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

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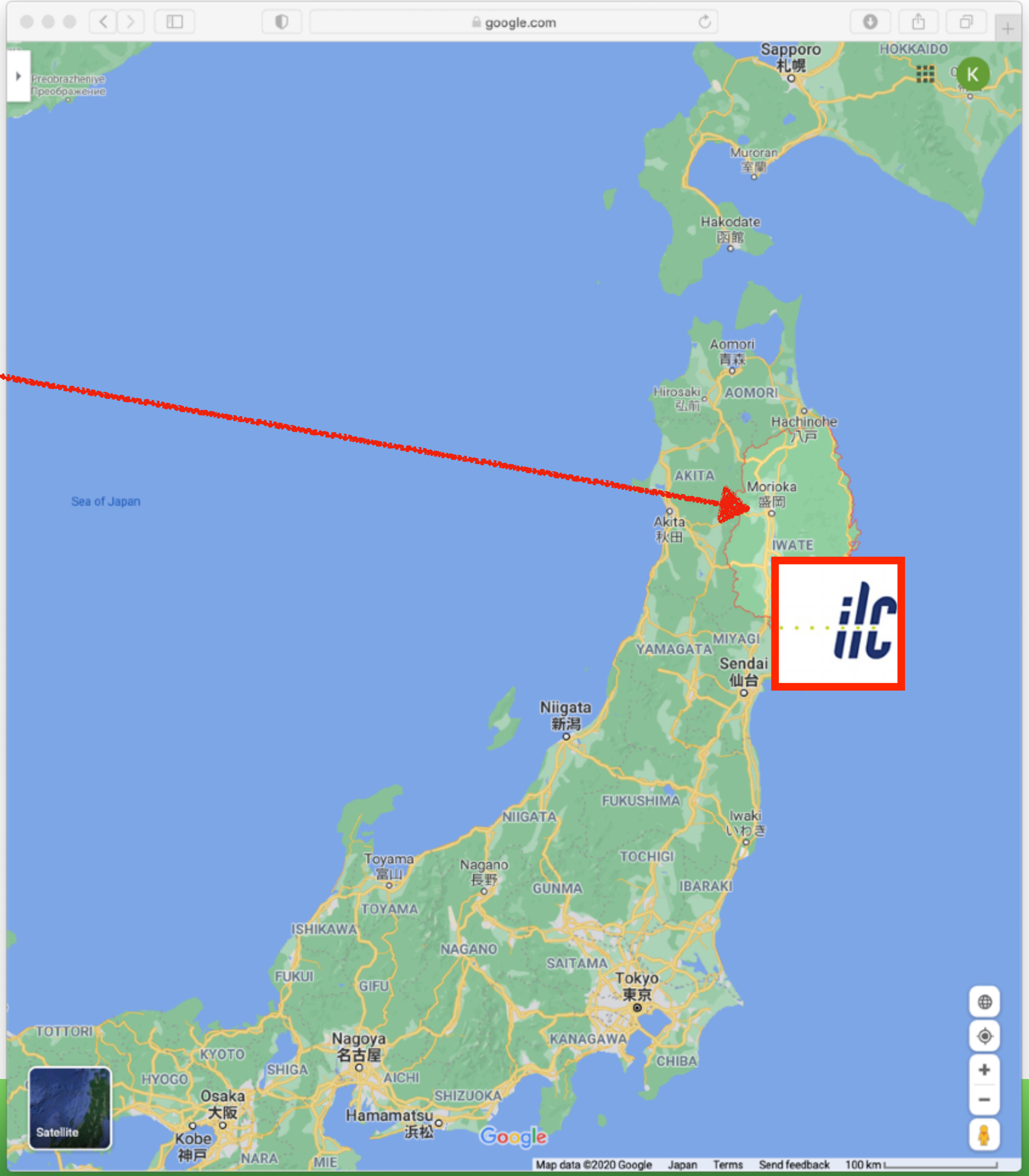
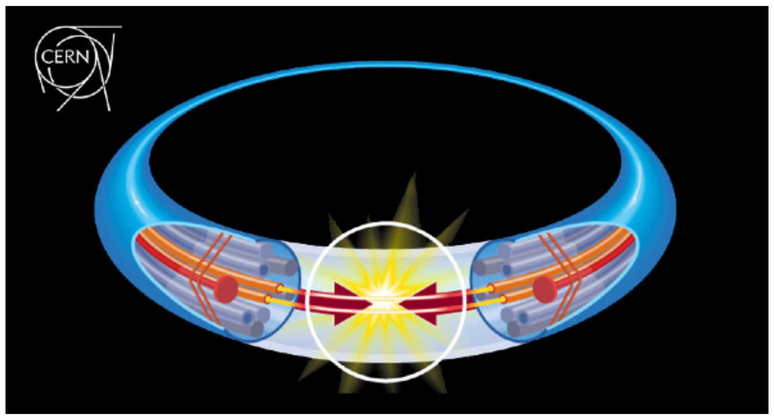
岩手大学



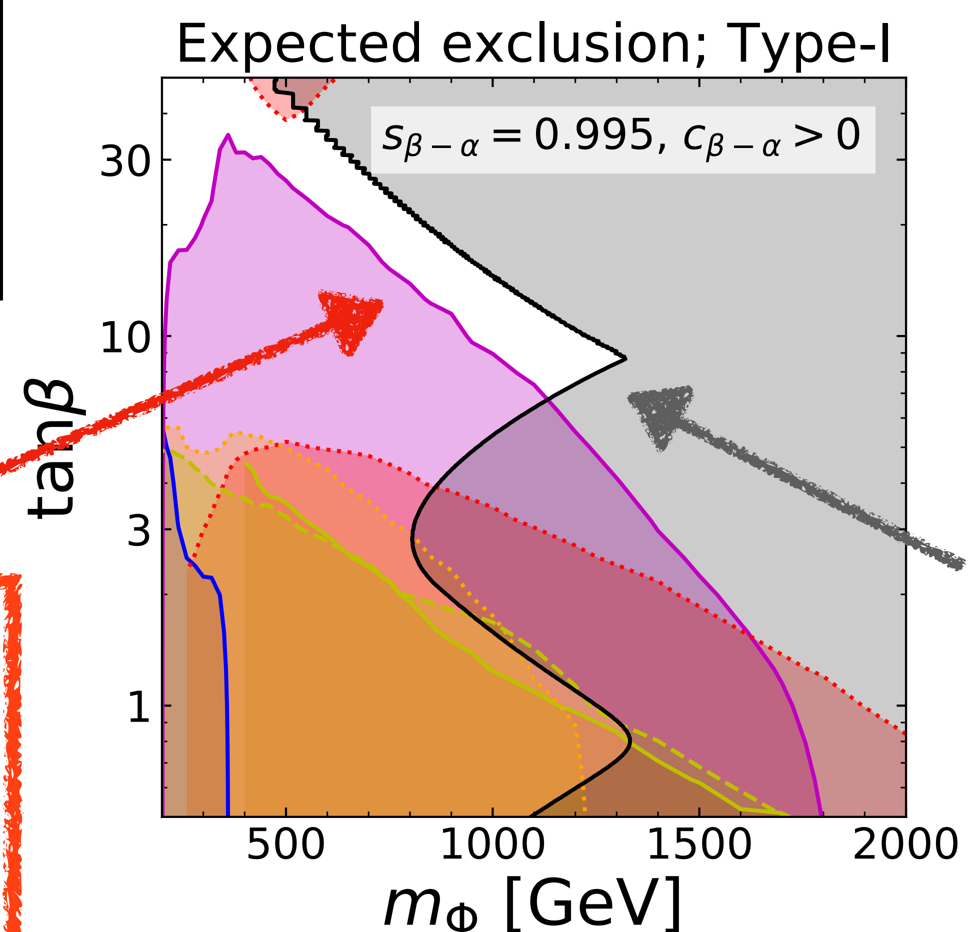
[arXiv: 2010.15057, appear in NPB]

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

Contents of my talk



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.

Introduction

- We are seeking for BSM physics.
- Many BSM models require some extensions of the Higgs sector, e.g. MSSM.
- Two Higgs doublet models (THDMs) are one of the simplest extensions, but immediately provides us rich theoretical and experimental discussions.

