Excluded by the unitary bound

Excluded by the vacuum stability bound



m_Φ = 900 GeV, sin(β-α) = 0.995

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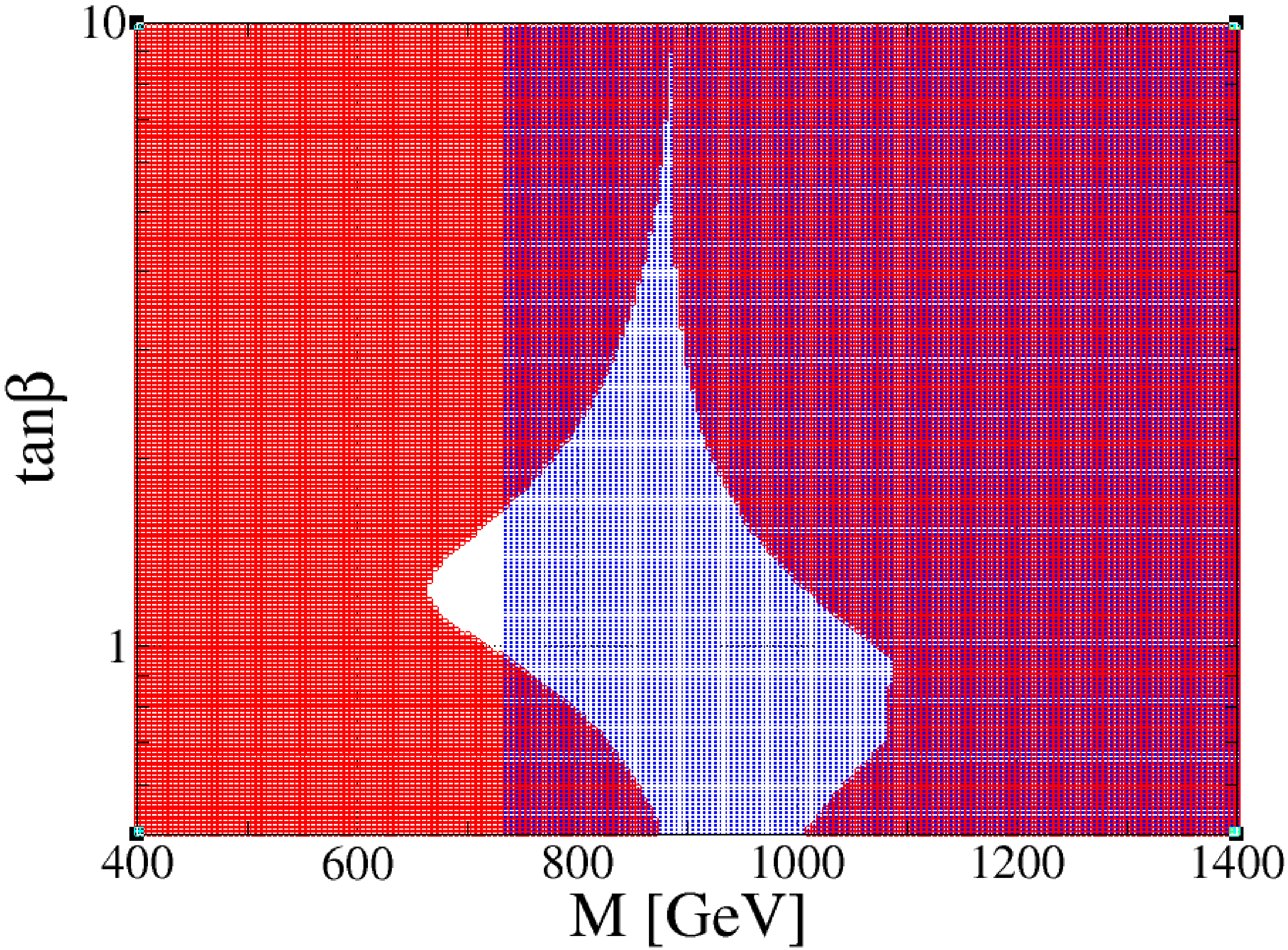
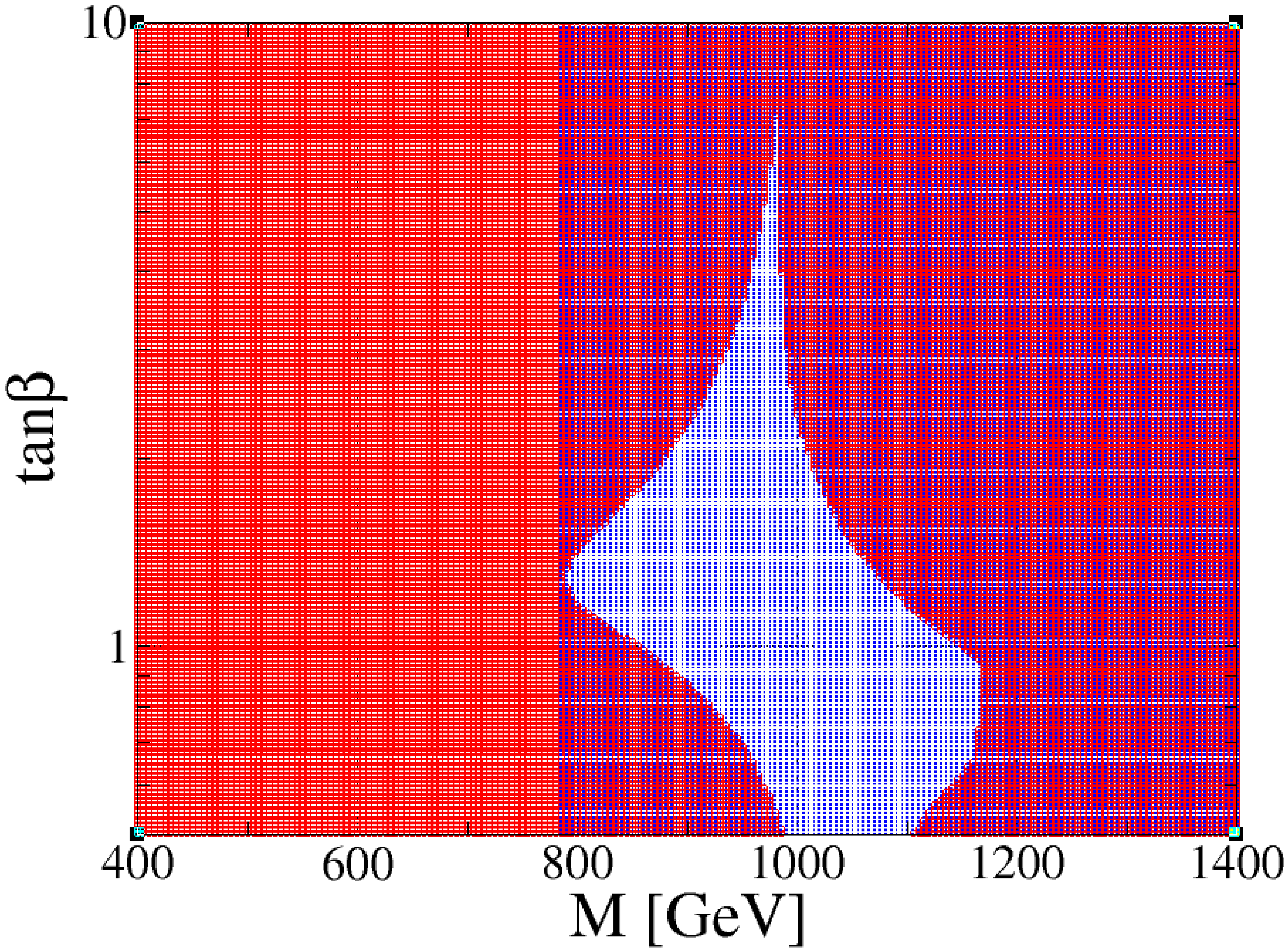


