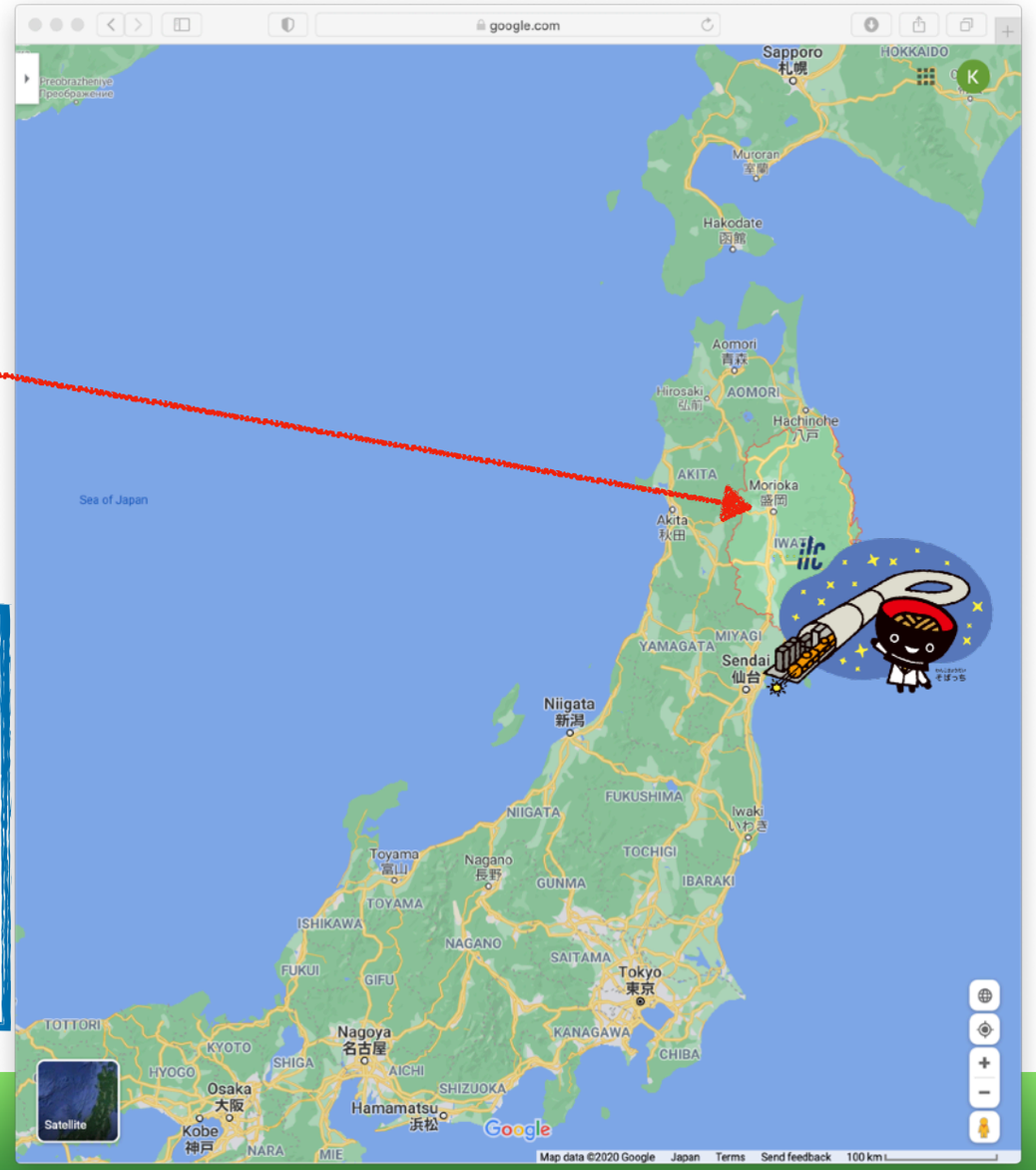
Probing extended Higgs sectors by the synergy between the LHC and the ILC

Kentarou Mawatari

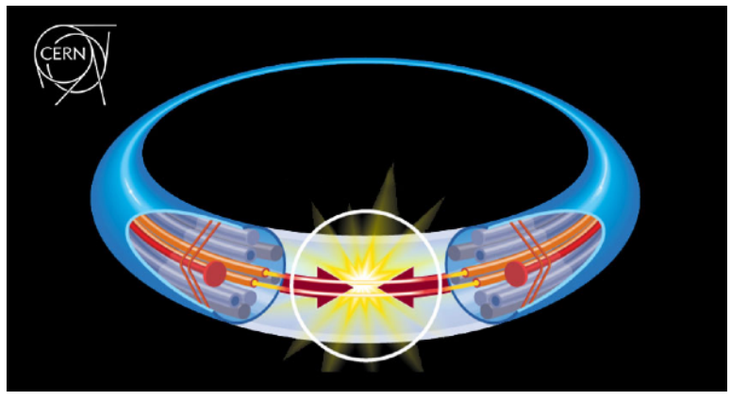
Iwate University 岩手大学



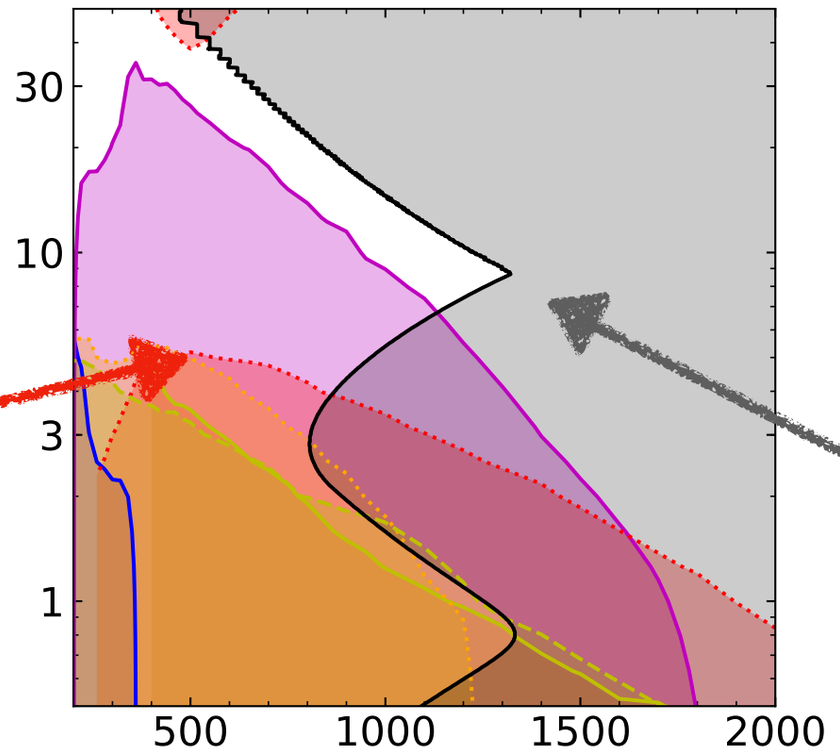
[arXiv: 2010.15057, NPB]

in collaboration with
- Masashi Aiko (Osaka U.)
- Shinya Kanemura (Osaka U.)
- Mariko Kikuchi (Kitakyushu College→Nihon U.)
- Kodai Sakurai (Karlsruhe→Tohoku U.)
- Kei Yagyu (Osaka U.)

Summary of my talk



synergy



(HL-)LHC
direct searches for additional Higgs bosons

ILC
precision measurements for the SM-like Higgs boson

Let's take THDMs as our benchmark model to explore new physics !

* Two Higgs doublet models is the one of the simplest extension of the SM, but the models provide us rich pheno.

Two Higgs doublet models in a nutshell

$$V(\Phi_1,\Phi_2) = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+\frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}]$$

- <u>Two important predictions:</u>
  1. additional Higgs bosons (H, A, H±)
  2. deviations of the h(125) couplings from the SM

  ➡ described by 6 free parameters: $m_H,\ m_A,\ m_{H^\pm},\ M^2,\ \tan\beta,\ s_{\beta-\alpha},$

- <u>Two important limits:</u>
  1. decoupling limit $M \to \infty$
     - H, A, H± become very heavy.
  2. alignment limit $\sin(\beta-\alpha) \to 1$
     - h behaves like the SM Higgs boson.
     - H, A, H± only couple to fermions.

In our study, we take

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

$$m_\Phi^2 = M^2 + \lambda_\Phi v^2 \quad (\Phi = H, A, H^\pm)$$

$$\kappa_X^\phi \equiv \frac{g_{\phi X\bar{X}}}{g_{h_{\rm SM}X\bar{X}}}$$

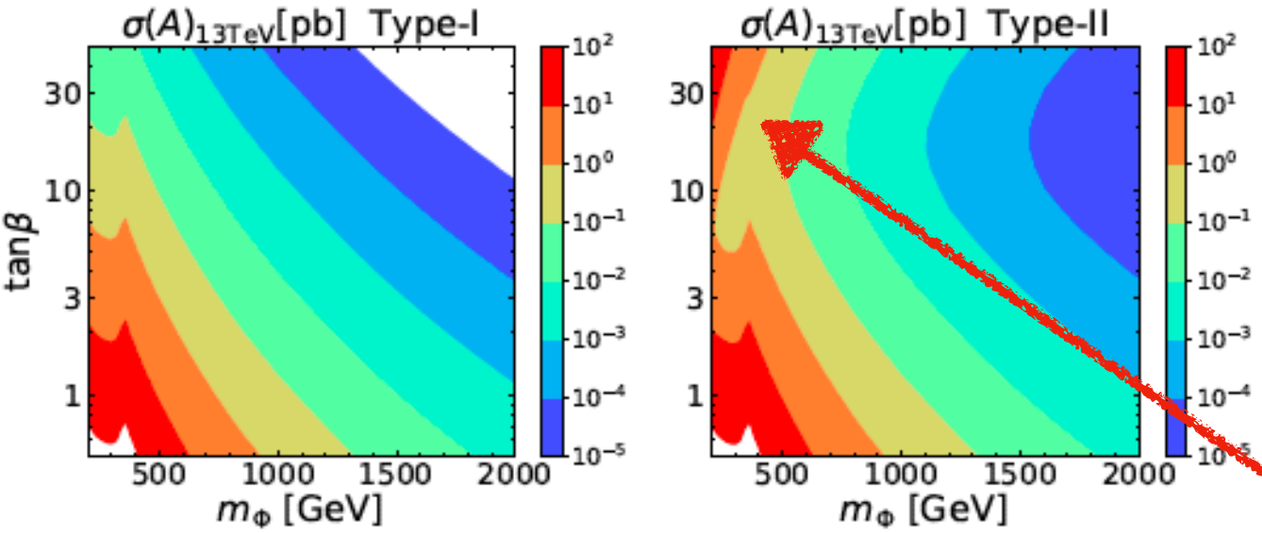
$$\kappa_V^h = s_{\beta-\alpha}, \quad \kappa_V^H = c_{\beta-\alpha}, \quad \kappa_V^A = 0,$$
$$\kappa_f^h = s_{\beta-\alpha} + c_{\beta-\alpha}\zeta_f, \quad \kappa_f^H = c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f, \quad \kappa_f^A = -2iI_f\zeta_f,$$

* ζ=1/tanβ or tanβ, depending on the type of THDMs.