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

THDM: Two Higgs doublet model

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

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

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

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

$$m_{H^\pm}^2 = M^2 - \frac{1}{2}v^2(\lambda_4 + \lambda_5),$$
$$m_A^2 = M^2 - v^2\lambda_5,$$

Decoupling limit: $M \to \infty$

- Masses of H,A,H± become infinity.

$$m_H^2 = M_{11}^2 c_{\beta-\alpha}^2 + M_{22}^2 s_{\beta-\alpha}^2 - M_{12}^2 s_{2(\beta-\alpha)},$$
$$m_h^2 = M_{11}^2 s_{\beta-\alpha}^2 + M_{22}^2 c_{\beta-\alpha}^2 + M_{12}^2 s_{2(\beta-\alpha)},$$
$$\tan 2(\beta-\alpha) = -\frac{2M_{12}^2}{M_{11}^2 - M_{22}^2},$$

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

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

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): $s_{\beta-\alpha} \to 1$

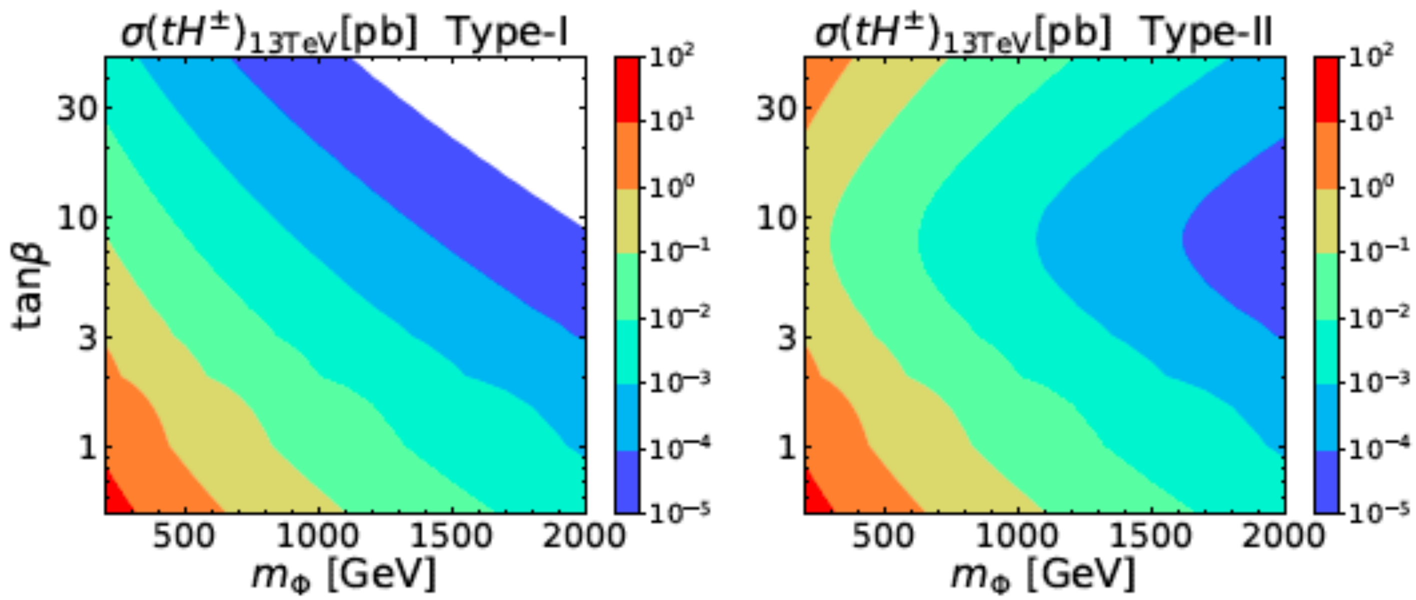
- h behaves like the SM Higgs boson.
- H,A,$H^\pm$ only couple to the fermions.

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

Production: charged Higgs bosons (H±)

b g → t H±

[HXSWG (Higgs cross section working group)]

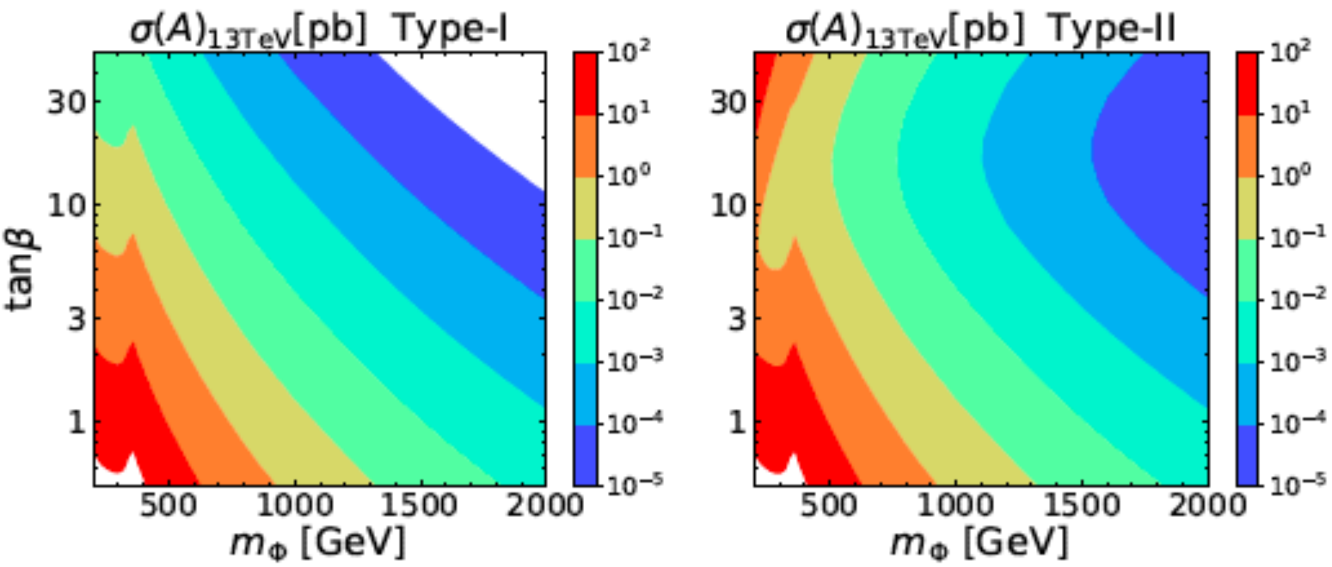


$$\mathcal{L}_Y^{H^\pm} = \frac{\sqrt{2}}{v}\left[\overline{u}_i(m_{u_i}V_{ij}\zeta_u P_L - V_{ij}m_{d_j}\zeta_d P_R)d_j H^+ + \text{h.c.}\right]$$