m_Φ = 1000 GeV, $\sin(\beta-\alpha)$ = 0.995

Excluded by the unitary bound

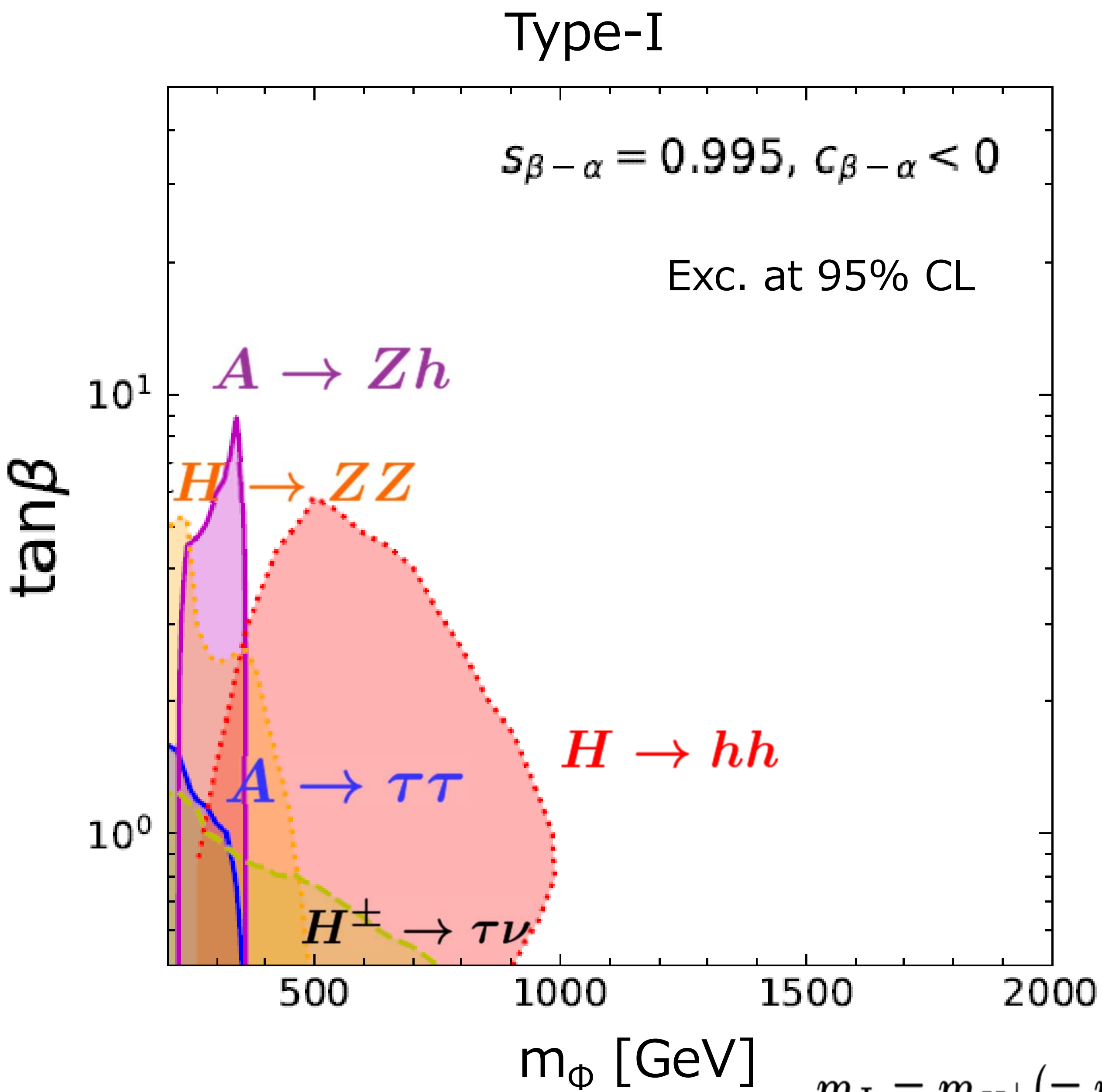
Excluded by the vacuum stability bound



Contents

Excluded region by current LHC data

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



Cross section: SusHi v1-7-0

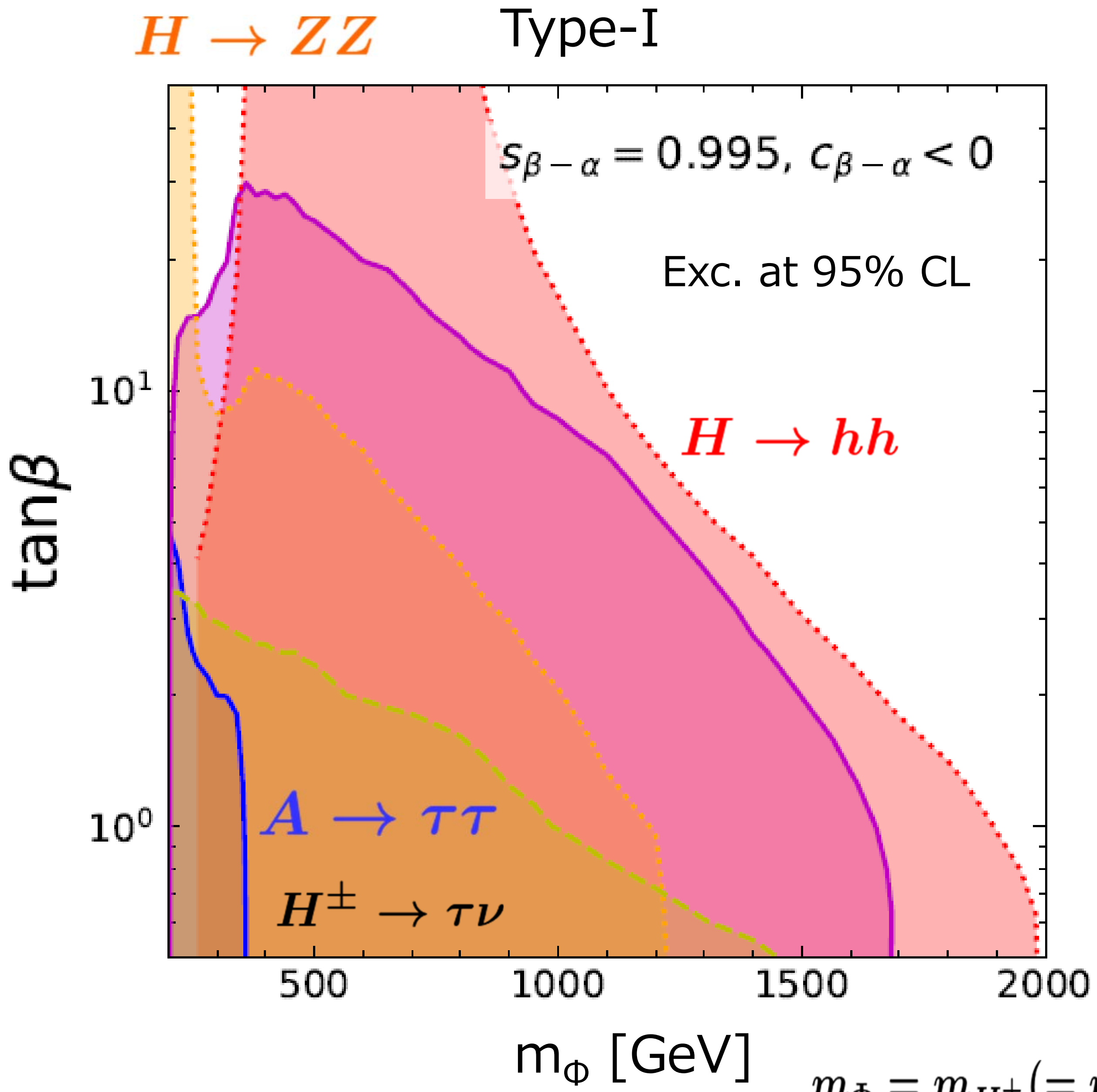
Harlander, Liebler, Mantler

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

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

Expected exclusion at HL-LHC

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



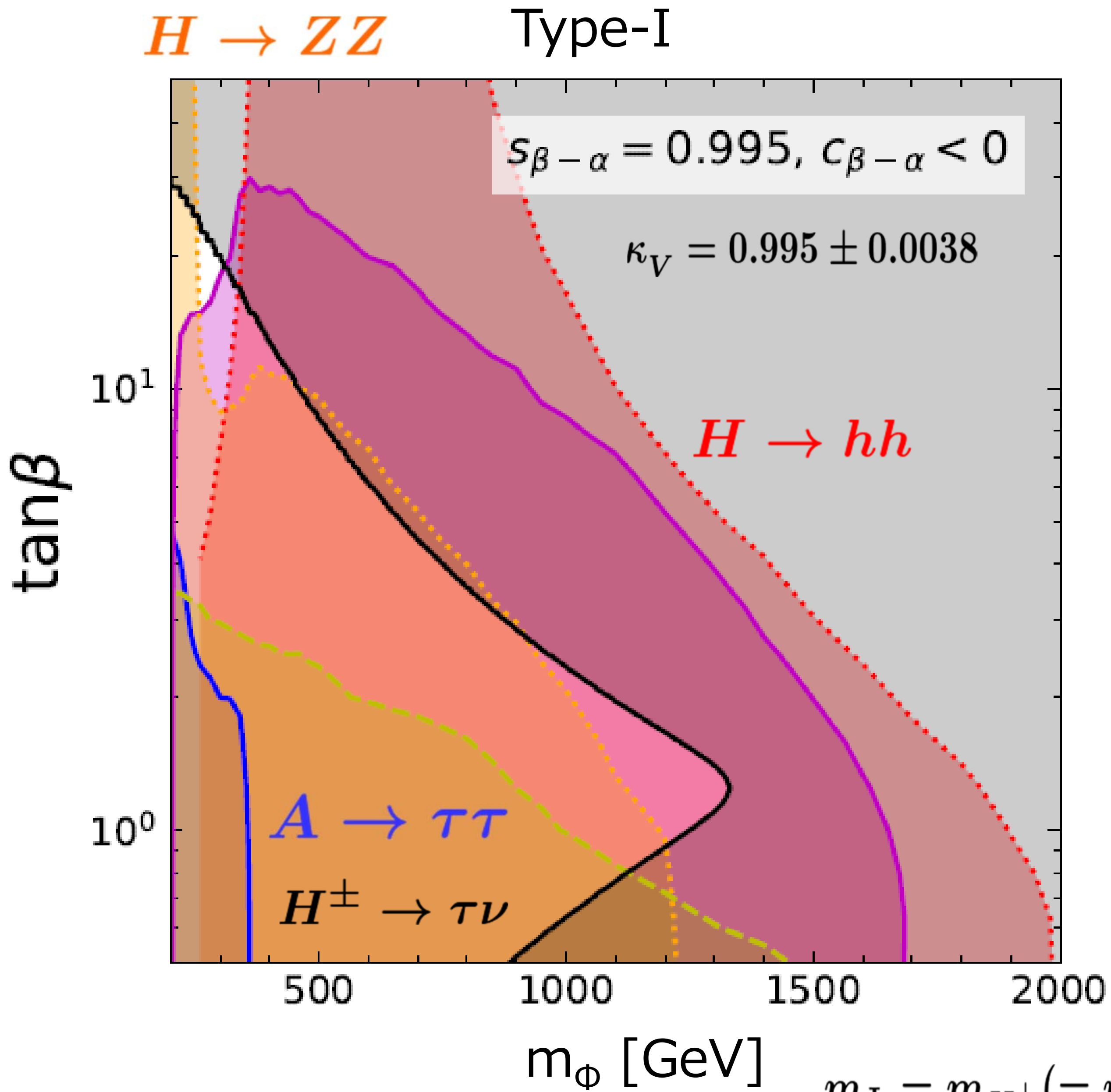
$m_\Phi = m_{H^\pm} (= m_A = m_H)$

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)