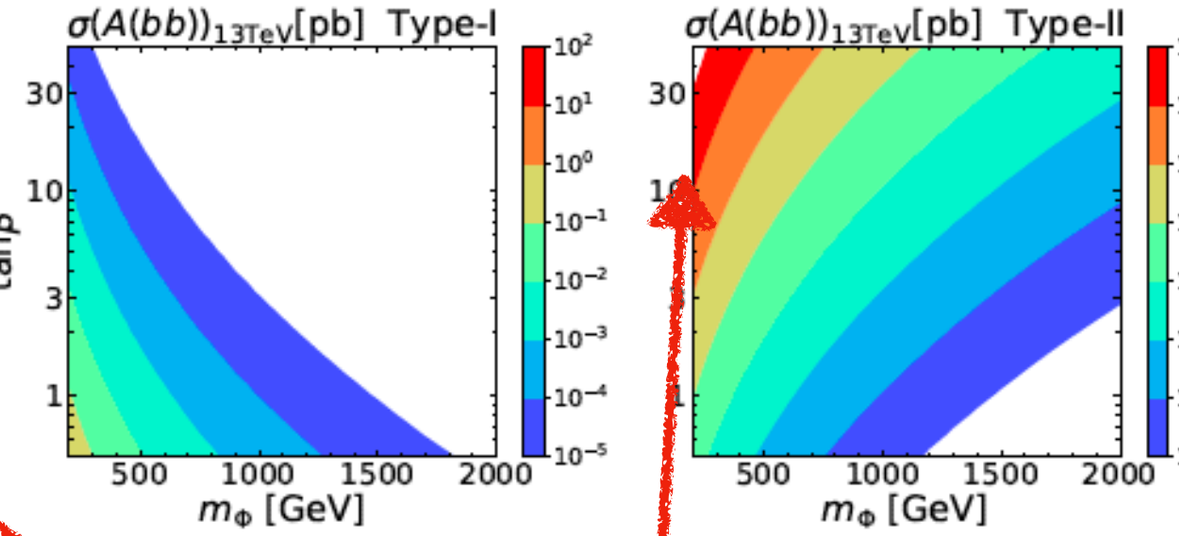
* σ (H, H±) in backup.

Production: CP-odd Higgs boson (A)

gluon fusion via heavy-quark loops



b-quark fusion (b-quark associated)



[Sushi-1.7.0]

$$\kappa_f^A = -2iI_f\zeta_f$$

	Q_L	u_R	d_R	ζ_u	ζ_d
Type-I	+	−	−	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	$\cot\beta$	$-\tan\beta$

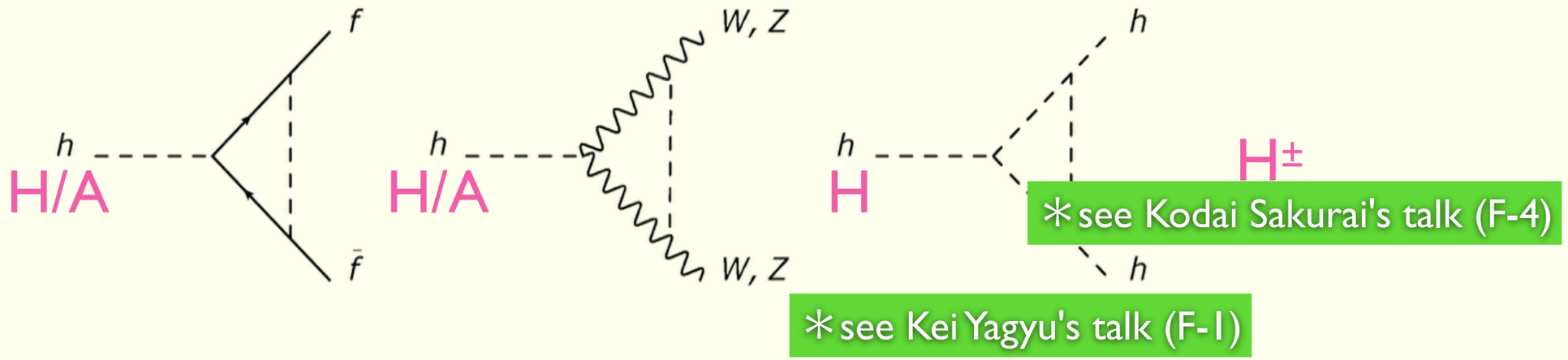
X

Y

tanβ enhancement

素 www-het.phys.sci.osaka-u.ac.jp/~hcoup/

H-COUP



＊see Kodai Sakurai's talk (F-4)

＊see Kei Yagyu's talk (F-1)

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.

→ version 3 (beta)

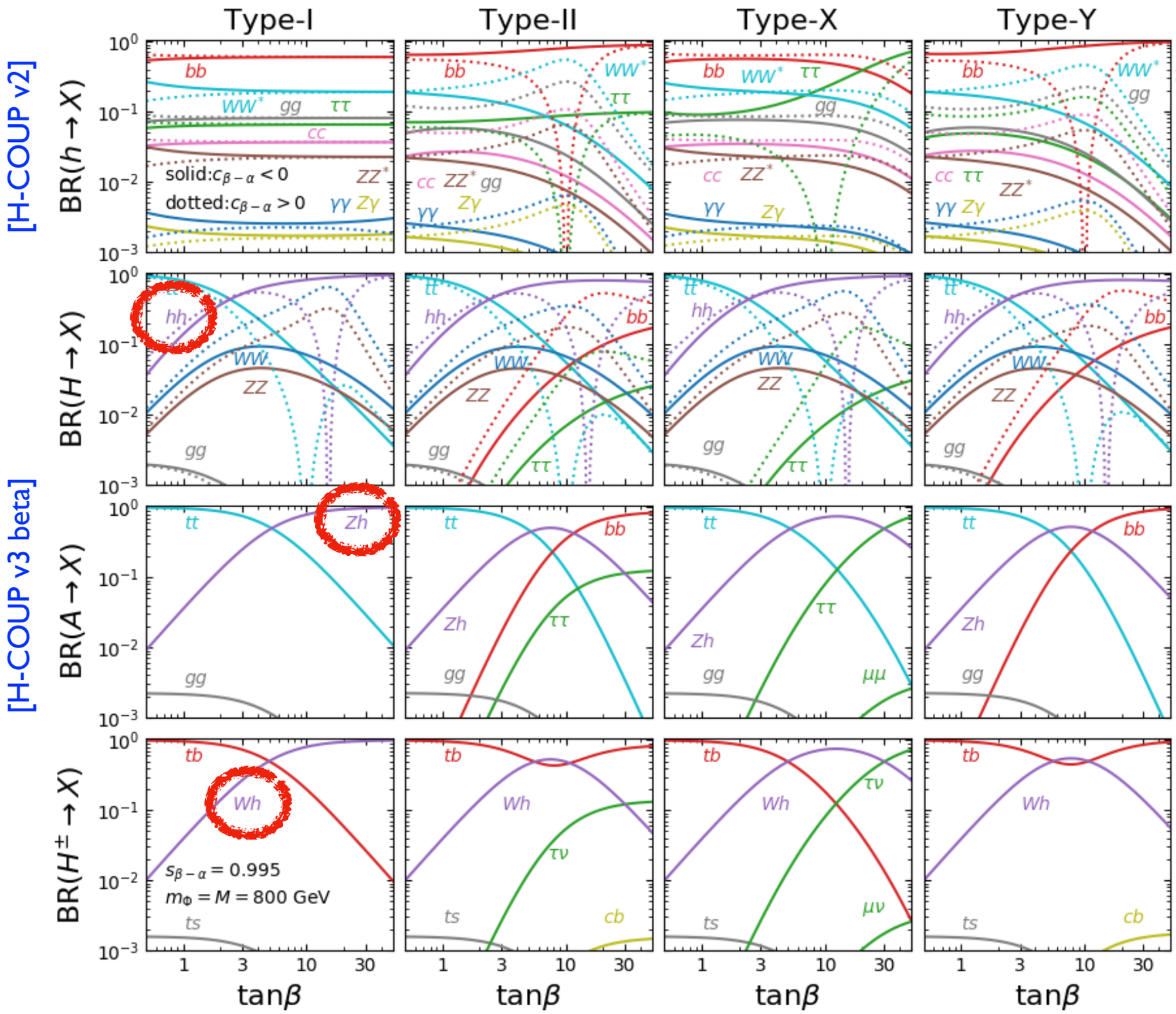
＊see Kei Yagyu's talk (F-2)

Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu + Aiko

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

＊m_Φ=200GeV in backup.