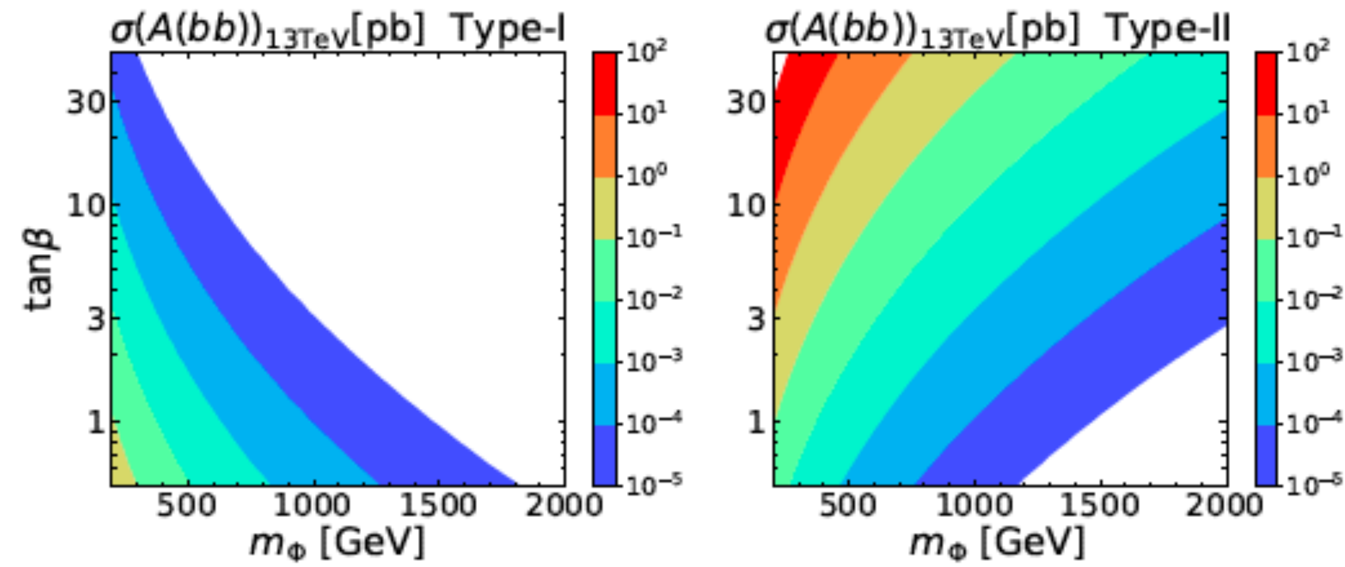
	Q_L	u_R	d_R	ζ_u	ζ_d
Type-I	$+$	$-$	$-$	$\cot\beta$	$\cot\beta$
Type-II	$+$	$-$	$+$	$\cot\beta$	$-\tan\beta$

Production: CP-odd Higgs boson (A)

gluon fusion via heavy-quark loops



b-quark fusion (b-quark associated)



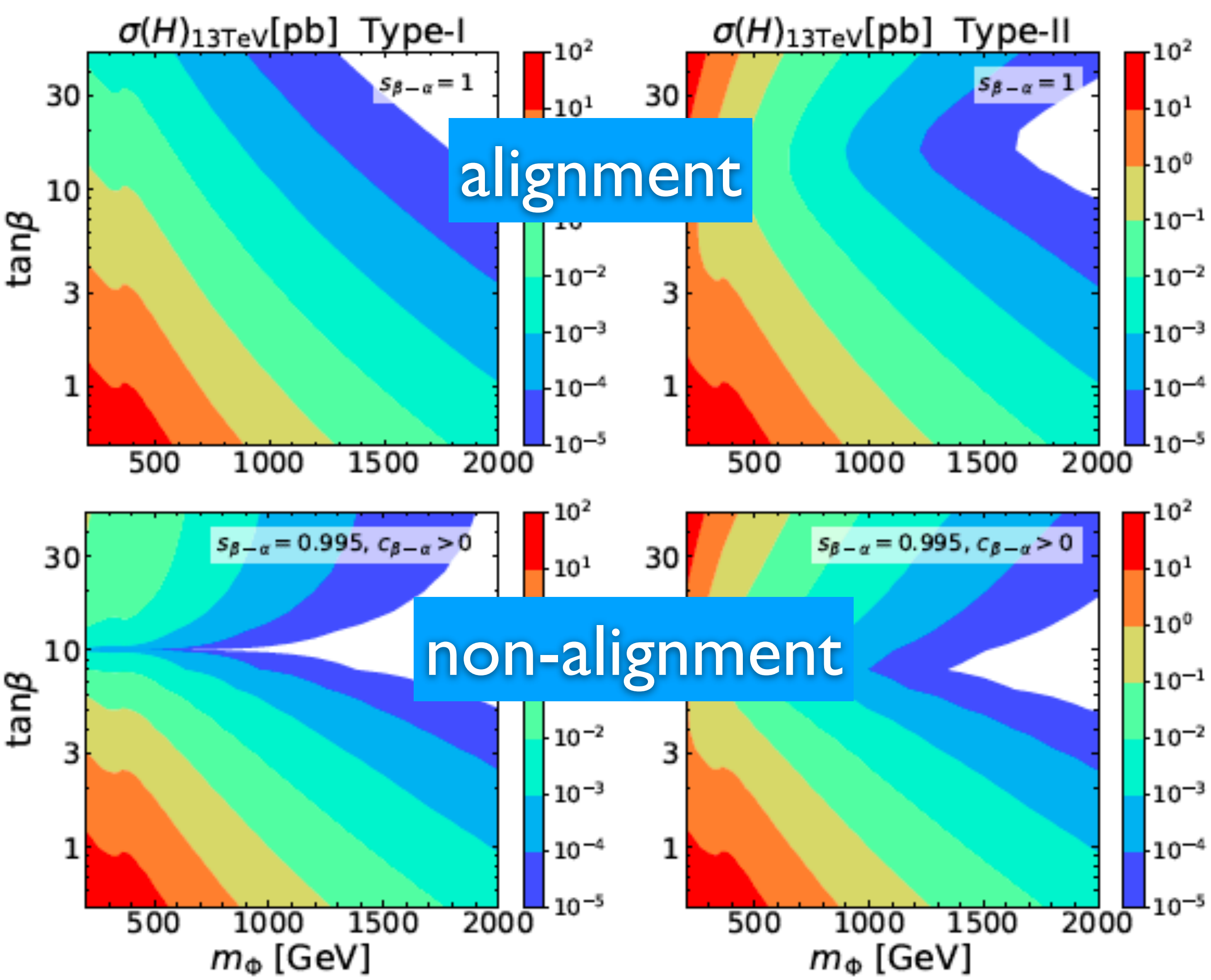
[Sushi-1.7.0]

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

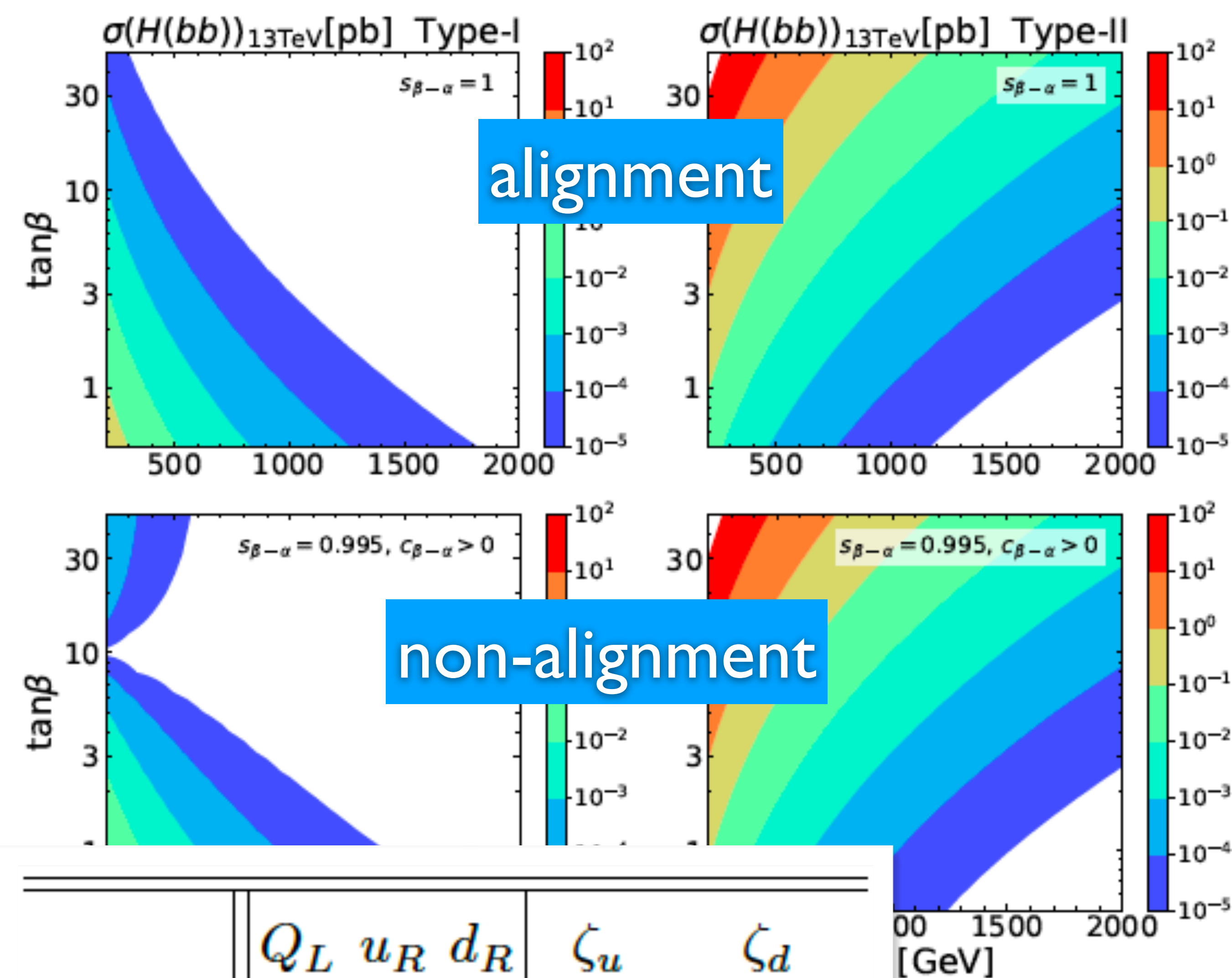
	Q_L	u_R	d_R	ζ_u	ζ_d
Type-I	$+$	$-$	$-$	$\cot\beta$	$\cot\beta$
Type-II	$+$	$-$	$+$	$\cot\beta$	$-\tan\beta$