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

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

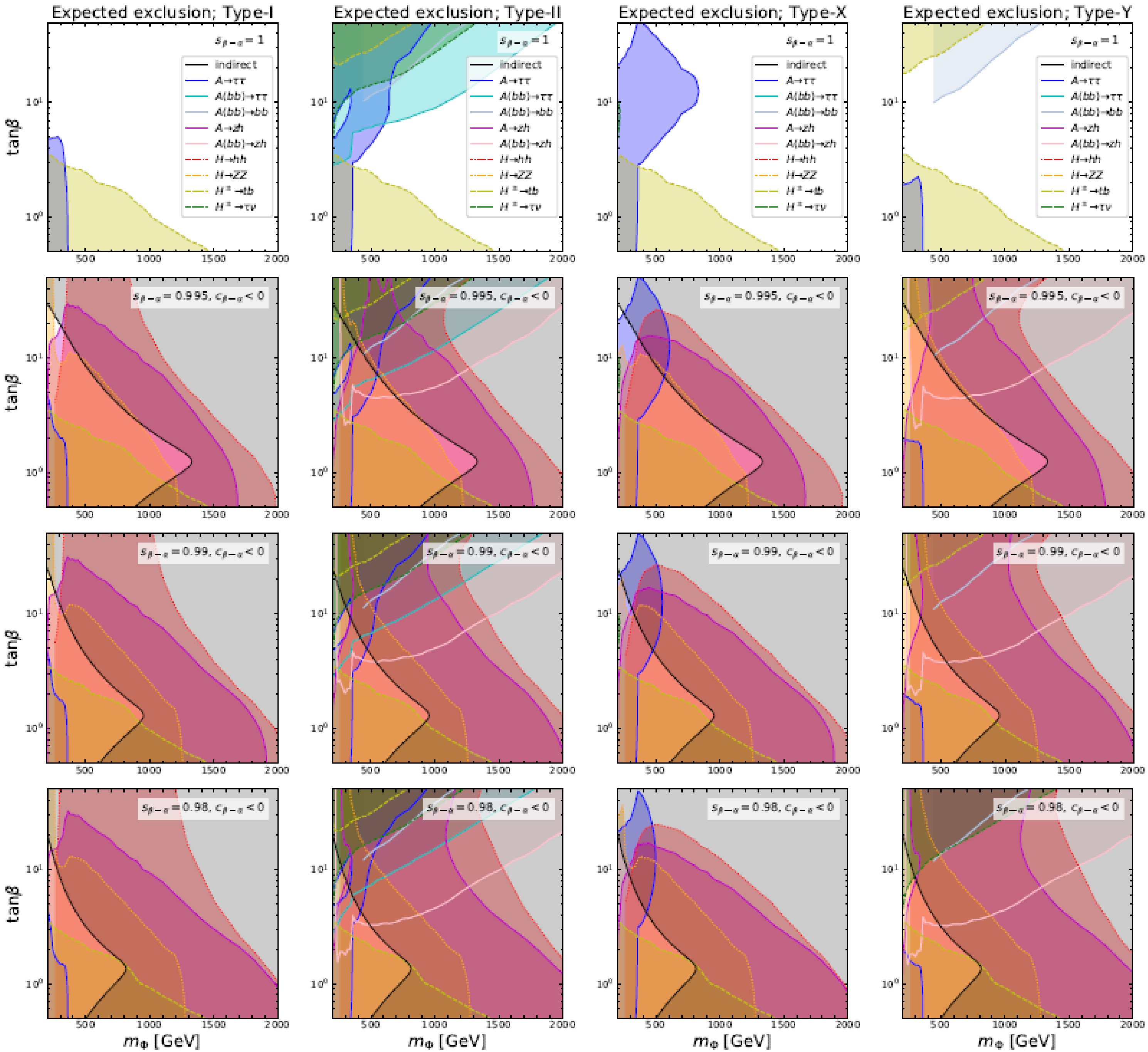
	Type-I	Type-II	Type-X	Type-Y

sin(β-α) = 1

sin(β-α) = 0.995

sin(β-α) = 0.99

sin(β-α) = 0.98



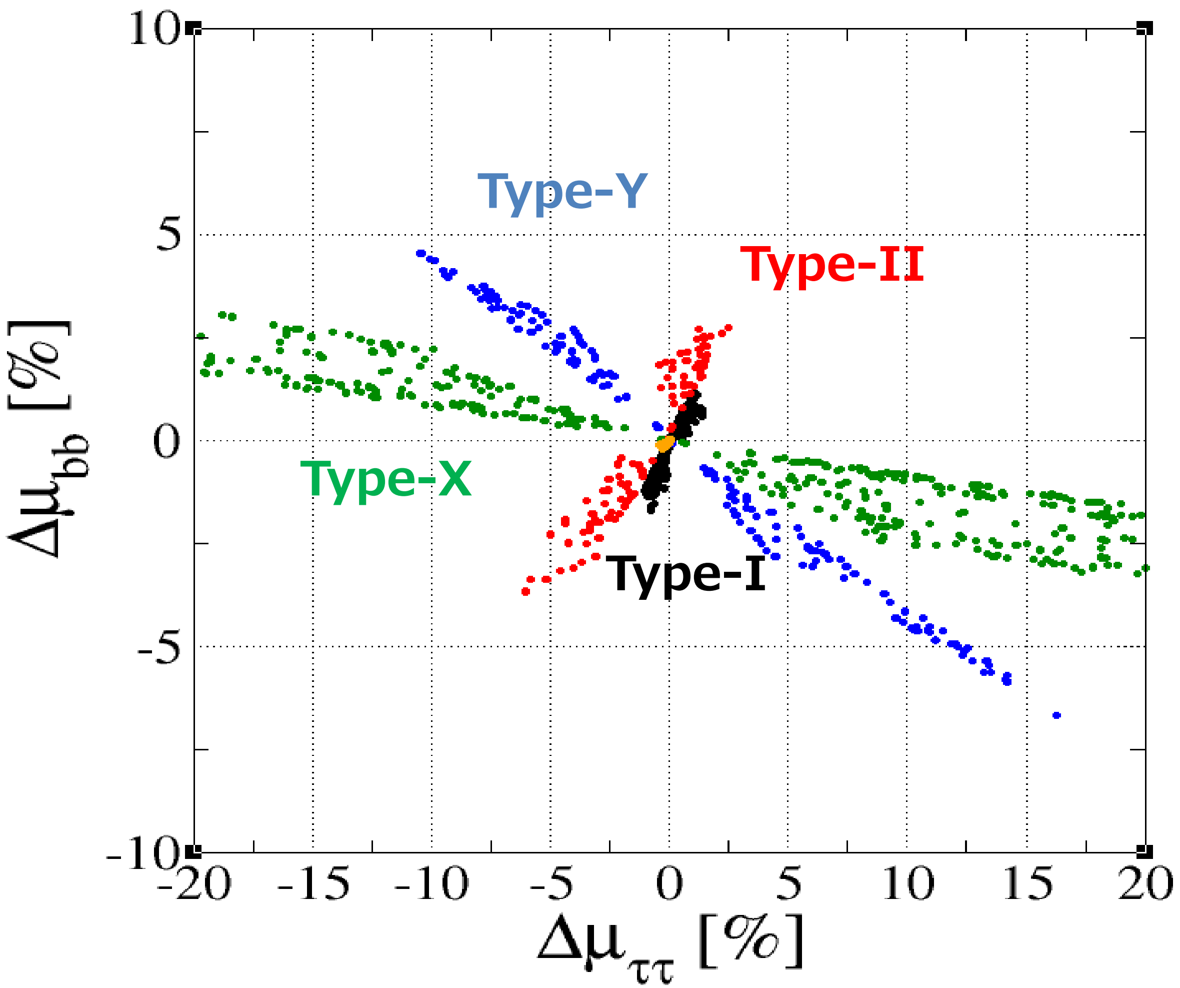
Fingerprinting the Higgs sector

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