Decay: non-alignment ($s_{\beta-\alpha}$=0.995), m_Φ=800GeV



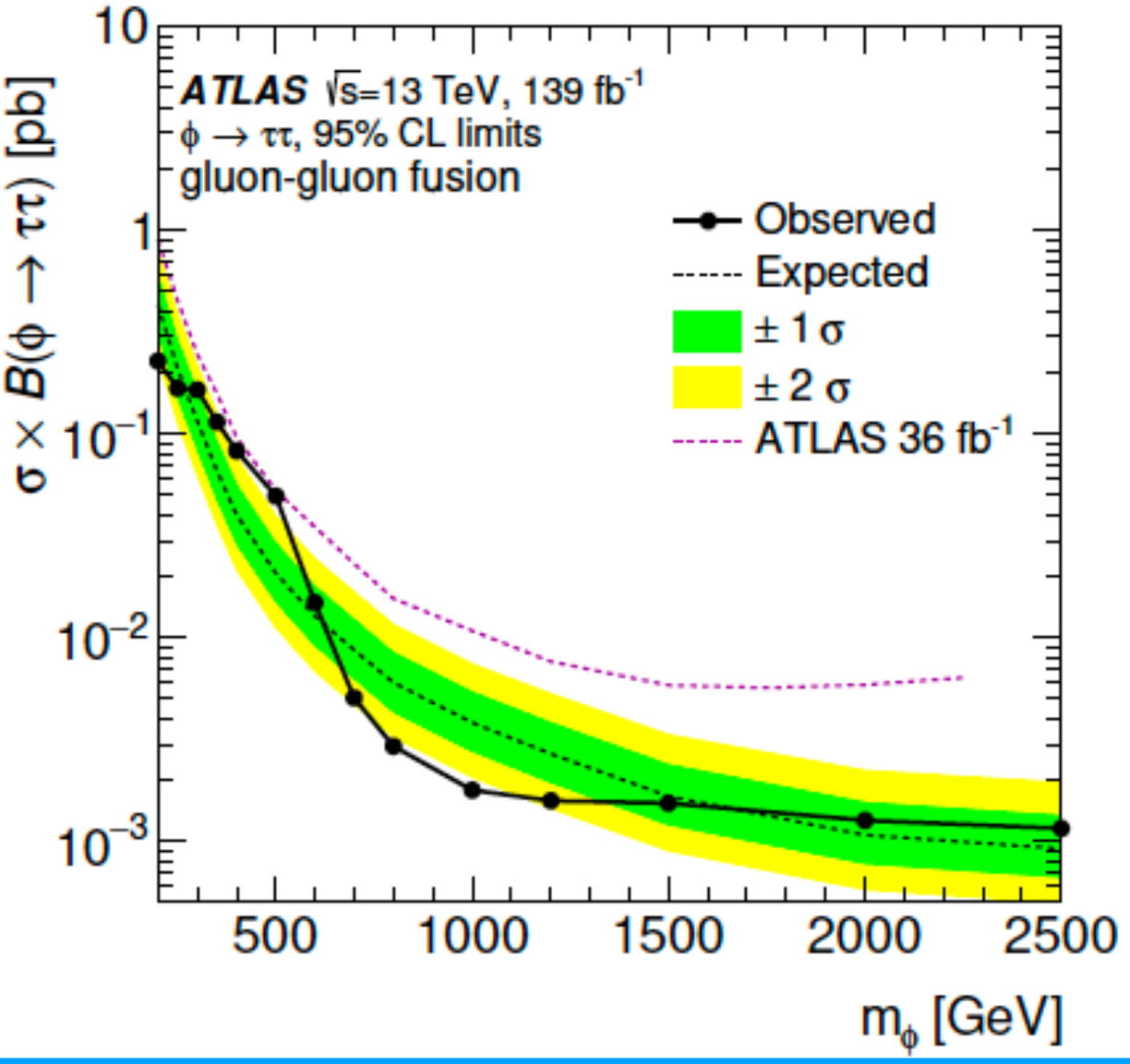
≠BR(h)$_{SM}$

	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

List of direct searches for new scalars at the LHC

LHC Run-II 36 fb^{-1} data

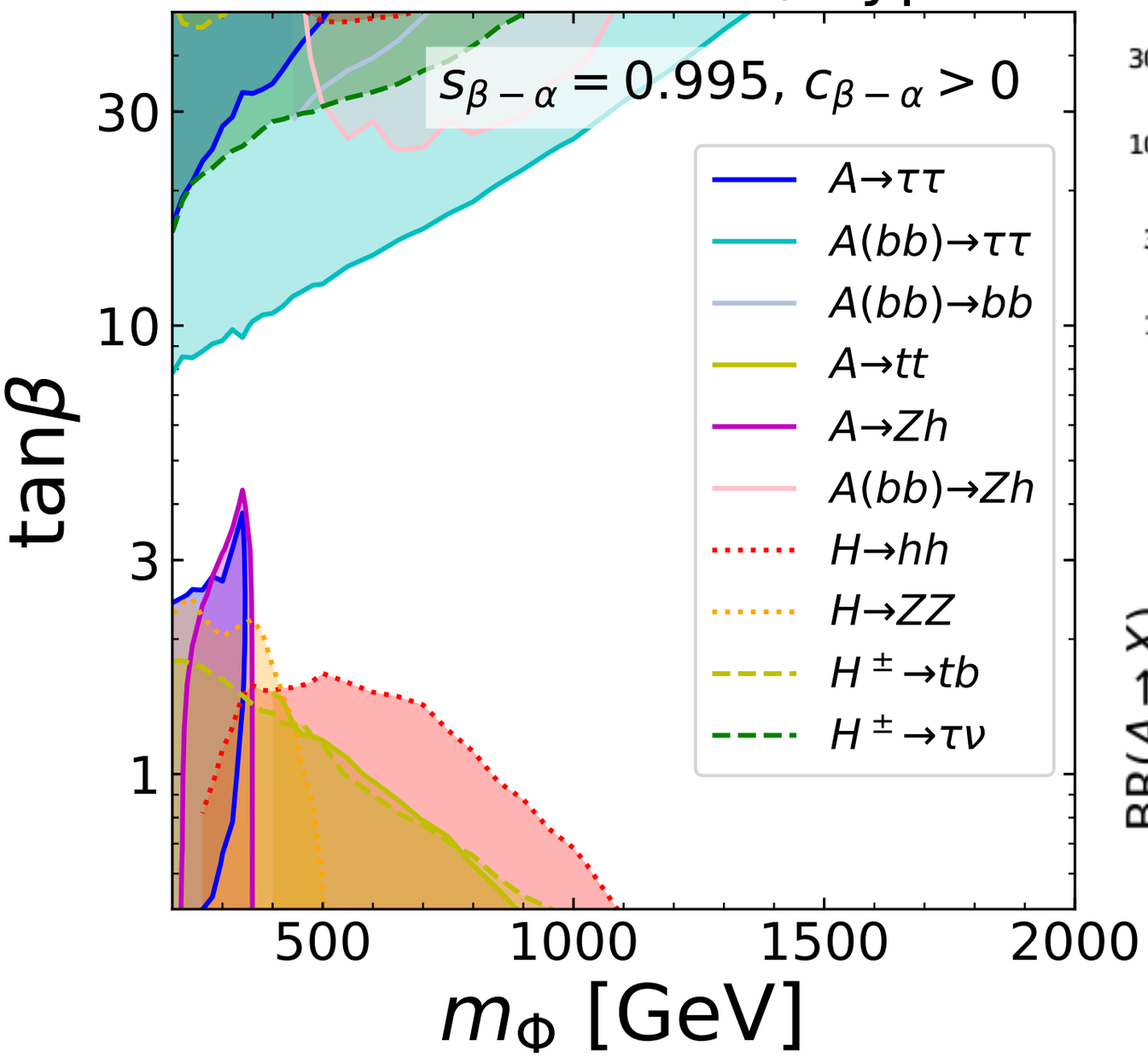
Constrained quantity
$\sigma(\phi) \times \mathrm{BR}(\phi \to \tau\tau)$
$\sigma(\phi(bb)) \times \mathrm{BR}(\phi \to \tau\tau)$
$\sigma(\phi(bb)) \times \mathrm{BR}(\phi \to bb)$
$\sigma(\phi) \times \mathrm{BR}(\phi \to tt)$
$\sigma(H) \times \mathrm{BR}(H \to hh) \times \mathrm{BR}(h \to bb)^2$
$\sigma(H) \times \mathrm{BR}(H \to WW)$
$\sigma(H) \times \mathrm{BR}(H \to ZZ)$
$\sigma(A) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to bb)$
$\sigma(A(bb)) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to bb)$
$\sigma(tH^{\pm}) \times \mathrm{BR}(H^{\pm} \to tb)$
$\sigma(tH^{\pm}) \times \mathrm{BR}(H^{\pm} \to \tau\nu)$

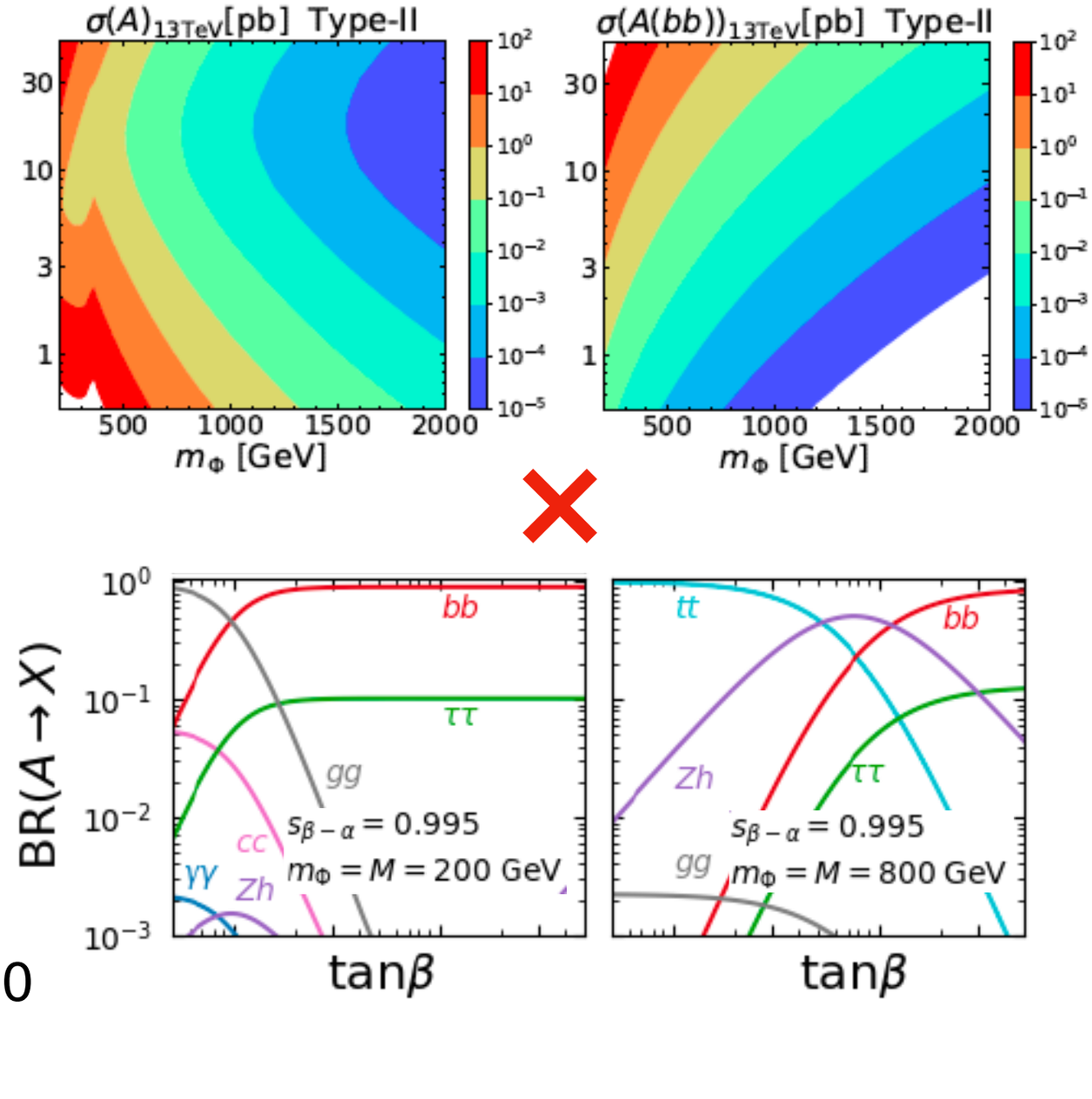


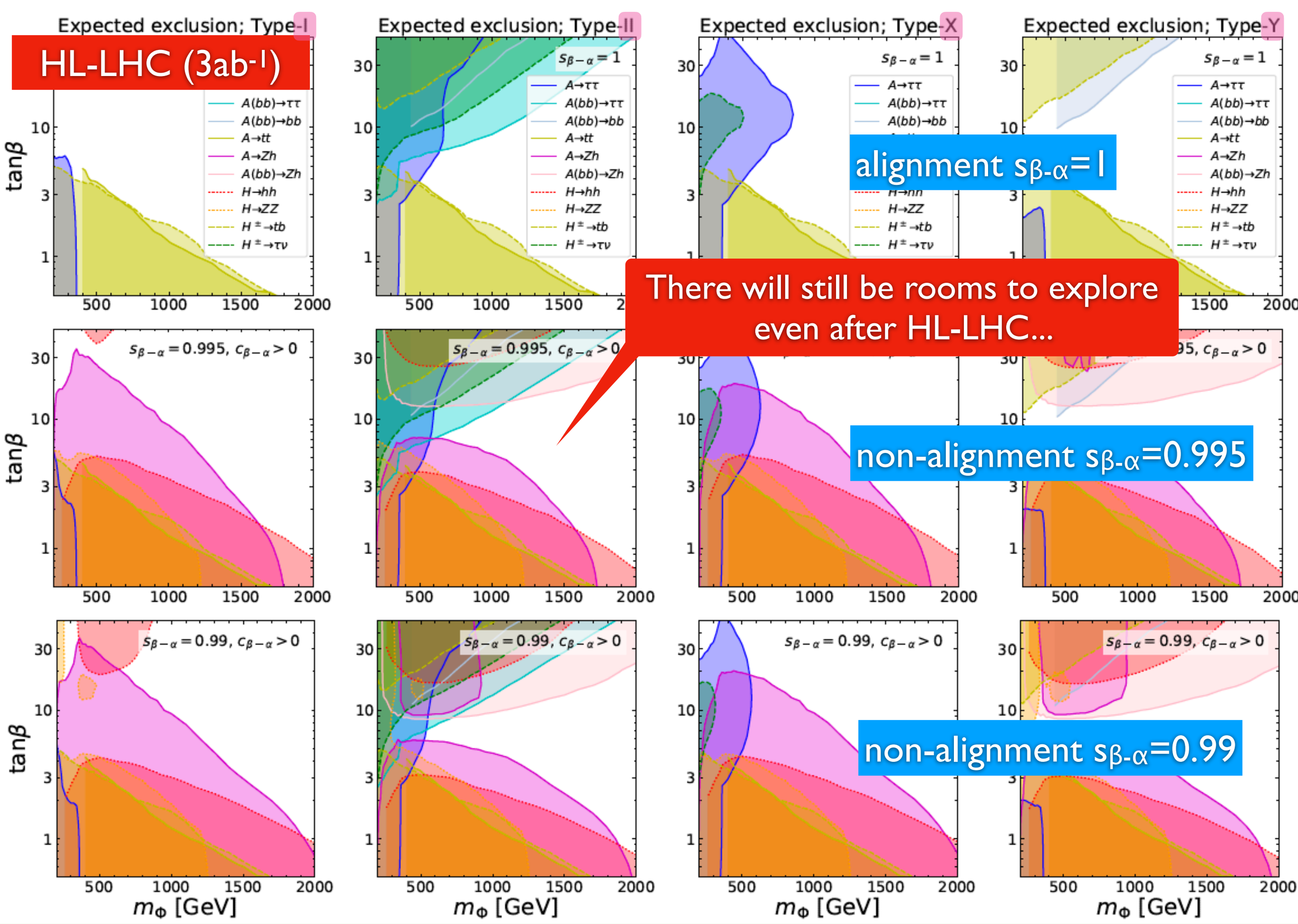
We interpret these model-independent exclusion limits to each type of THDMs on the m_Φ–tanβ plane with a fixed $s_{\beta-\alpha}$.