Production: CP-even Higgs boson (H)

gluon fusion via heavy-quark loops



b-quark fusion (b-quark associated)



[Sushi-1.7.0]

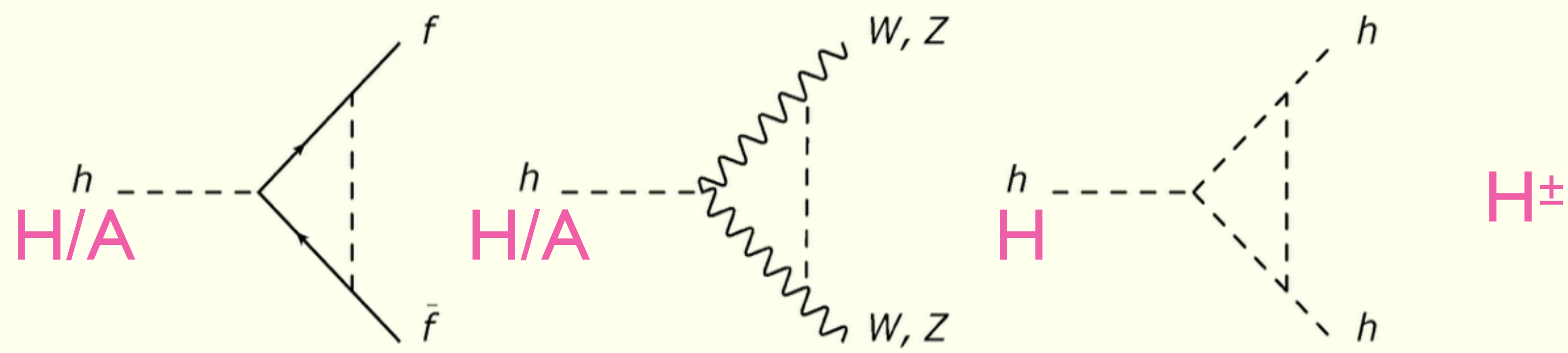
$$\kappa_f^H = c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f$$

	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 ?

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

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.

→ version 3 (beta)

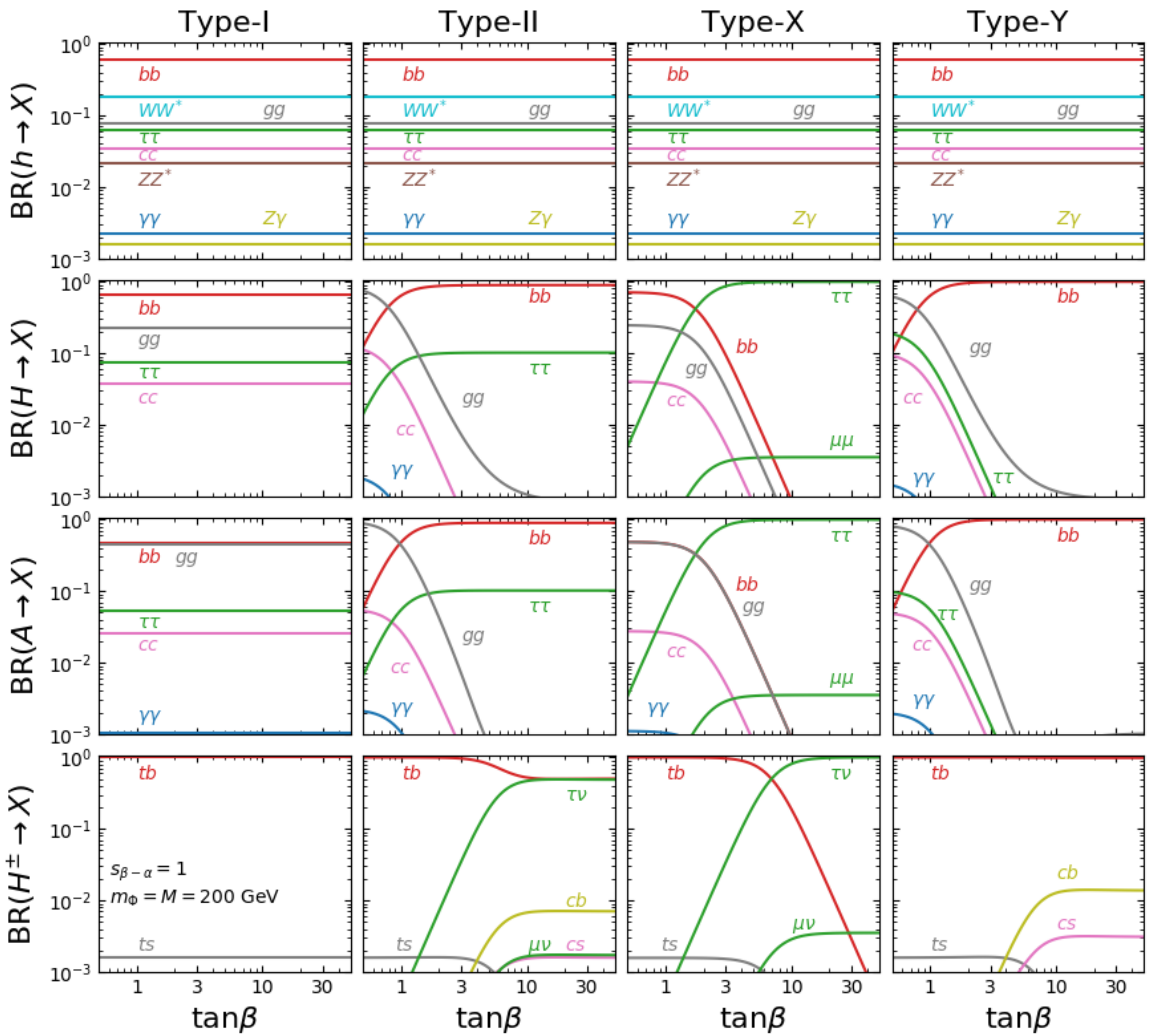
Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu + Aiko

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

Decay: alignment, m=200GeV

[H-COUP v2]

[H-COUP v3 beta]