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

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

m_Φ > 600 GeV



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

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

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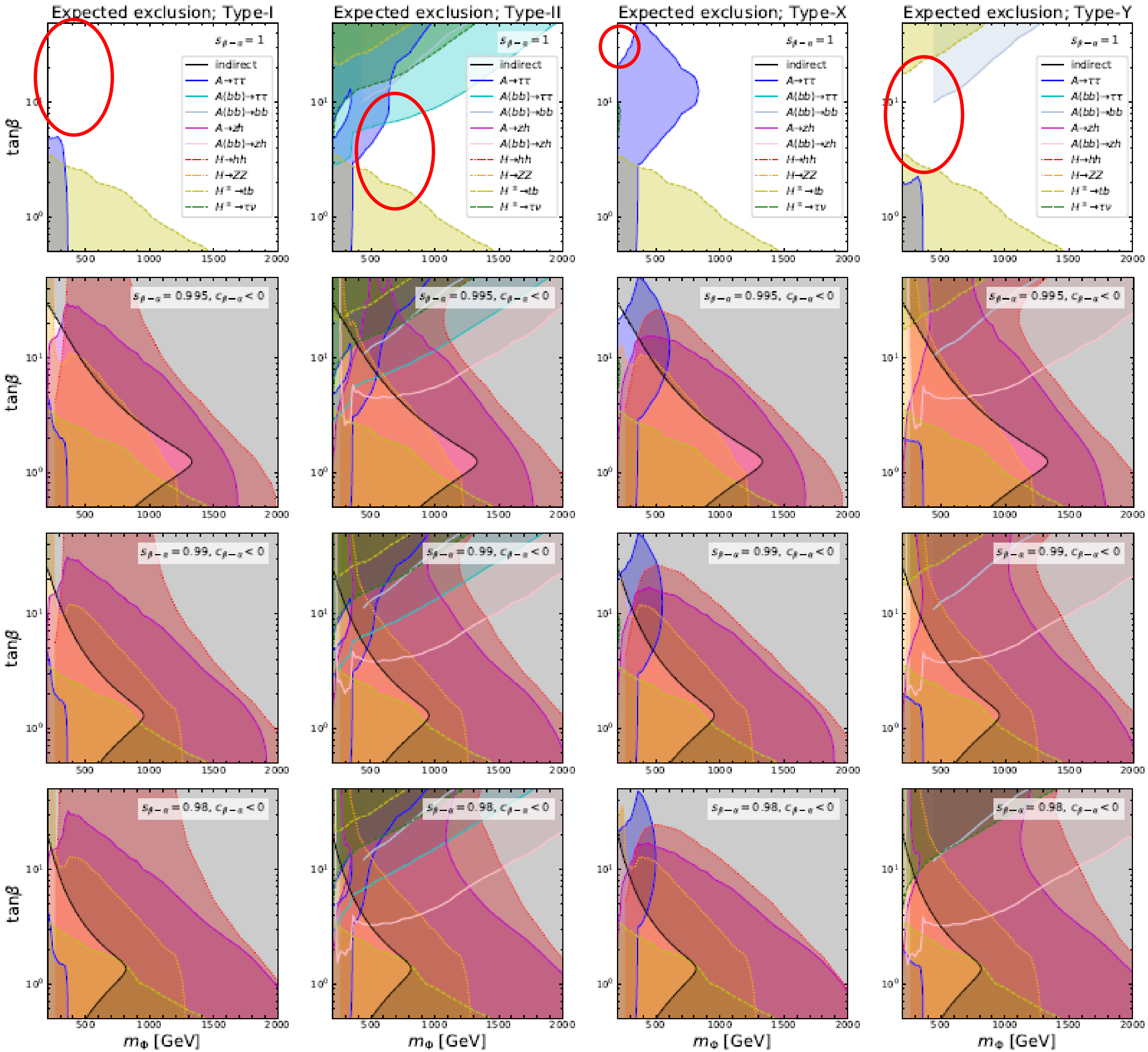
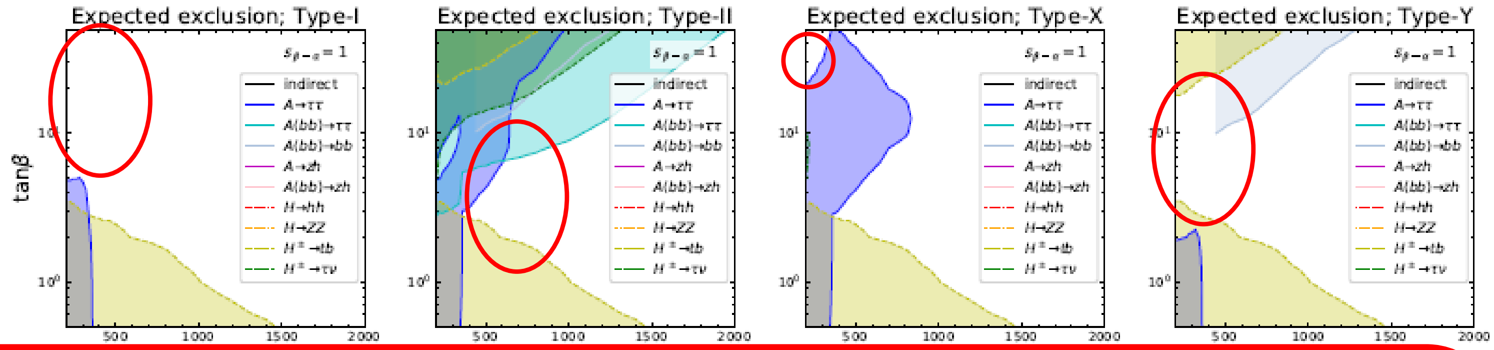


Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, KY (in preparation)

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

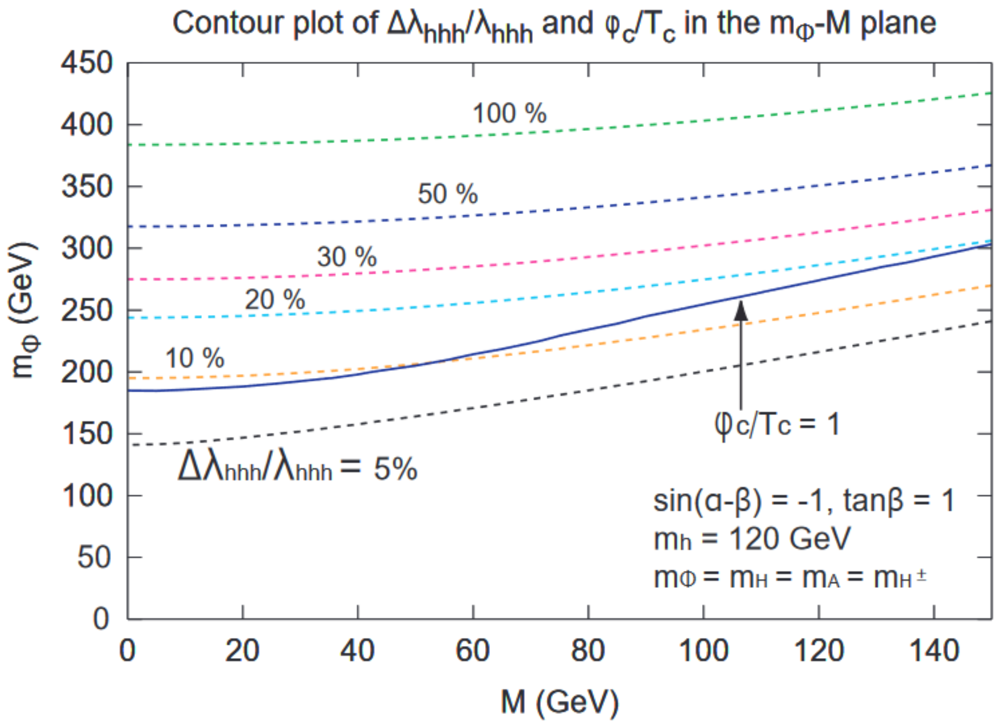
- μ(g-2) anomaly

Chun et. al, (2014)

Abe, Sato, Yagyu (2015), etc.

etc.

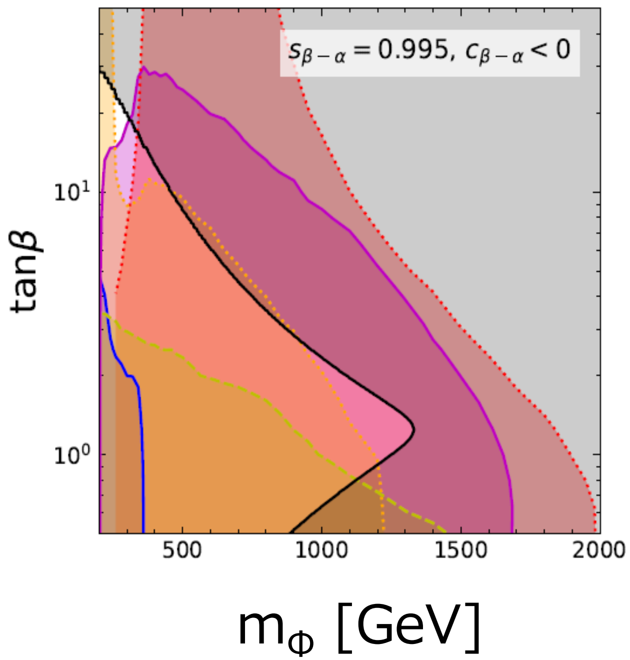
Kanemura, Okada, Senaha (2004)



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.