Exclusion region [e.g. Type-II, non-alignment ($s_{\beta-\alpha}$=0.995)]

Current exclusion; Type-II

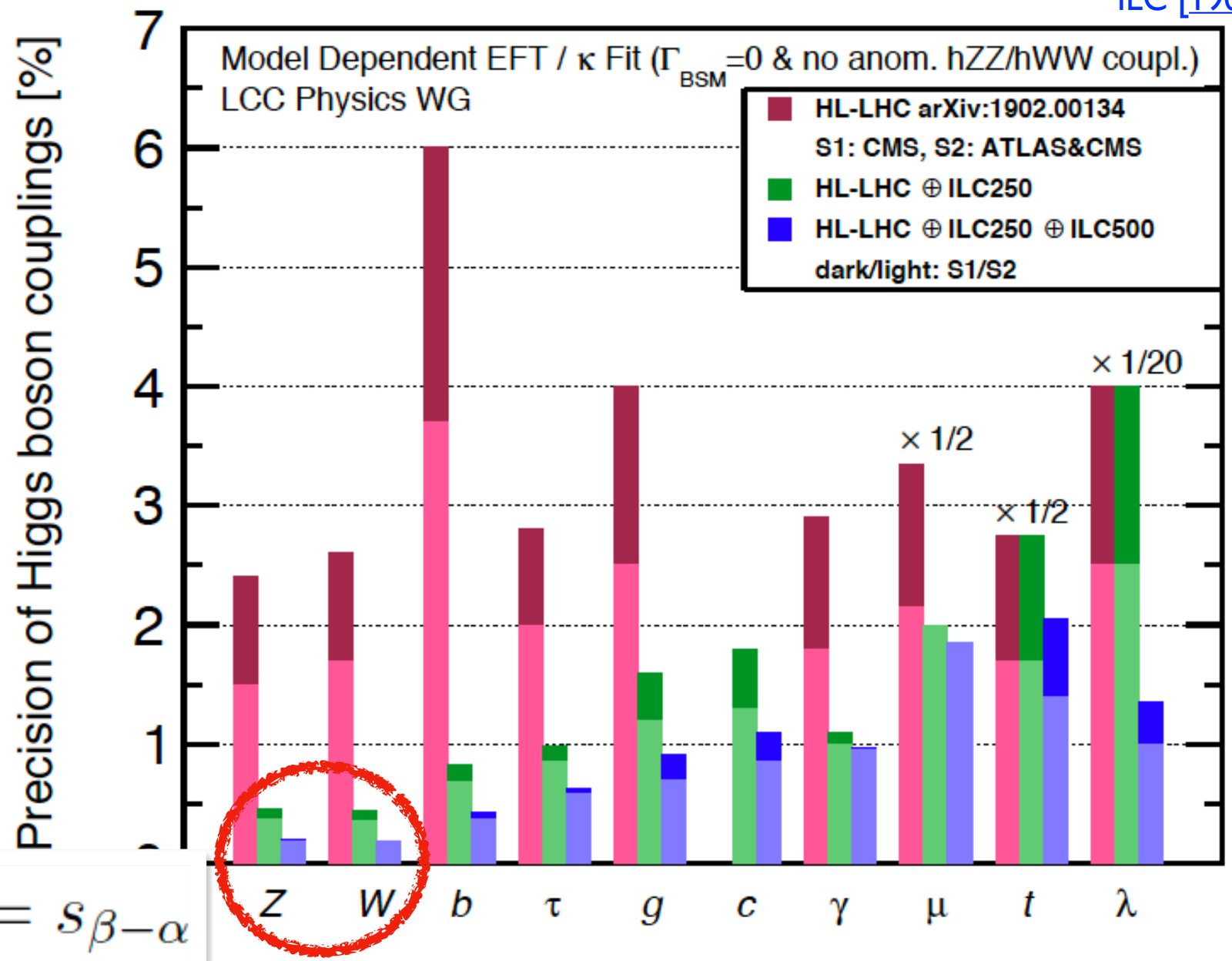





Expected exclusion; Type-I
Expected exclusion; Type-II
Expected exclusion; Type-X
Expected exclusion; Type-Y
HL-LHC (3ab-1)
$s_{\beta-\alpha}=1$
$s_{\beta-\alpha}=0.995,\ c_{\beta-\alpha}>0$
$s_{\beta-\alpha}=0.99,\ c_{\beta-\alpha}>0$
A→ττ
A(bb)→ττ
A(bb)→bb
A→tt
A→Zh
A(bb)→Zh
H→hh
H→ZZ
H±→tb
H±→τν
tanβ
m_Φ [GeV]
alignment sβ-α=1
There will still be rooms to explore even after HL-LHC...
non-alignment sβ-α=0.995
non-alignment sβ-α=0.99

Higgs precision measurements @ HL-LHC + ILC

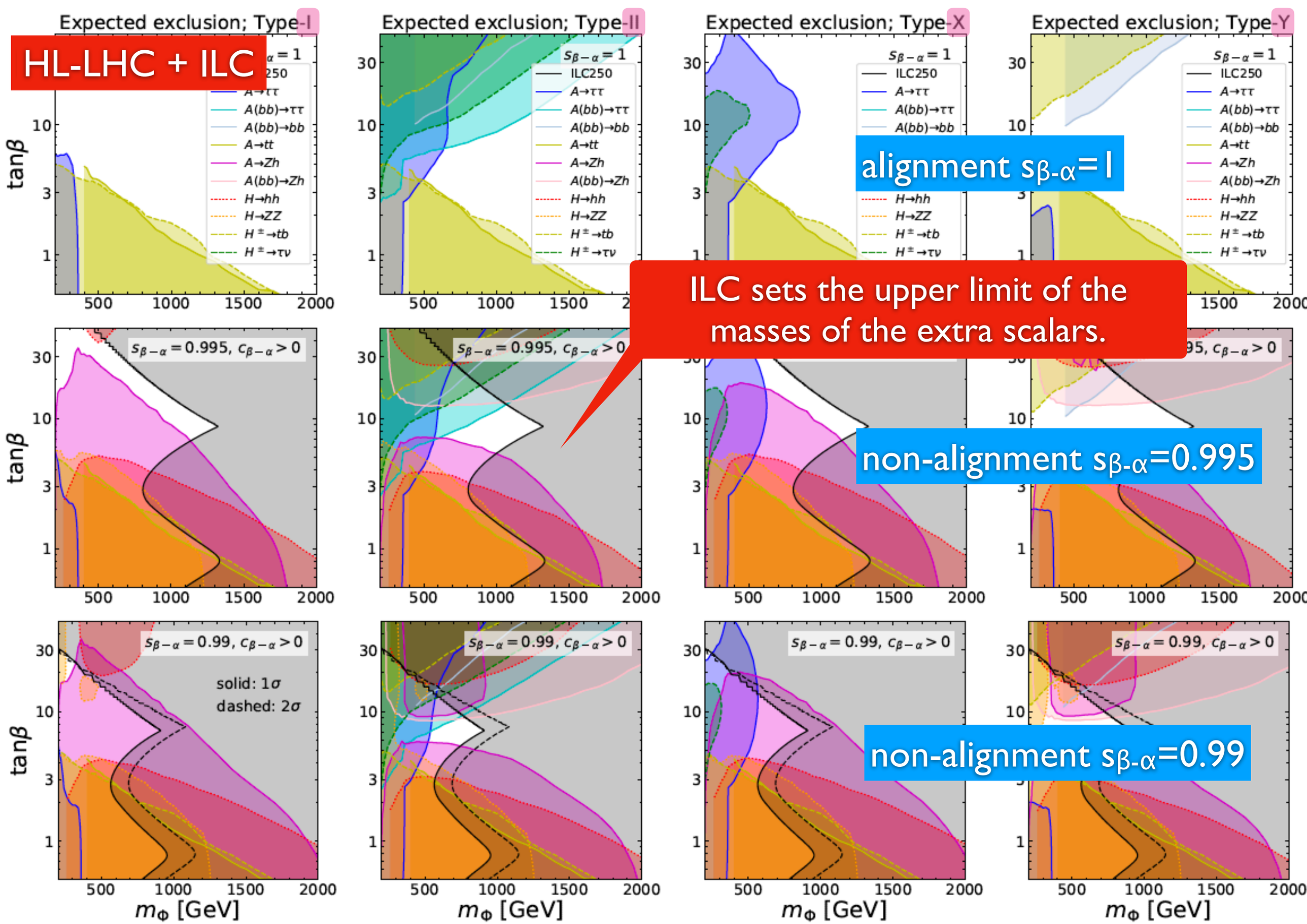
ILC [1903.01629]



$$\kappa_V^h = s_{\beta-\alpha}$$

We assume that we observe a deviation at the ILC as $\kappa_V^h = [0.995, 0.99, 0.98] \pm 0.0038\ (0.0076)$

HL-LHC + ILC



alignment $s_{\beta-\alpha}=1$

ILC sets the upper limit of the masses of the extra scalars.

non-alignment $s_{\beta-\alpha}=0.995$

non-alignment $s_{\beta-\alpha}=0.99$

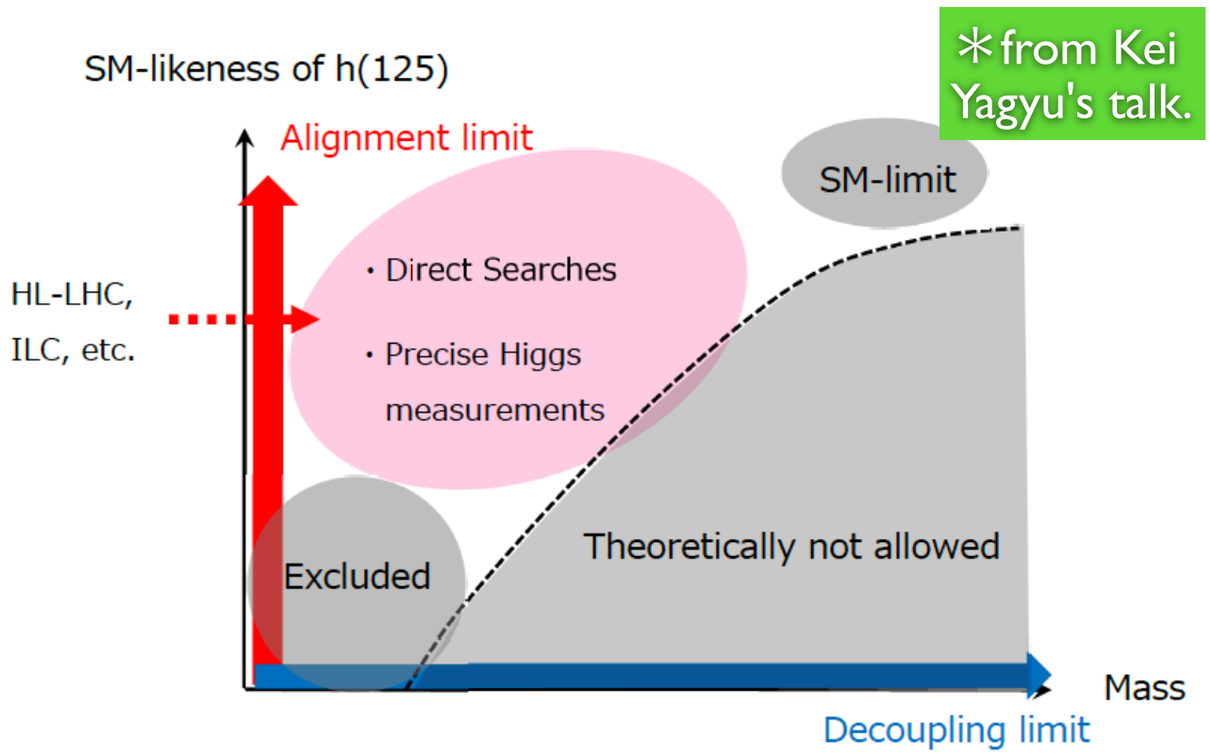
Upper limits on the masses from precision measurements

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

  - NO ! $m_h^2 = \lambda v^2 + \cos^2(\beta-\alpha) M^2 = (125\ \mathrm{GeV})^2$

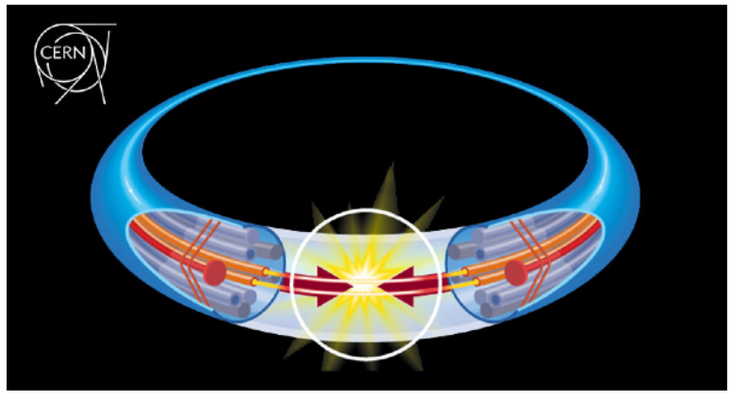
➡ If $\sin(\beta-\alpha) \neq 1$, the upper limit on M is set.