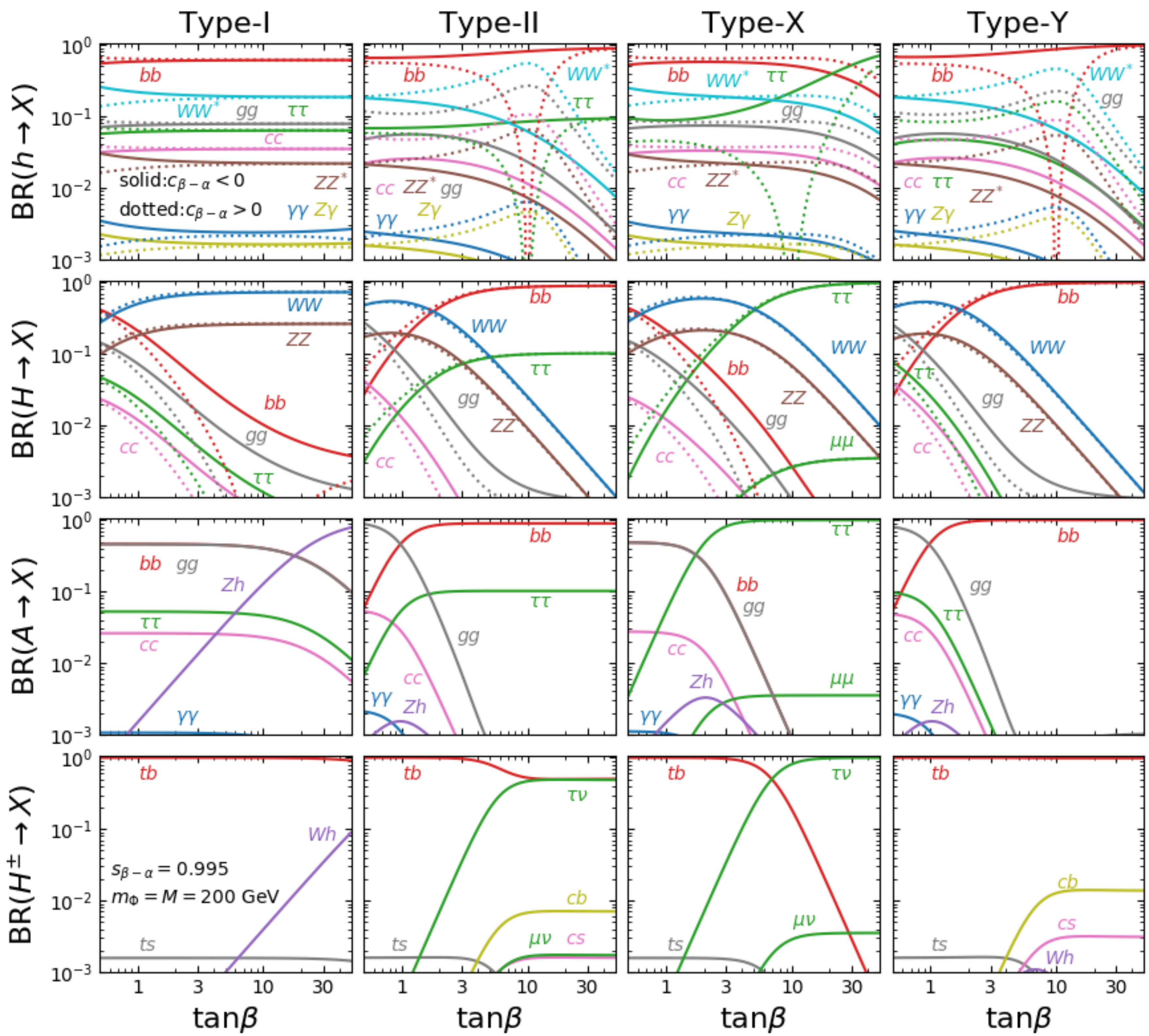


	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Decay: non-alignment, m=200GeV

[H-COUP v2]

[H-COUP v3 beta]

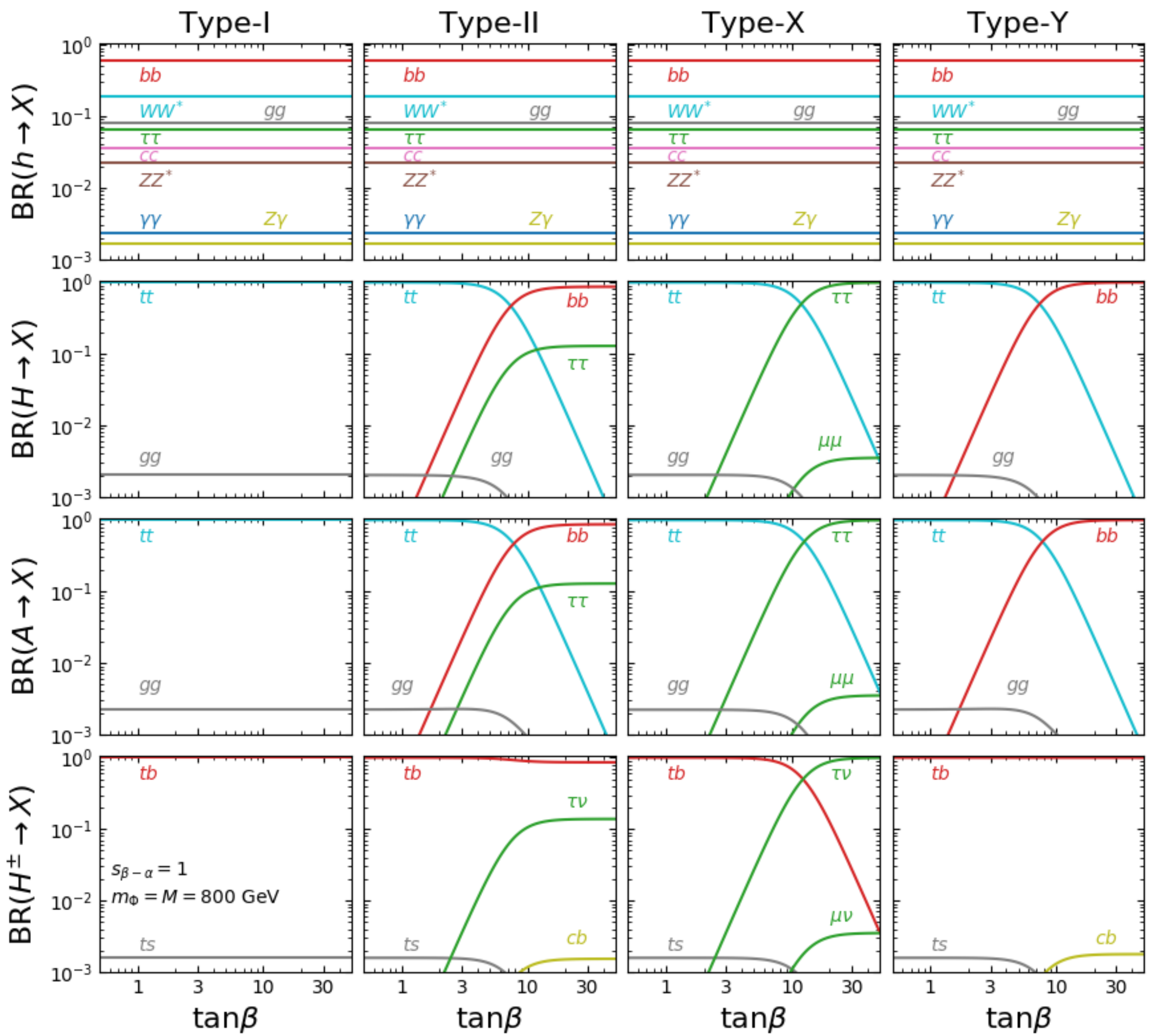


	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Decay: alignment, m=800GeV

[H-COUP v2]

[H-COUP v3 beta]