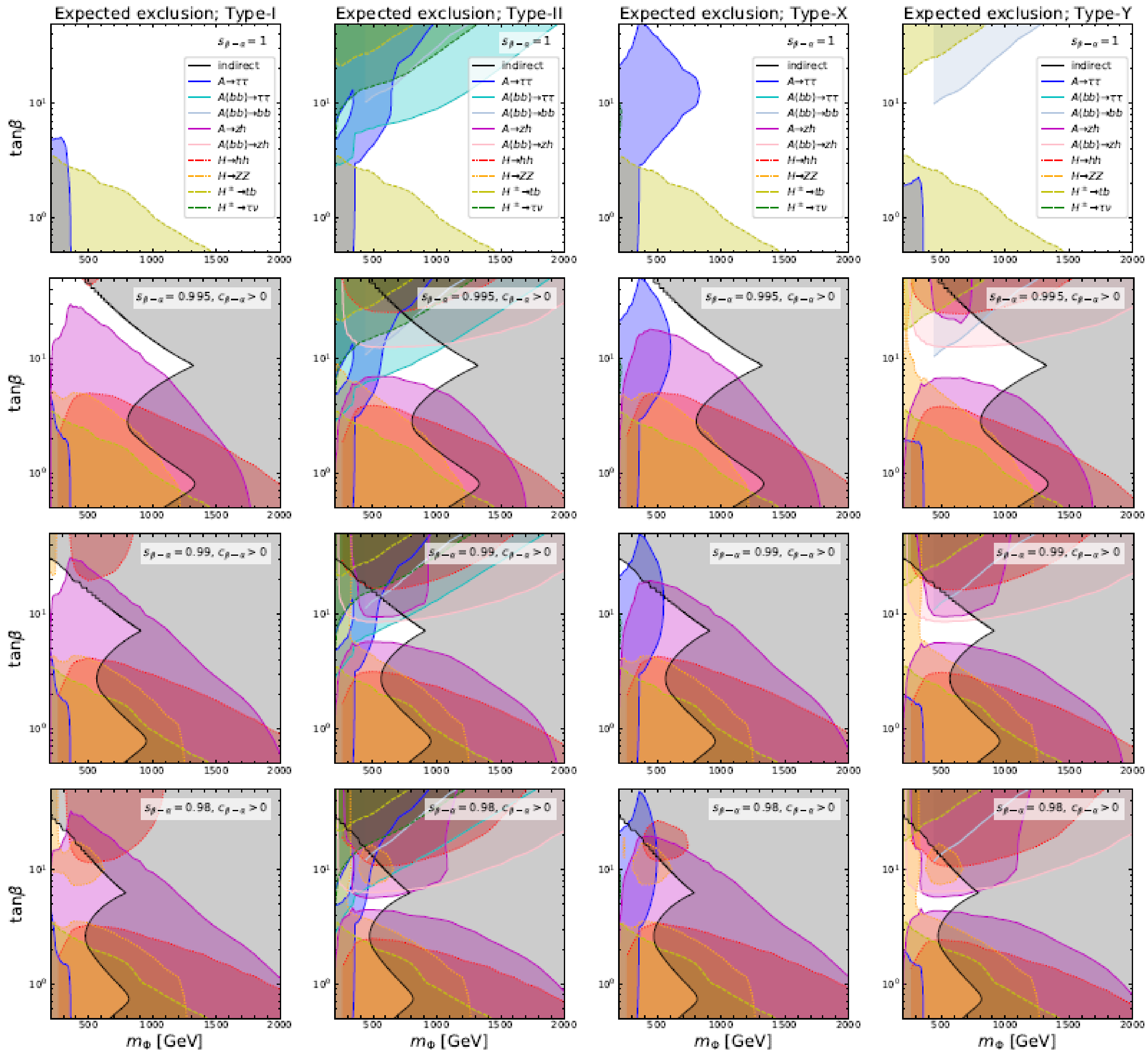
- If we find signatures → Possible new physics can be further narrowed down by the fingerprinting of the Higgs sector.



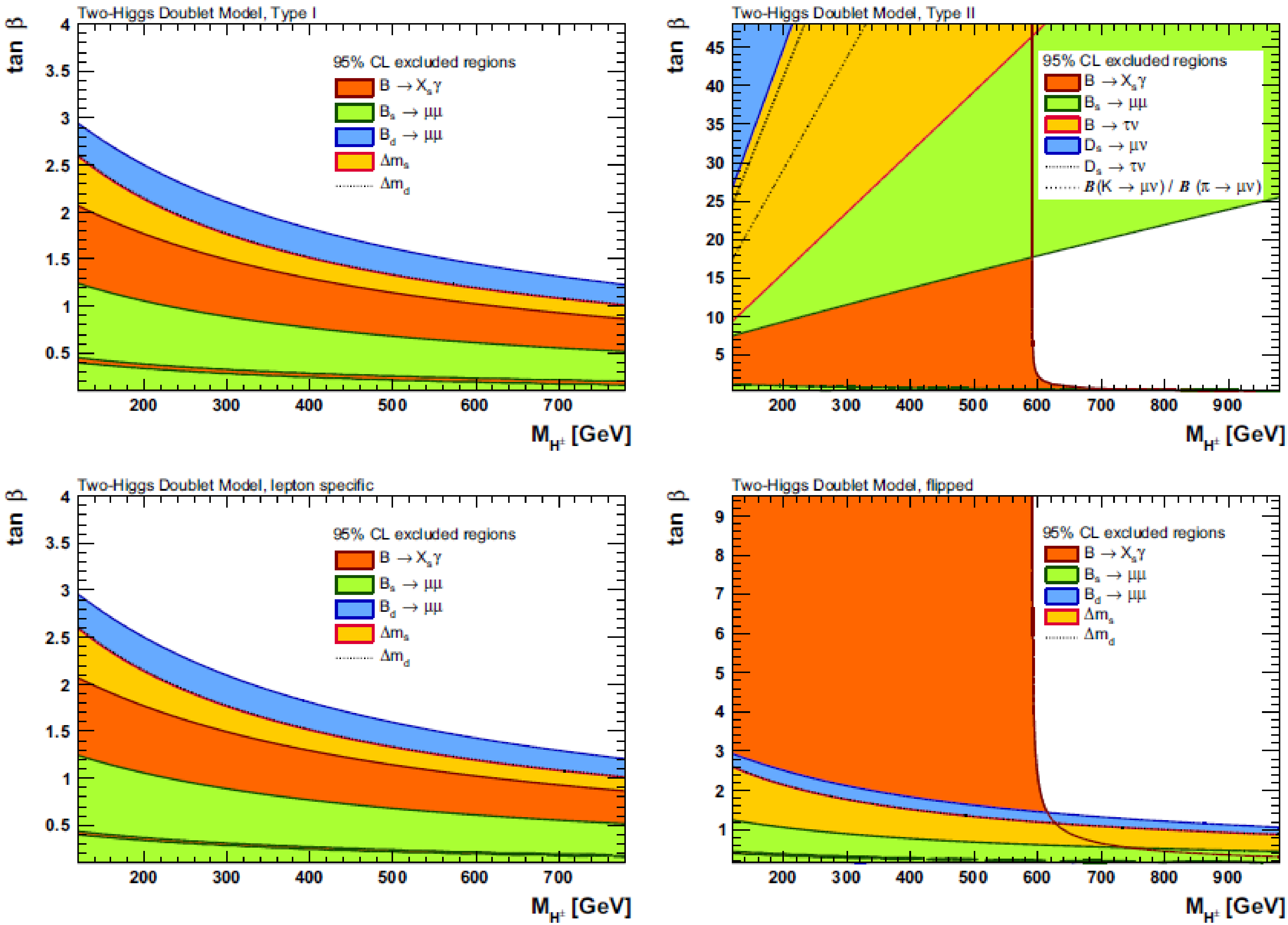
- If we do not find signatures → alignment w/o decoupling scenario can still remain.
  - Motivations: EWBG, Inert dark matter, muon g – 2, etc.