➡ When the ILC observes the deviation of the Higgs couplings, we are able to know the mass scale of the extra scalars.

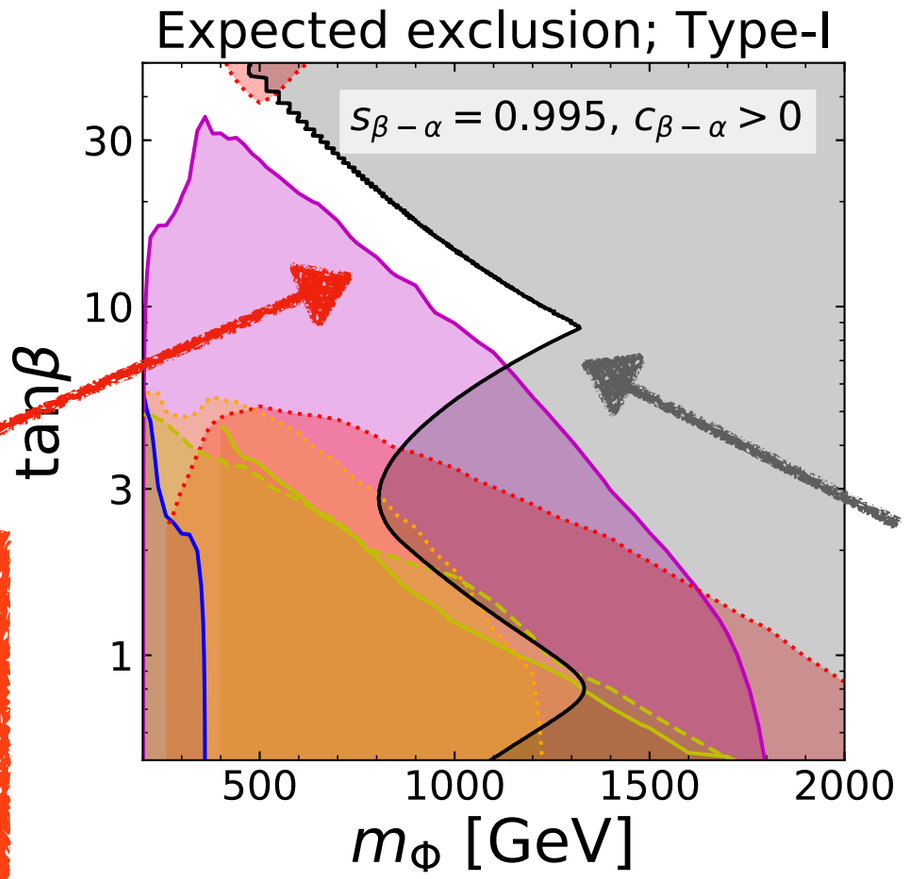


＊from Kei Yagyu's talk.

Summary



synergy



The direct searches for additional Higgs bosons give lower limits of the masses.

The precision measurements for the SM-like Higgs boson set upper limits of the masses.

[arXiv: 2010.15057, NPB]

@ aiina (next to Morioka station in Iwate)

Back-up

THDM: Two Higgs doublet model

$$V(\Phi_1,\Phi_2) = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}]$$

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix}$$

$v = (v_1^2 + v_2^2)^{1/2}$
$\tan\beta = v_2/v_1$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta)\begin{pmatrix} G^0 \\ A \end{pmatrix}, \quad \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

$$m_{H^\pm}^2 = M^2 - \frac{1}{2}v^2(\lambda_4+\lambda_5),$$
$$m_A^2 = M^2 - v^2\lambda_5,$$
$$m_H^2 = M_{11}^2 c_{\beta-\alpha}^2 + M_{22}^2 s_{\beta-\alpha}^2 - M_{12}^2 s_{2(\beta-\alpha)},$$
$$m_h^2 = M_{11}^2 s_{\beta-\alpha}^2 + M_{22}^2 c_{\beta-\alpha}^2 + M_{12}^2 s_{2(\beta-\alpha)},$$
$$\tan 2(\beta-\alpha) = -\frac{2M_{12}^2}{M_{11}^2 - M_{22}^2},$$

Decoupling limit: $M \to \infty$
- Masses of H,A,H± become infinity.

$$M_{11}^2 = v^2(\lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \lambda_{345} s_\beta^2 c_\beta^2),$$
$$M_{22}^2 = M^2 + \frac{1}{2}v^2 s_{2\beta}^2(\lambda_1+\lambda_2-2\lambda_{345}),$$
$$M_{12}^2 = \frac{1}{2}v^2 s_{2\beta}(-\lambda_1 c_\beta^2 + \lambda_2 s_\beta^2 + \lambda_{345} c_{2\beta}),$$

6 free parameters in the THDMs: $m_H,\ m_A,\ m_{H^\pm},\ M^2,\ \tan\beta,\ s_{\beta-\alpha},$

THDM : Feynman rules

$$\kappa_X^\phi \equiv \frac{g_{\phi X \bar{X}}}{g_{h_{\rm SM} X \bar{X}}}, \quad \phi = h, H, A$$

$$\kappa_V^h = s_{\beta-\alpha}, \quad \kappa_V^H = c_{\beta-\alpha}, \quad \kappa_V^A = 0,$$

$$\kappa_f^h = s_{\beta-\alpha} + c_{\beta-\alpha}\zeta_f, \quad \kappa_f^H = c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f, \quad \kappa_f^A = -2iI_f\zeta_f,$$

Z_2 charge assignment (to avoid the tree-level FCNCs)

	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Alignment limit (SM-like limit): $s_{\beta-\alpha} \to 1$

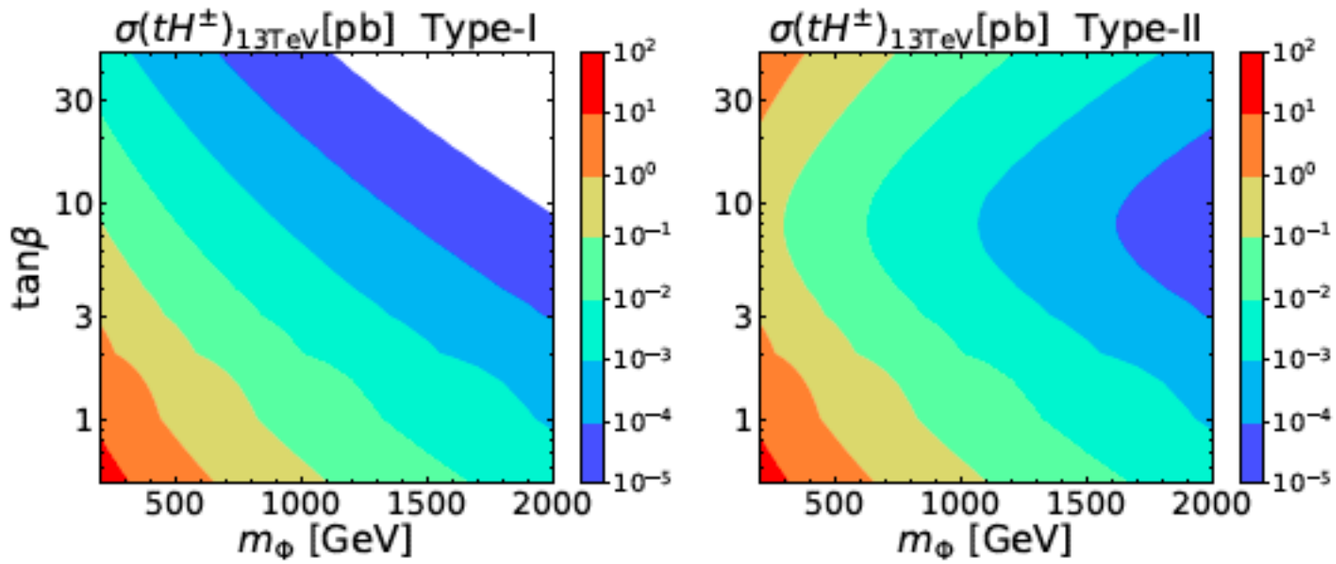
- h behaves like the SM Higgs boson.
- H,A,H± only couple to the fermions.

- How and how much are the extra Higgs bosons produced at the LHC ?

Production: charged Higgs bosons ($H^\pm$)

$b\,g \to t\,H^\pm$

[HXSWG (Higgs cross section working group)]

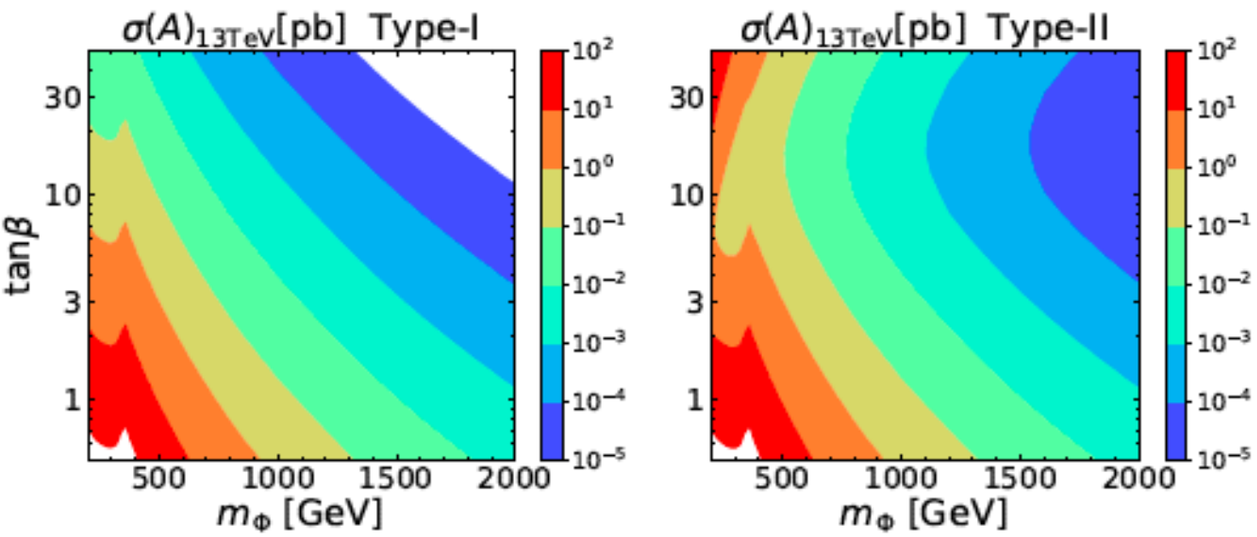


$$\mathcal{L}_Y^{H^\pm} = \frac{\sqrt{2}}{v}\left[\overline{u}_i(m_{u_i}V_{ij}\zeta_u P_L - V_{ij}m_{d_j}\zeta_d P_R)d_j H^+ + \text{h.c.}\right]$$