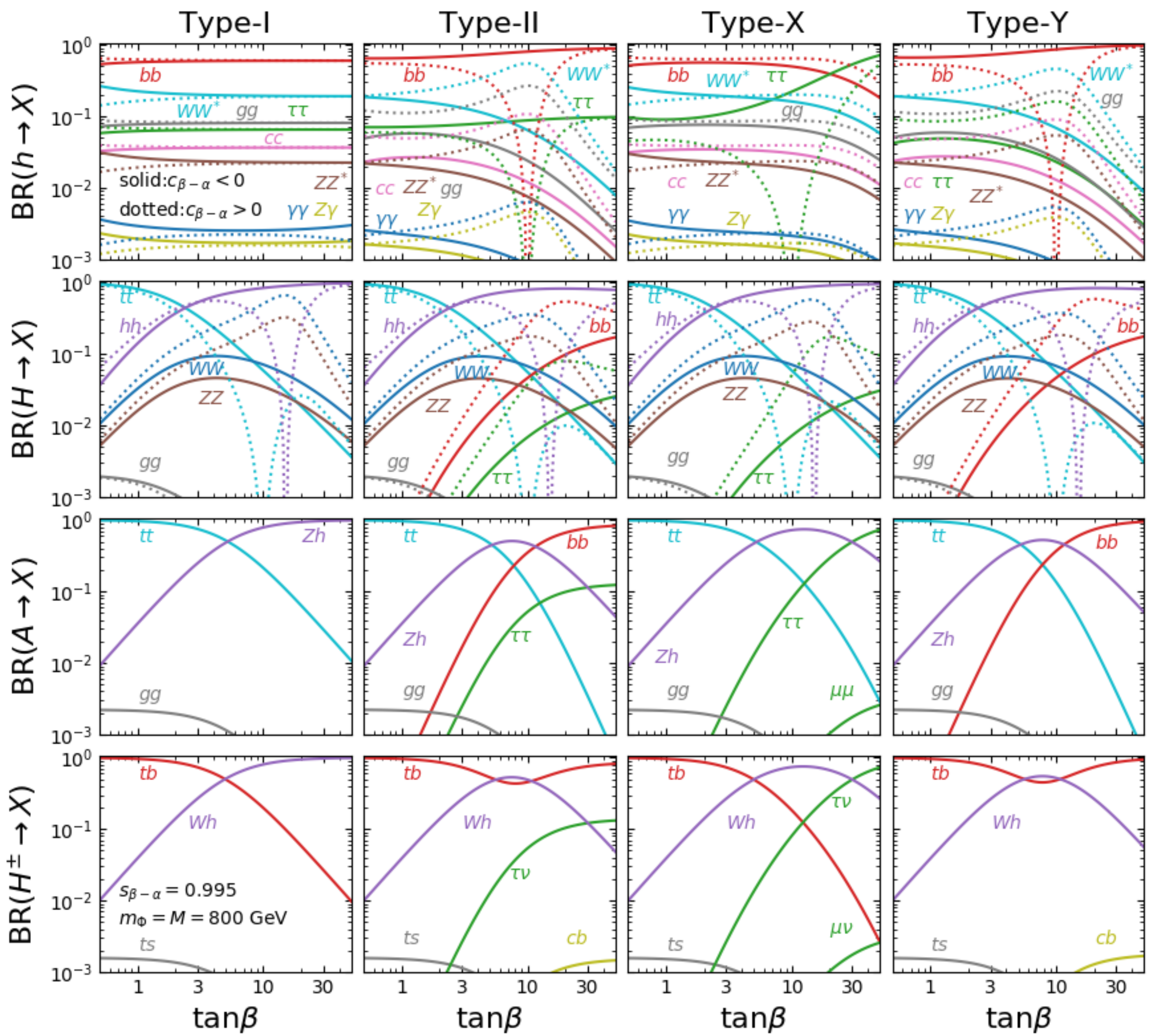


	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type-I	+	−	+	+	−	−	−	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	+	−	+	+	−	+	+	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X (lepton-specific)	+	−	+	+	−	−	+	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y (flipped)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

Decay: non-alignment, m=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)	+	−	+	+	−	+	−	$\cot\beta$	$-\tan\beta$	$\cot\beta$

- So far, unfortunately, there is no report on new particle discovery from the LHC...

➡constraints on the parameters of the models.

6 free parameters in the THDMs:

$$m_H, \quad m_A, \quad m_{H^\pm}, \quad M^2, \quad \tan\beta, \quad s_{\beta-\alpha},$$