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

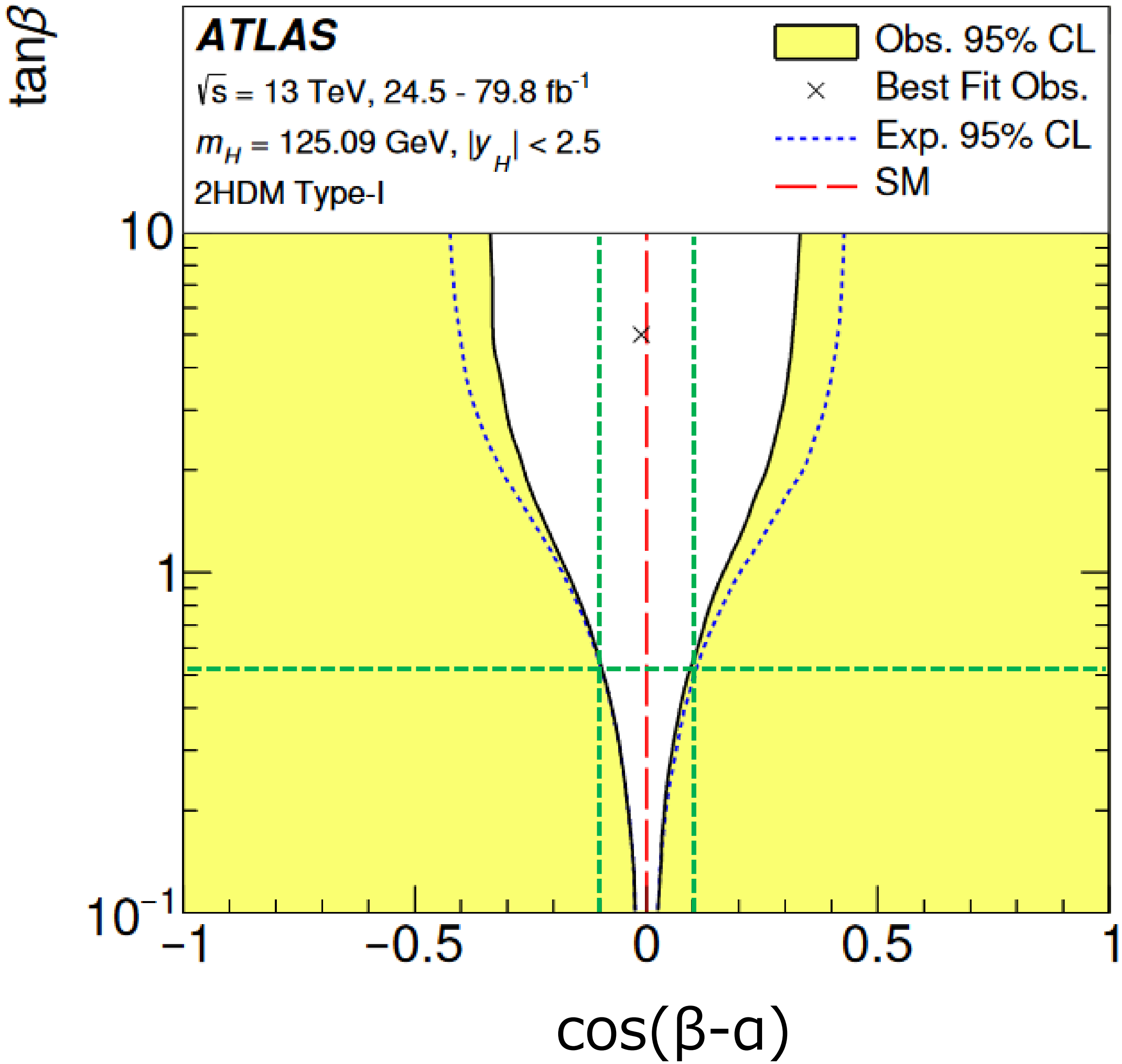
Case for cos(β-α) > 0



The G-Fitter Group, Haller et al. EPJC78 (2018)



ATLAS, arXiv:1909.02845 [hep-ex].