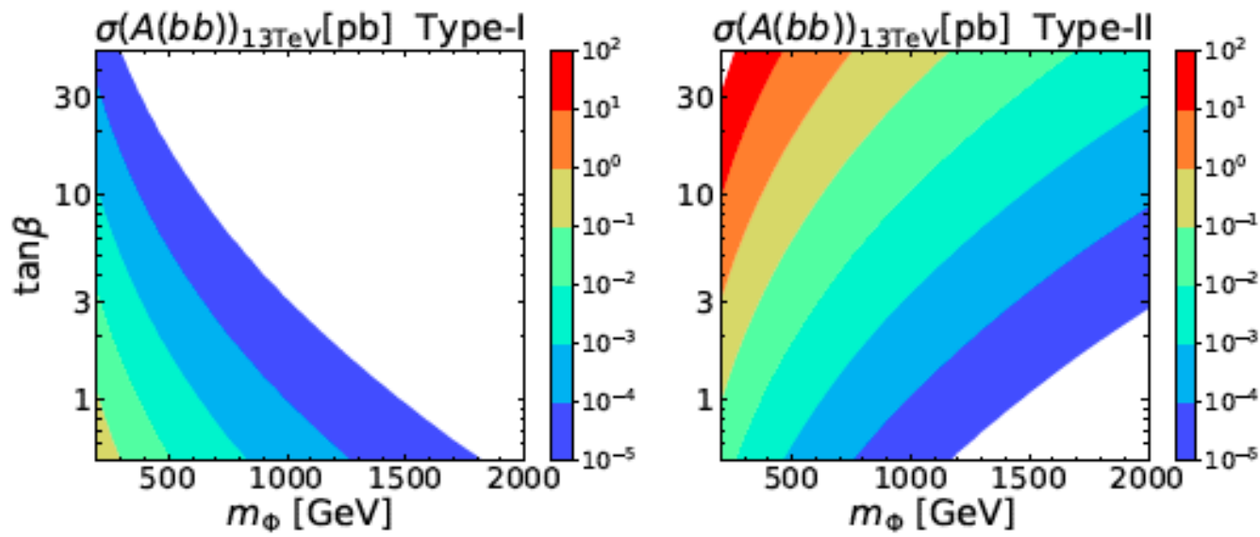
	Q_L	u_R	d_R	ζ_u	ζ_d
Type-I	+	−	−	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	$\cot\beta$	$-\tan\beta$

Production: CP-odd Higgs boson (A)

gluon fusion via heavy-quark loops



b-quark fusion (b-quark associated)



[Sushi-1.7.0]

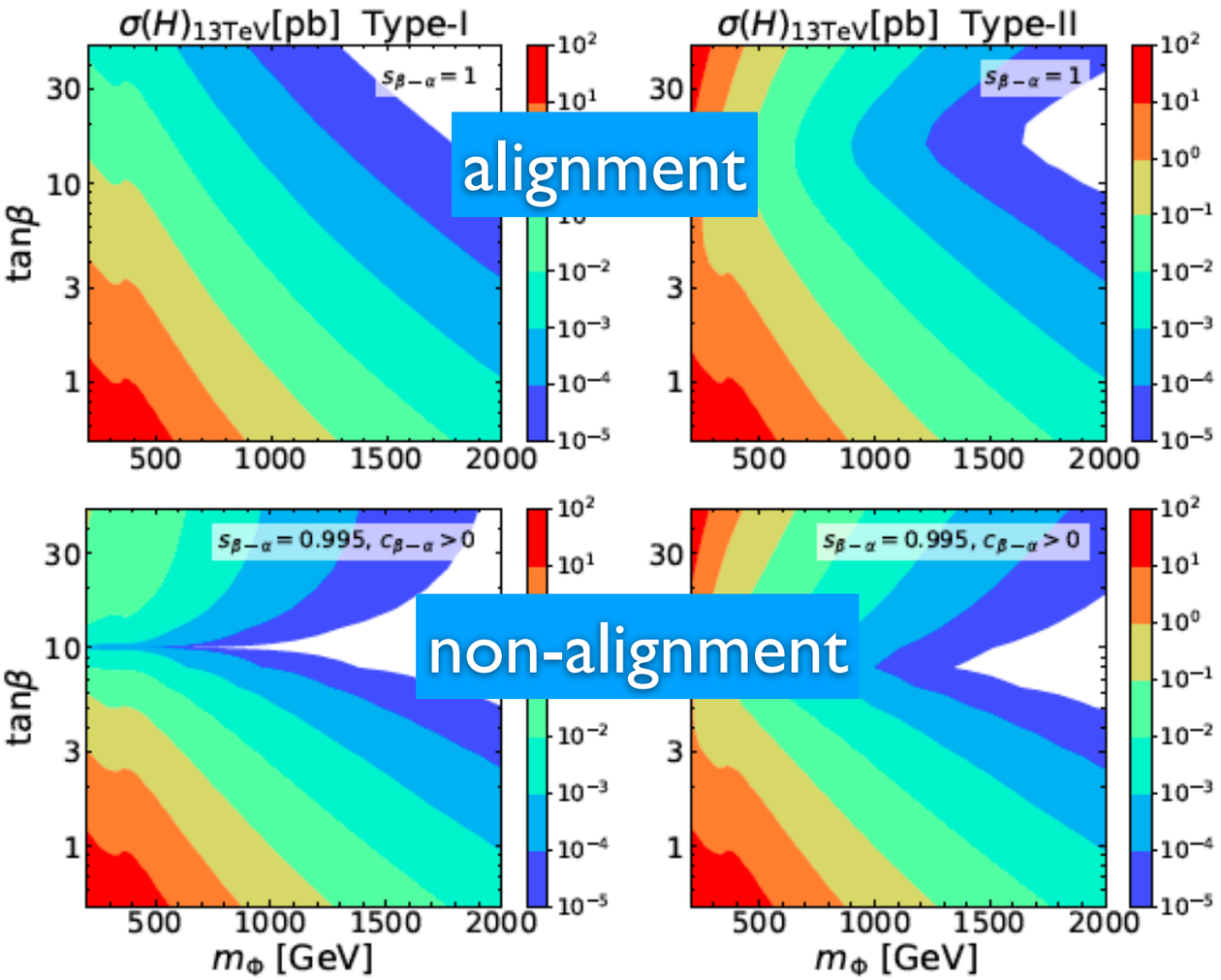
$$\kappa_f^A = -2iI_f\zeta_f$$

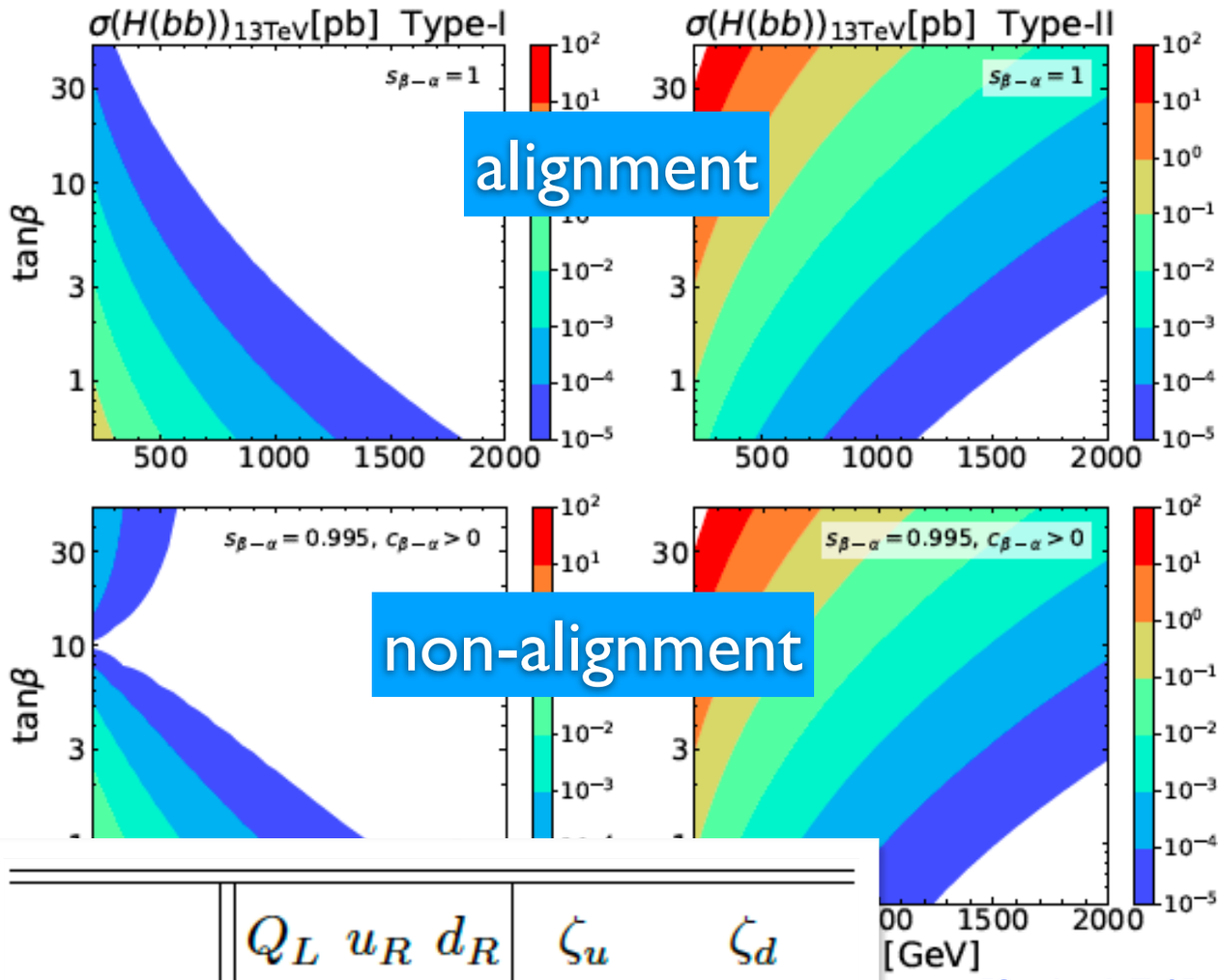
	Q_L	u_R	d_R	ζ_u	ζ_d
Type-I	+	−	−	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	$\cot\beta$	$-\tan\beta$

Production: CP-even Higgs boson (H)

gluon fusion via heavy-quark loops

b-quark fusion (b-quark associated)