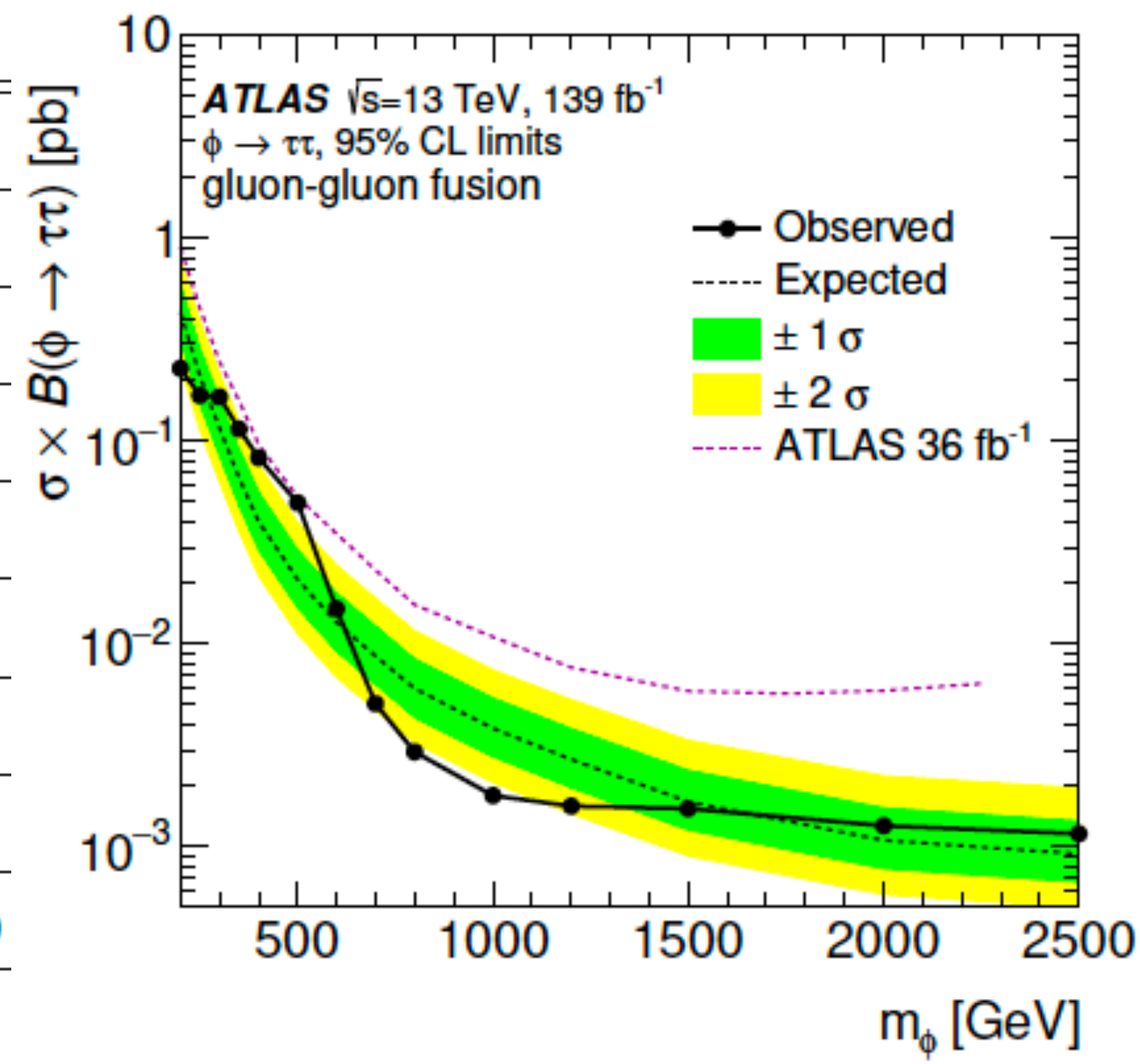
In our study, we take

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

List of LHC constraints used in our study

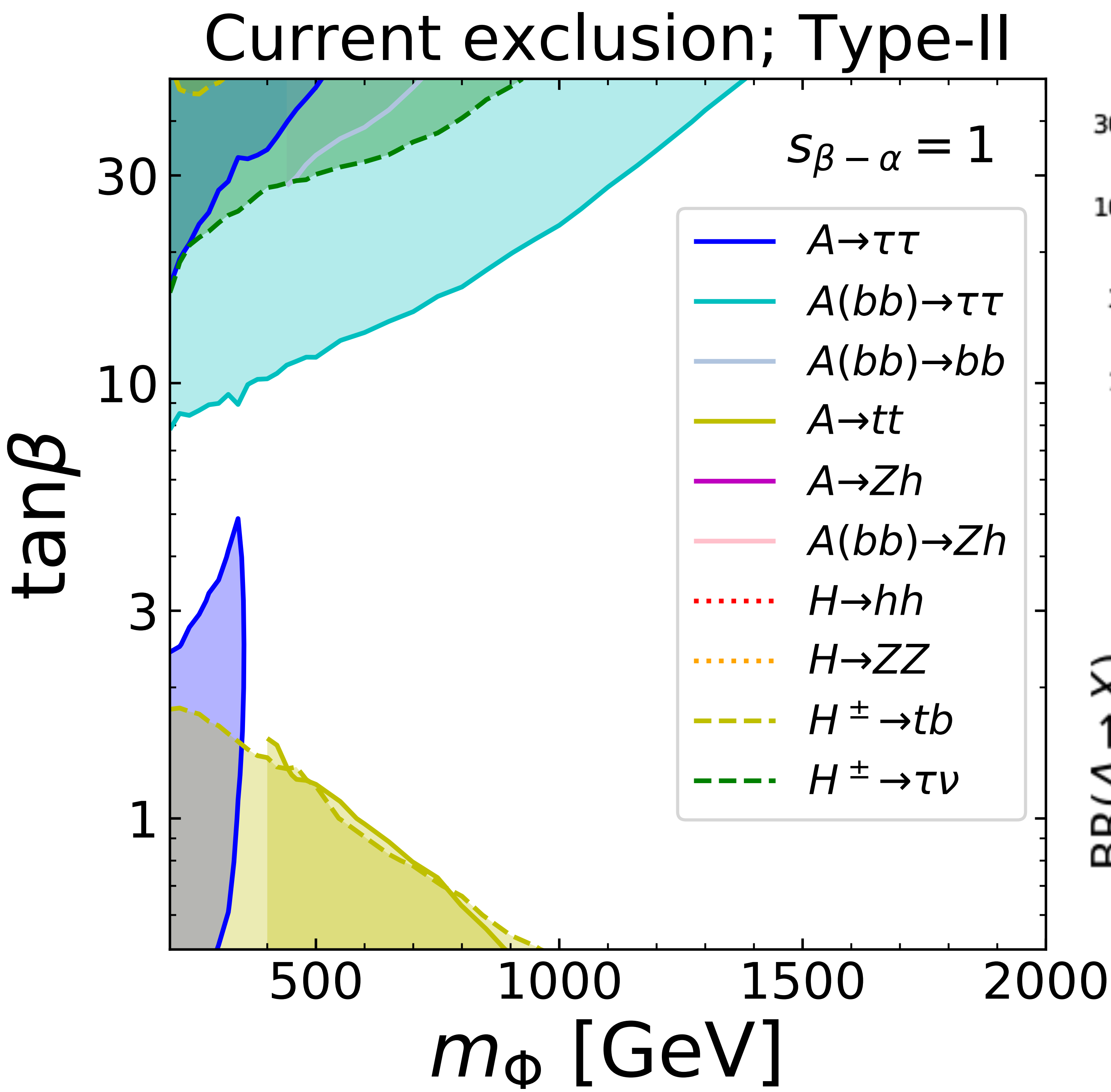
LHC Run-II 36 fb[-1] data

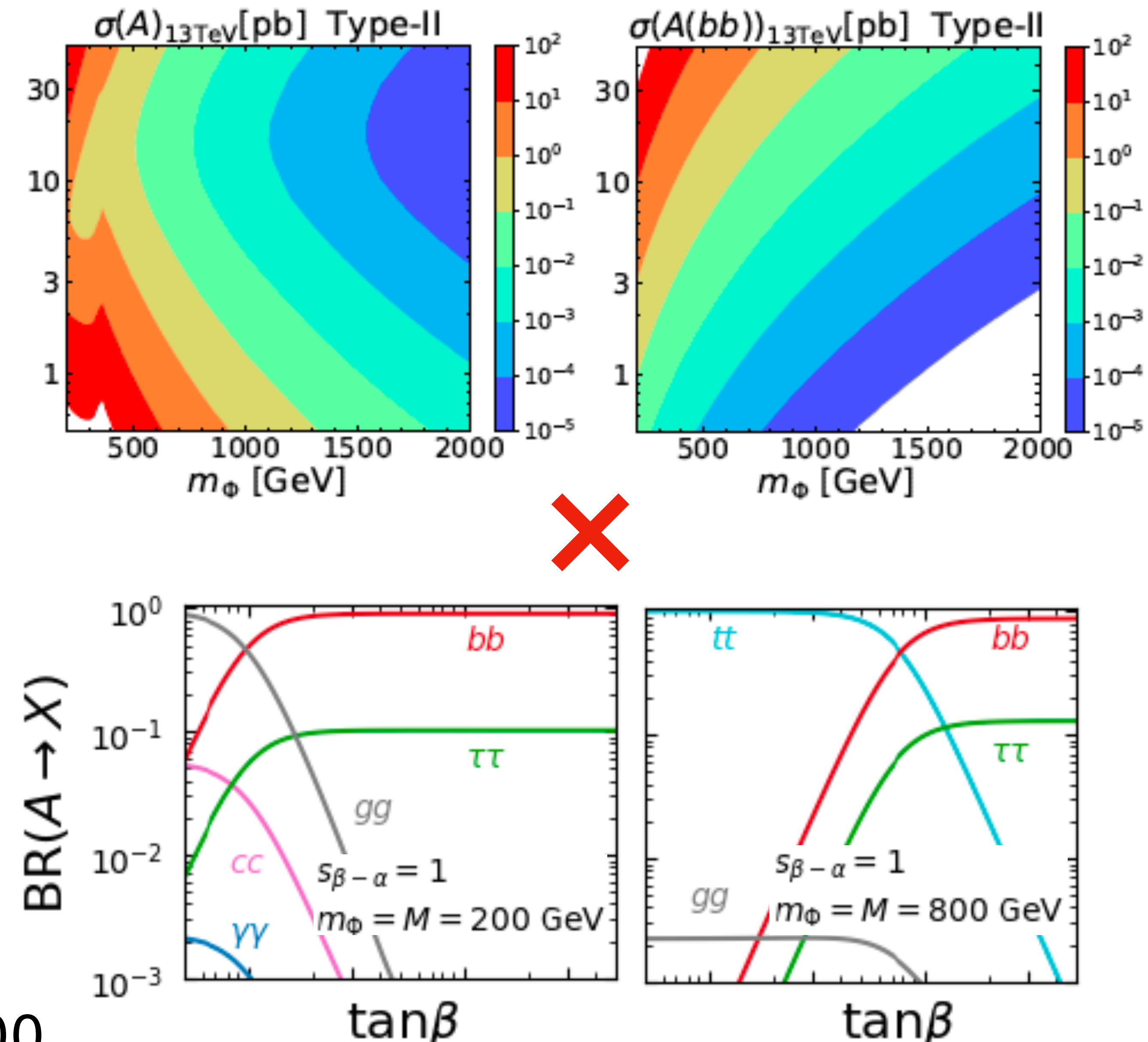
Constrained quantity	
$\sigma(\phi) \times \mathrm{BR}(\phi \to \tau\tau)$	
$\sigma(\phi(bb)) \times \mathrm{BR}(\phi \to \tau\tau)$	
$\sigma(\phi(bb)) \times \mathrm{BR}(\phi \to bb)$	
$\sigma(\phi) \times \mathrm{BR}(\phi \to tt)$	
$\sigma(H) \times \mathrm{BR}(H \to hh) \times \mathrm{BR}(h \to bb)^2$	
$\sigma(H) \times \mathrm{BR}(H \to WW)$	
$\sigma(H) \times \mathrm{BR}(H \to ZZ)$	
$\sigma(A) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to bb)$	
$\sigma(A(bb)) \times \mathrm{BR}(A \to Zh) \times \mathrm{BR}(h \to bb)$	
$\sigma(tH^\pm) \times \mathrm{BR}(H^\pm \to tb)$	
$\sigma(tH^\pm) \times \mathrm{BR}(H^\pm \to \tau\nu)$	$200 < m_\Phi <$