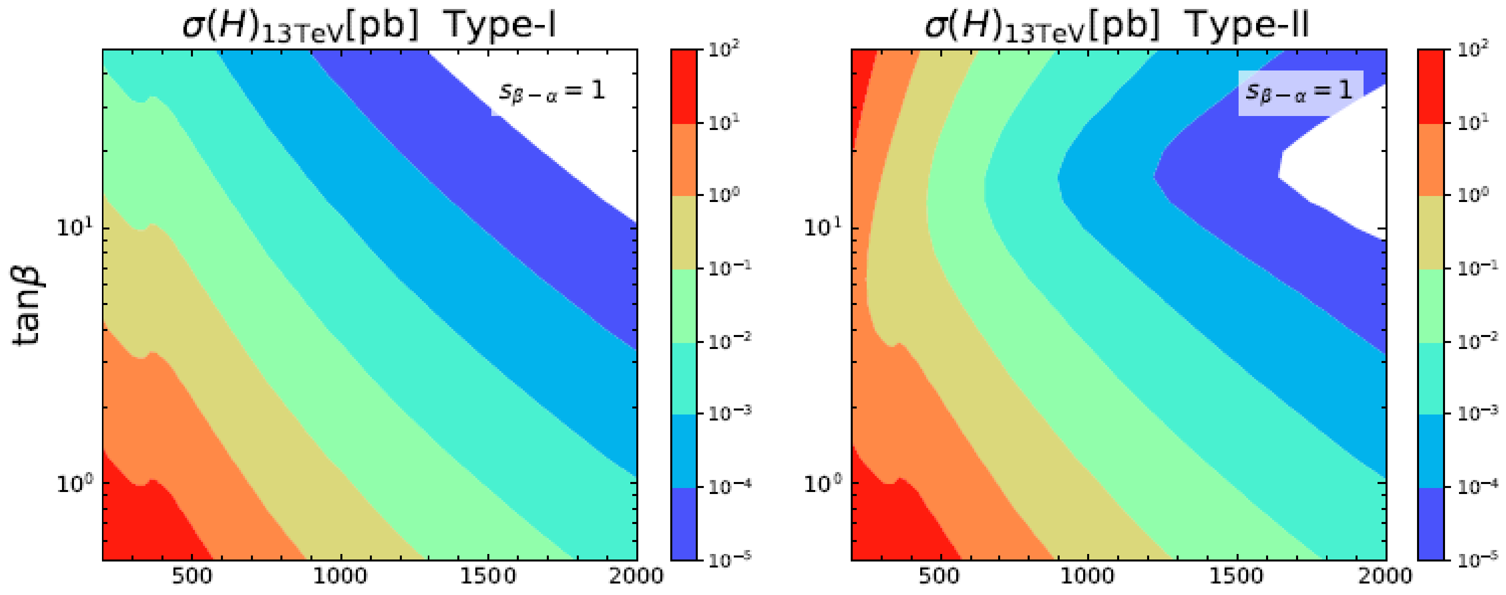


$$\tan\beta \gtrsim 0.5$$

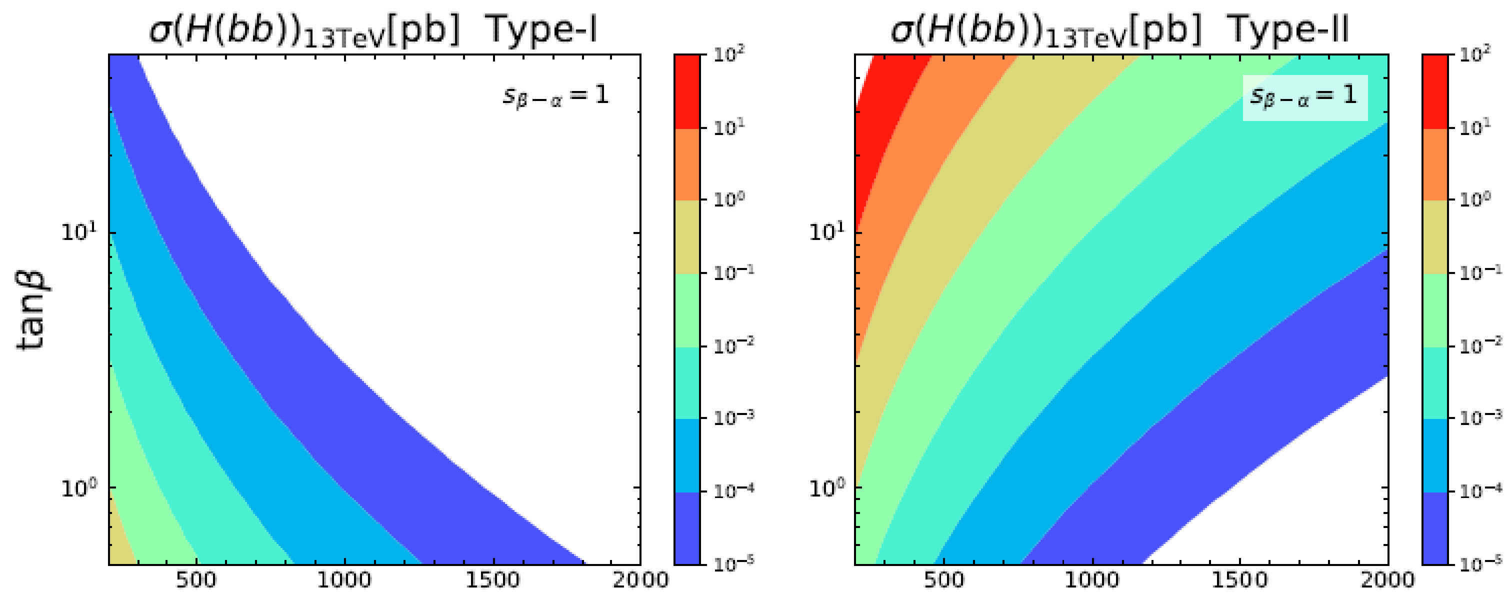
	Current (ATLAS,CMS)	HL-LHC (ATLAS,CMS) [%]	ILC250 [%]	ILC500 [%]
κ_Z	$(1.11 \pm 0.08, 1.00 \pm 0.11)$	(2.6,2.4)	0.38	0.30
κ_W	$(1.05 \pm 0.09, -1.13^{+0.16}_{-0.13})$	(3.1,2.6)	1.8	0.40
κ_b	$(1.03^{+0.19}_{-0.17}, 1.17^{+0.27}_{-0.31})$	(6.2, 6.0)	1.8	0.60
κ_t	$(1.09^{+0.15}_{-0.14}, 0.98 \pm 0.14)$	(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
$\sigma(\phi) \times B(\phi \to \tau\tau)$	$200 < m_\Phi < 2000$ GeV	Fig. 7(a) in [1]
$\sigma(\phi(bb)) \times B(\phi \to \tau\tau)$	$200 < m_\Phi < 2000$ GeV	Fig. 7(b) in [1]
$\sigma(\phi(bb)) \times B(\phi \to bb)$	$450 < m_\Phi < 1400$ GeV	Fig. 8 in [2]
$\sigma(\phi) \times B(\phi \to tt)$	$400 < m_\Phi < 5000$ GeV	Fig. 14 in [3]
$\sigma(H) \times B(H \to hh) \times B(h \to bb)^2$	$260 < m_\Phi < 2000$ GeV	Fig. 9(a) in [4]
$\sigma(H) \times B(H \to WW)$	$200 < m_\Phi < 2000$ GeV	Fig. 5 in [5]
$\sigma(H) \times B(H \to ZZ)$	$200 < m_\Phi < 2000$ GeV	Fig. 6 in [6]
$\sigma(A) \times B(A \to Zh) \times B(h \to bb)$	$200 < m_\Phi < 2000$ GeV	Fig. 6(a) in [7]
$\sigma(A(bb)) \times B(A \to Zh) \times B(h \to bb)$	$200 < m_\Phi < 2000$ GeV	Fig. 6(b) in [7]
$\sigma(tH^\pm) \times B(H^\pm \to tb)$	$200 < m_\Phi < 2000$ GeV	Fig. 8 in [8]
$\sigma(tH^\pm) \times B(H^\pm \to \tau\nu)$	$200 < m_\Phi < 2000$ GeV	Fig. 8(a) in [9]

gg → H/A

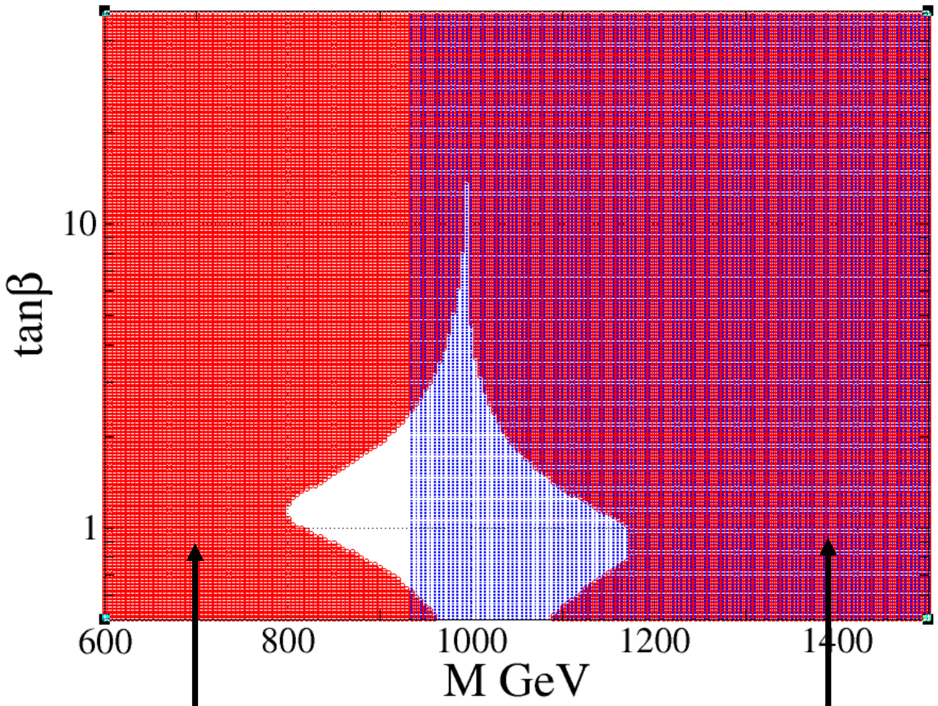


gg → bbH/bbA

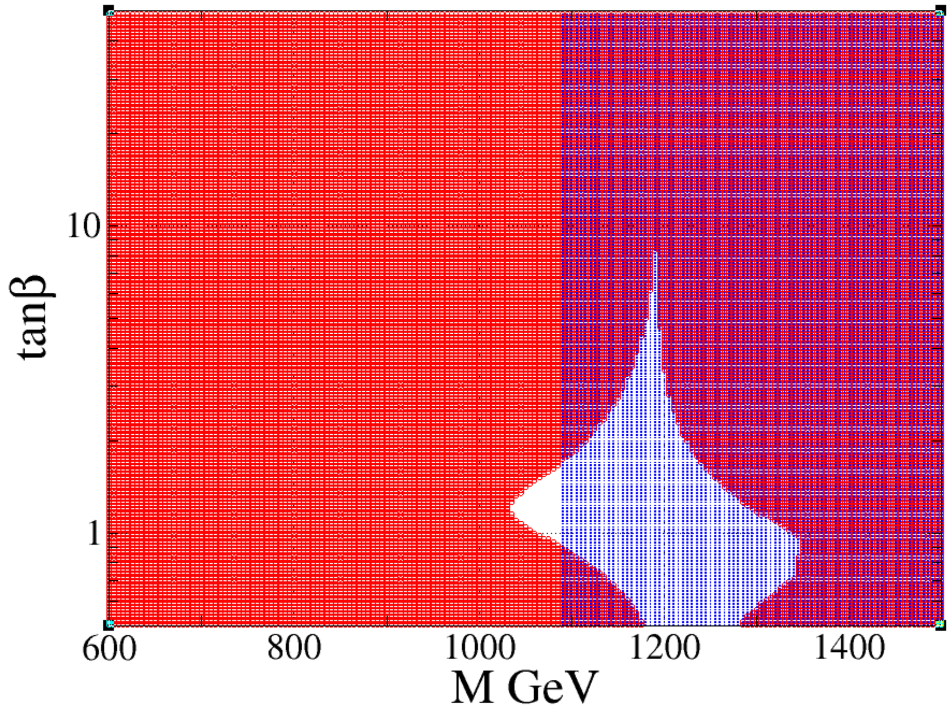


$\sin(\beta-\alpha) = 0.995$, $\cos(\beta-\alpha) < 0$

$m_\Phi = 1000$ GeV



$m_\Phi = 1200$ 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.