[Sushi-1.7.0]

$$\kappa_f^H = c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f$$

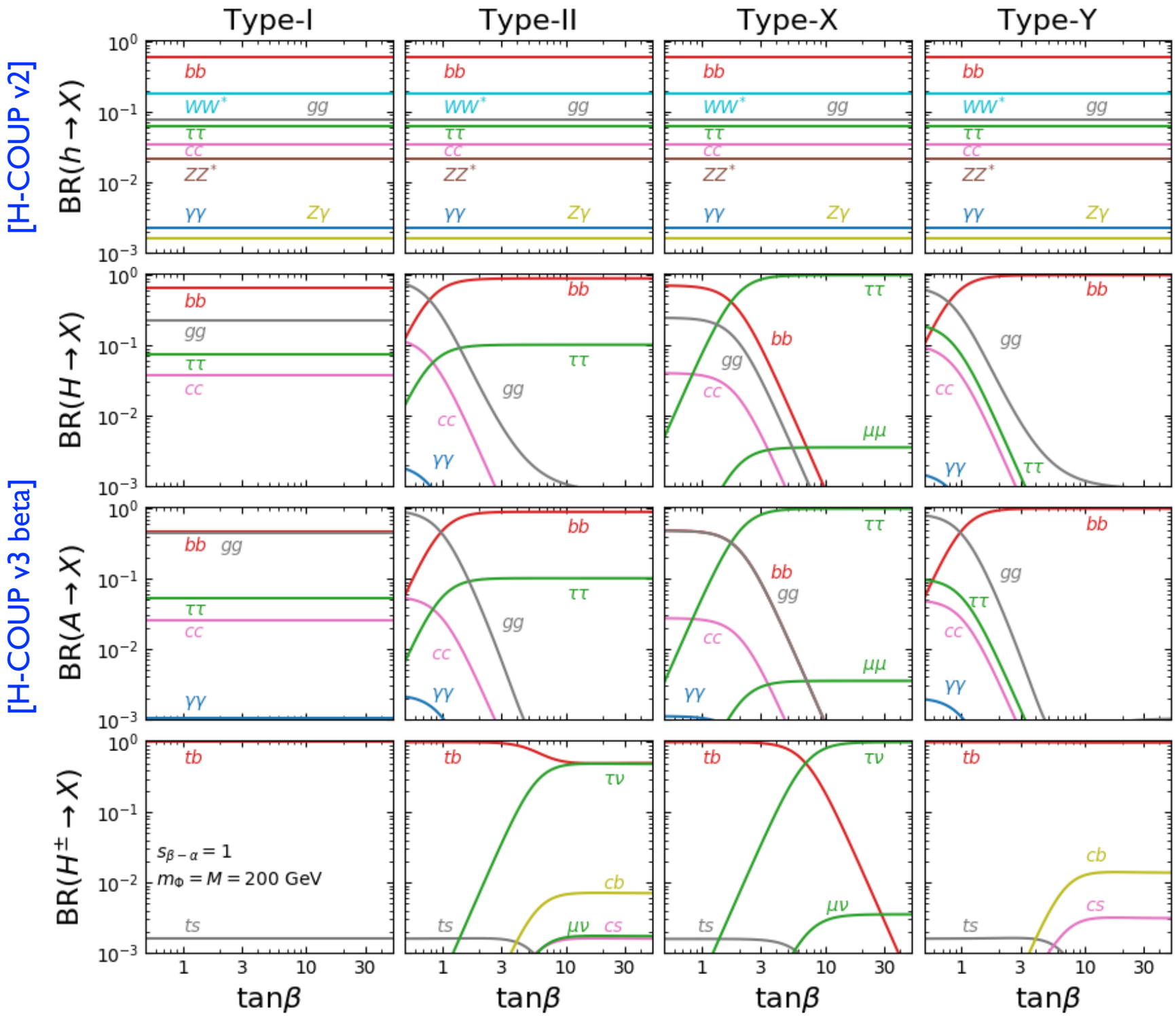
	Q_L	u_R	d_R	ζ_u	ζ_d
Type-I	+	−	−	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	$\cot\beta$	$-\tan\beta$

- How do the Higgs bosons decay ?

Decay: alignment ($s_{\beta-\alpha}=1$), m_Φ=200GeV

[H-COUP v2]

[H-COUP v3 beta]

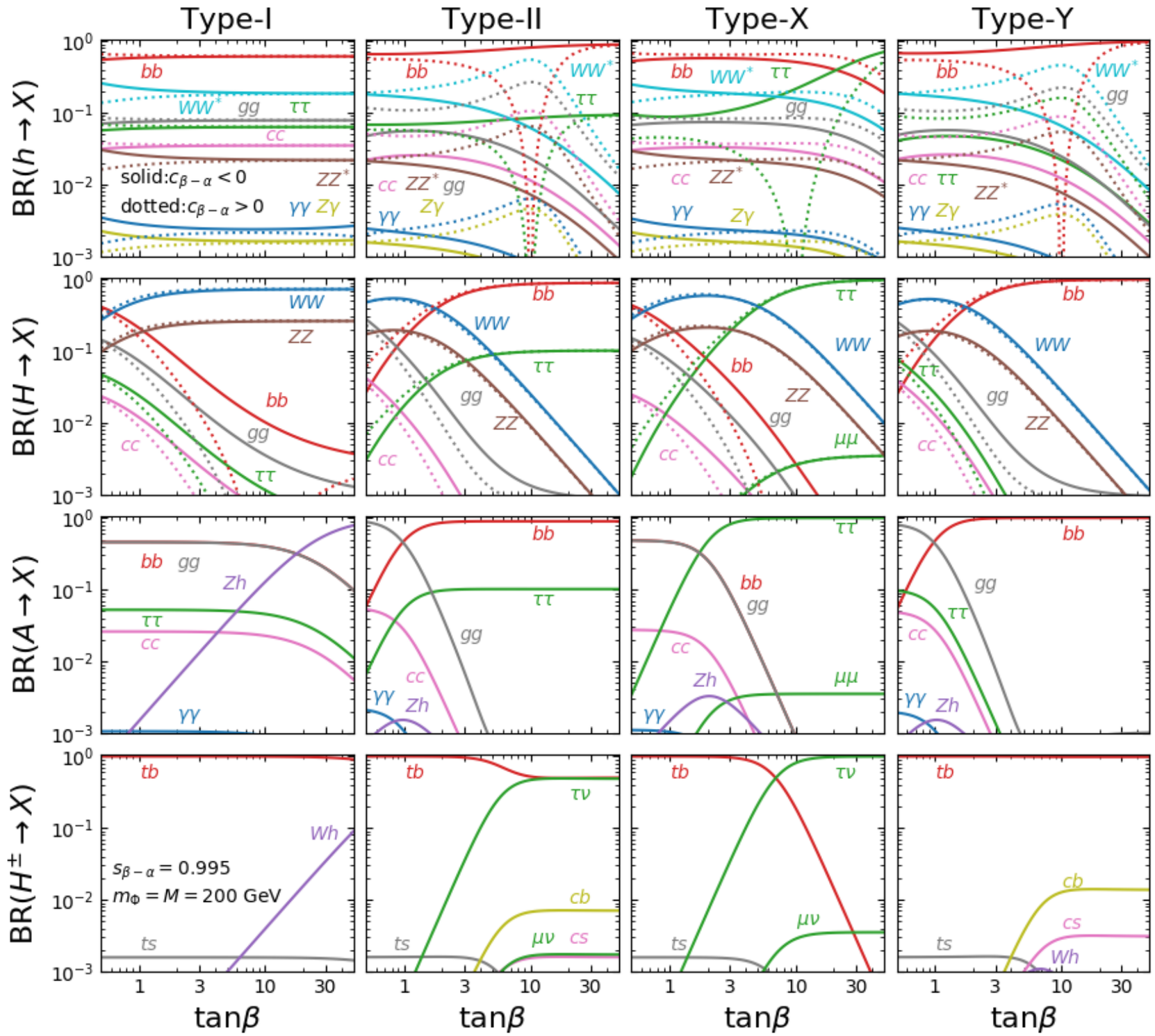


	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Decay: non-alignment ($s_{\beta-\alpha}$=0.995), m_Φ=200GeV

[H-COUP v2]

[H-COUP v3 beta]

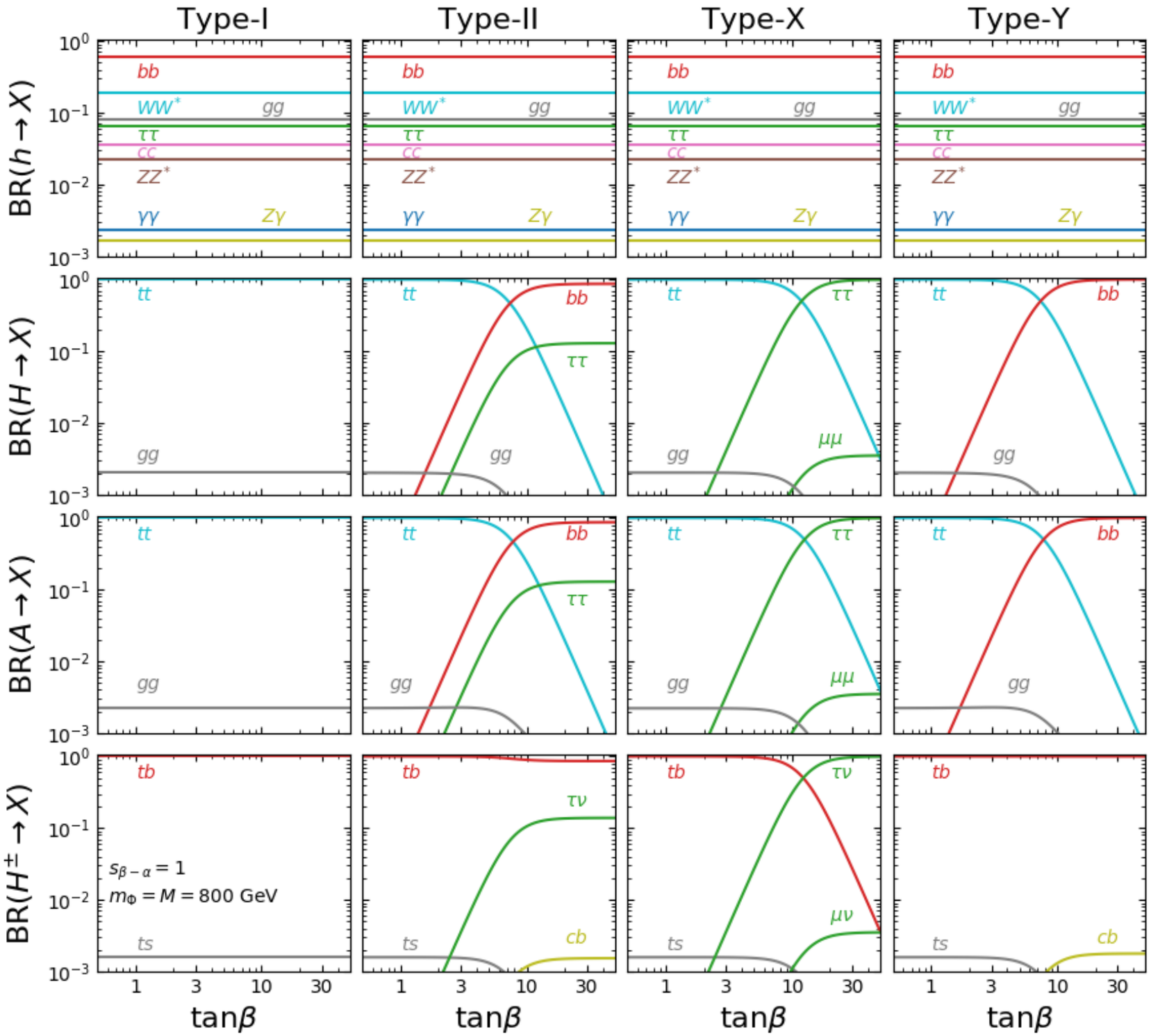


	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	+	−	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Decay: alignment ($s_{\beta-\alpha}=1$), m_Φ=800GeV

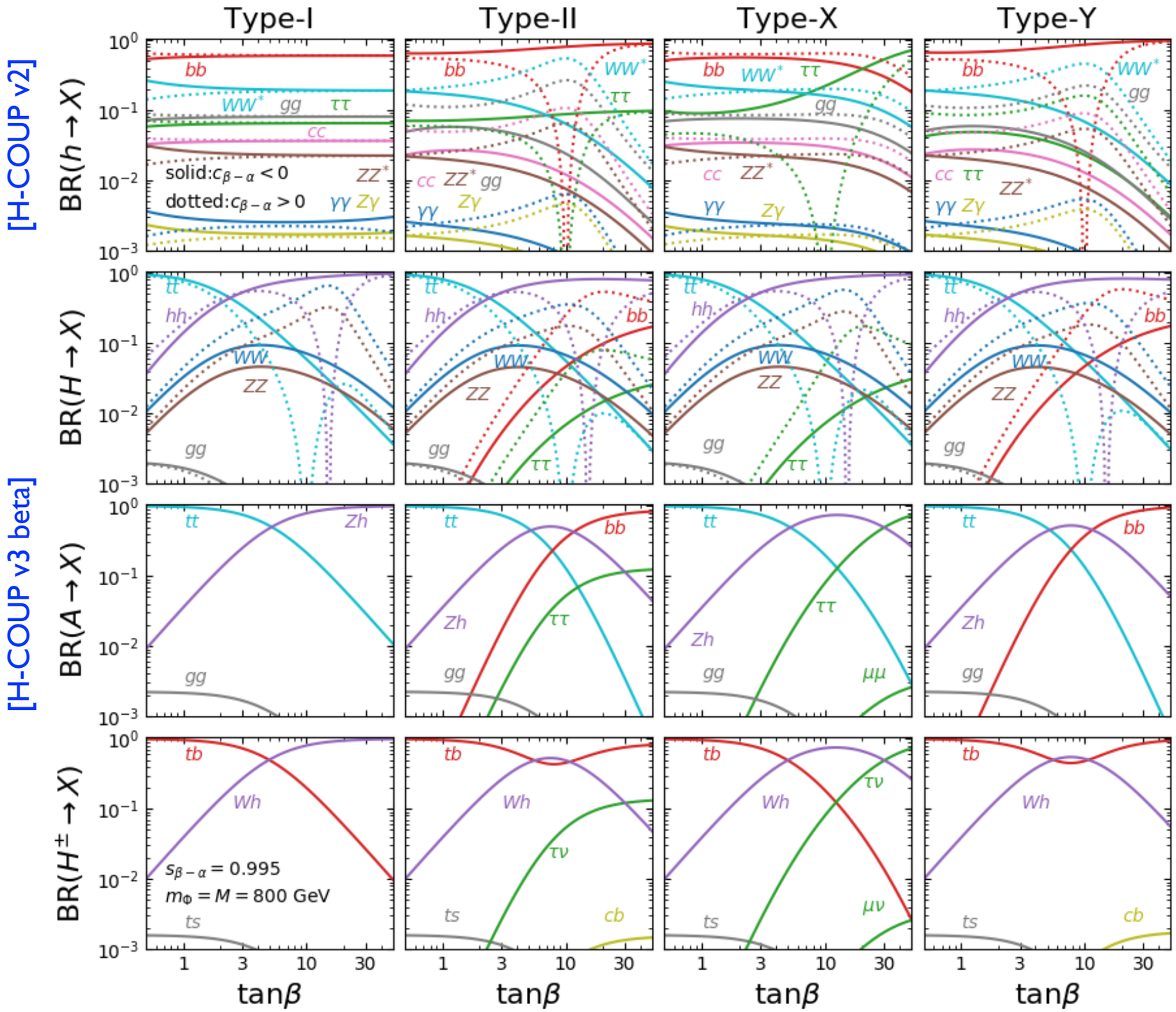
[H-COUP v2]

[H-COUP v3 beta]

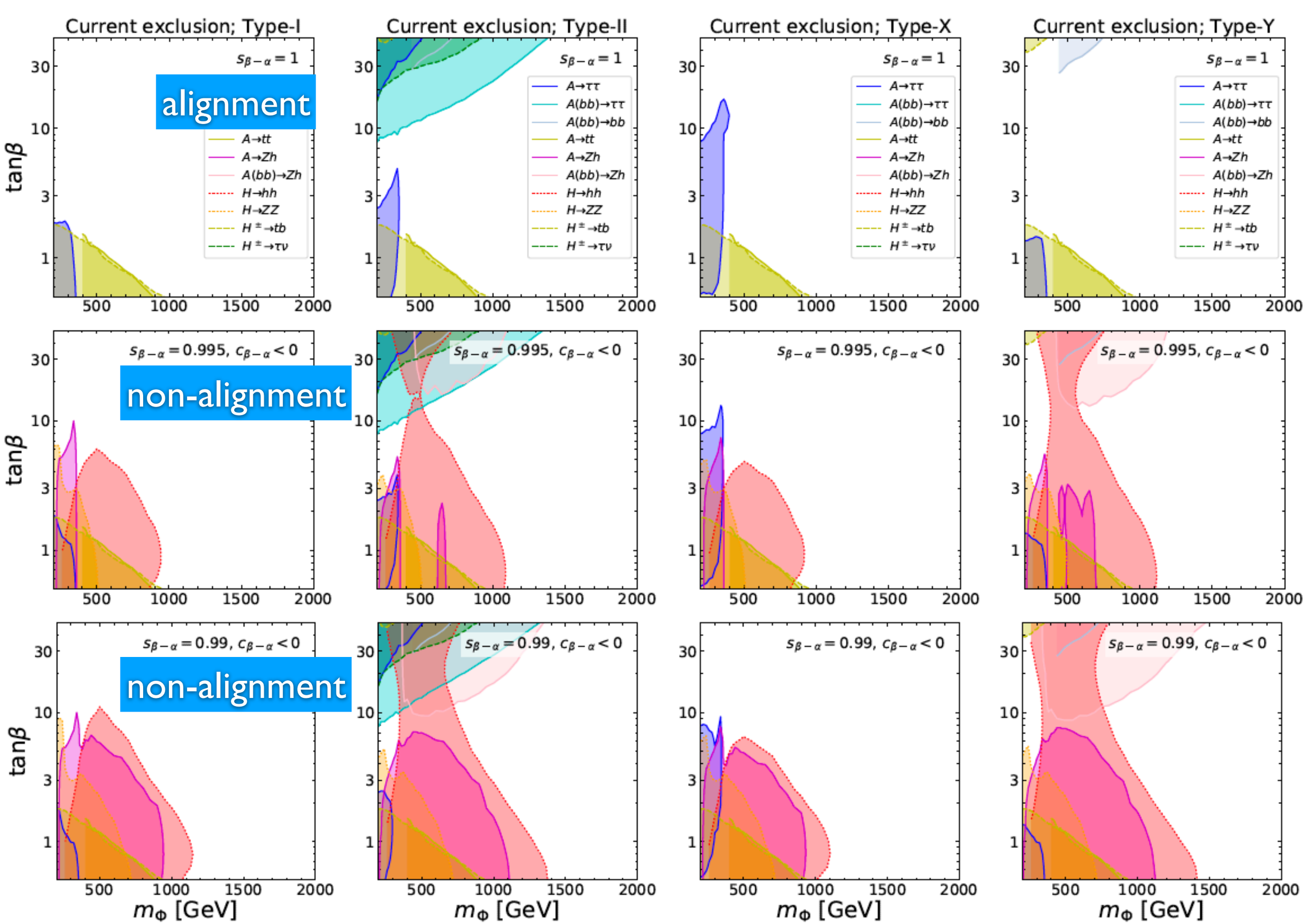


	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	+	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	+	−	+	$\cot\beta$	$-\tan\beta$	$\tan\beta$
Type-X (lepton-specific)	+	−	+	+	+	−	−	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	+	−	+	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Decay: non-alignment ($s_{\beta-\alpha}$=0.995), m_Φ=800GeV



	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$


Current exclusion; Type-I
Current exclusion; Type-II
Current exclusion; Type-X
Current exclusion; Type-Y
alignment
non-alignment
non-alignment
$s_{\beta-\alpha}=1$
$s_{\beta-\alpha}=0.995,\ c_{\beta-\alpha}<0$
$s_{\beta-\alpha}=0.99,\ c_{\beta-\alpha}<0$
$A\to\tau\tau$
$A(bb)\to\tau\tau$
$A(bb)\to bb$
$A\to tt$
$A\to Zh$
$A(bb)\to Zh$
$H\to hh$
$H\to ZZ$
$H^\pm\to tb$
$H^\pm\to\tau\nu$
tanβ
m_Φ [GeV]
500
1000
1500
2000
1
3
10
30

Expected exclusion; Type-I

Expected exclusion; Type-II

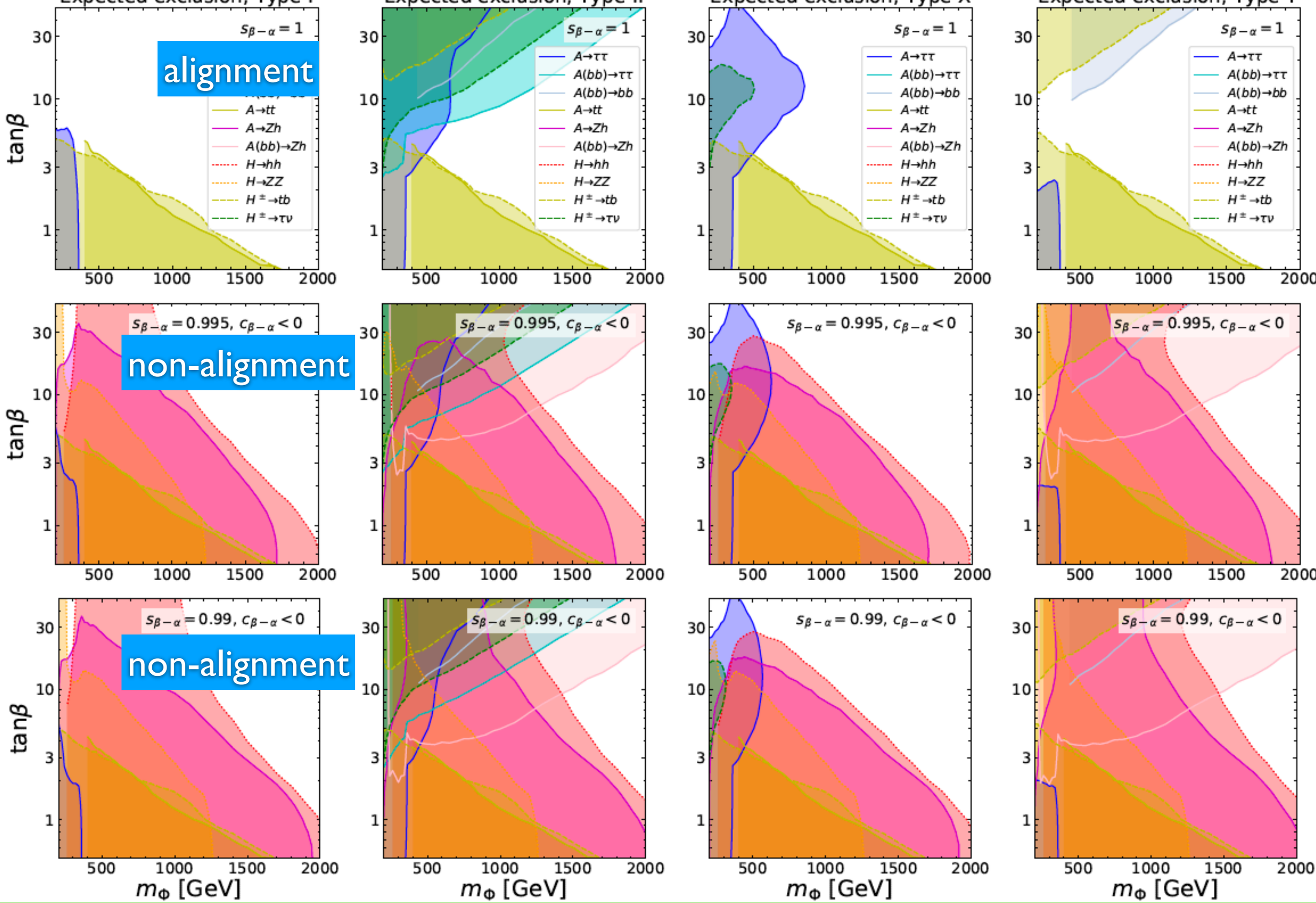
Expected exclusion; Type-X

Expected exclusion; Type-Y

alignment

non-alignment

non-alignment



HL-LHC + ILC

alignment

non-alignment

non-alignment

Type-I

Expected exclusion; Type-II

Expected exclusion; Type-X

Expected exclusion; Type-Y

$s_{\beta-\alpha}=1$

ILC250

$A\to\tau\tau$

$A(bb)\to\tau\tau$

$A(bb)\to bb$

$A\to tt$

$A\to Zh$

$A(bb)\to Zh$

$H\to hh$

$H\to ZZ$

$H^\pm\to tb$

$H^\pm\to\tau\nu$

$s_{\beta-\alpha}=0.995,\ c_{\beta-\alpha}<0$

$s_{\beta-\alpha}=0.99,\ c_{\beta-\alpha}<0$

solid: 1σ

dashed: 2σ

$\tan\beta$

m_Φ [GeV]