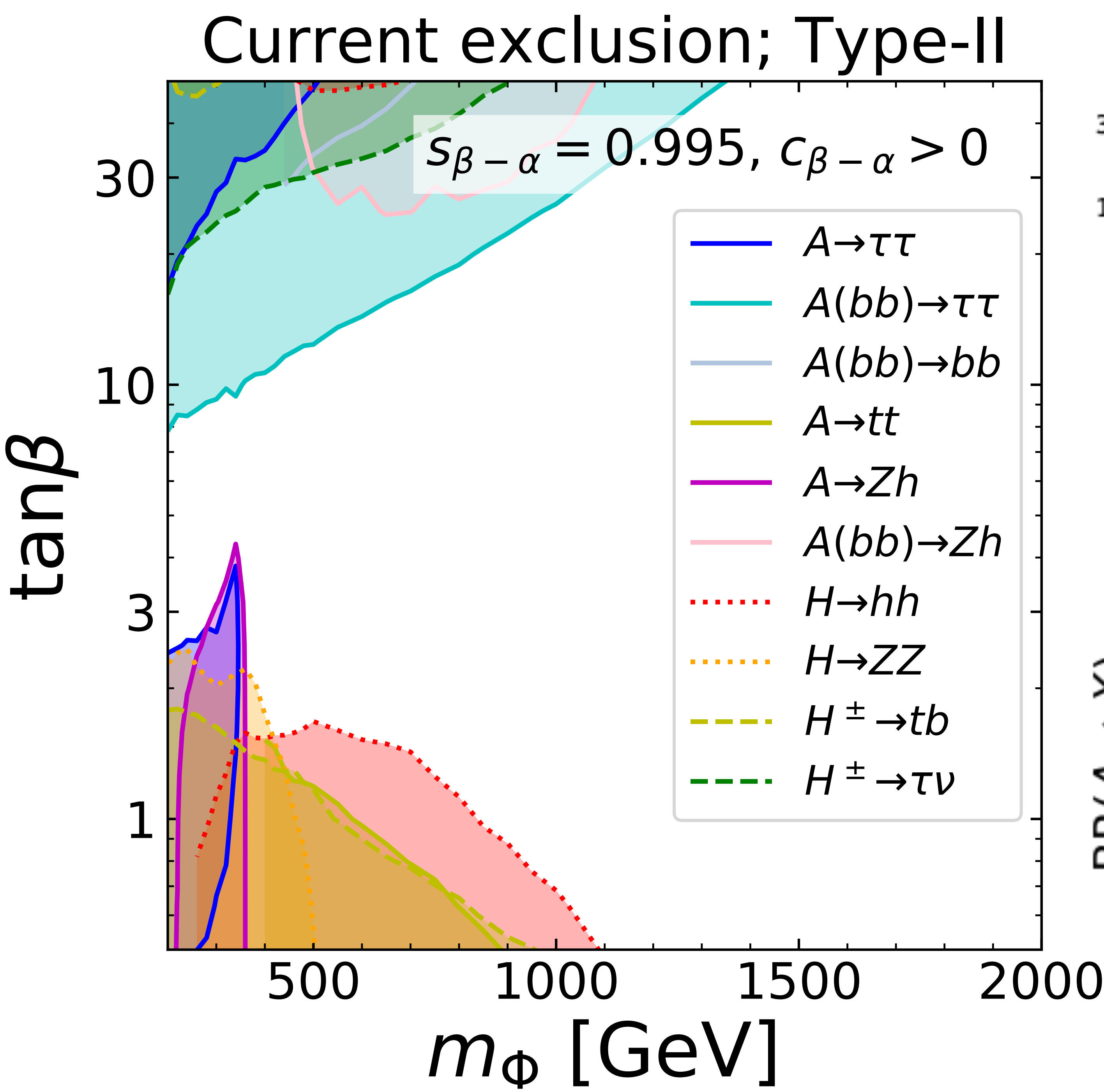
model-independent constraints
➡interpretation to THDMs

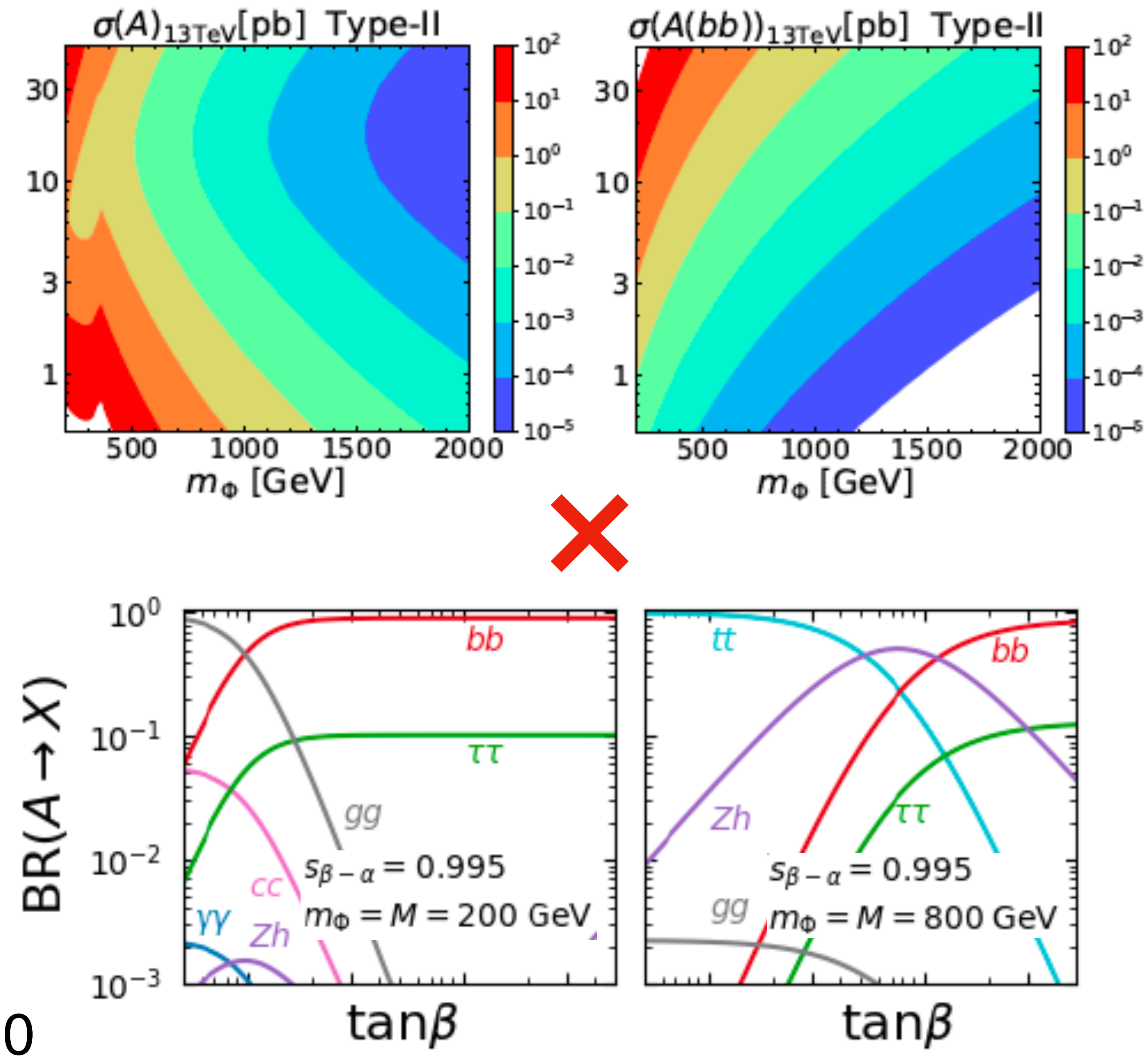
Exclusion region (e.g. Type-II, alignment)

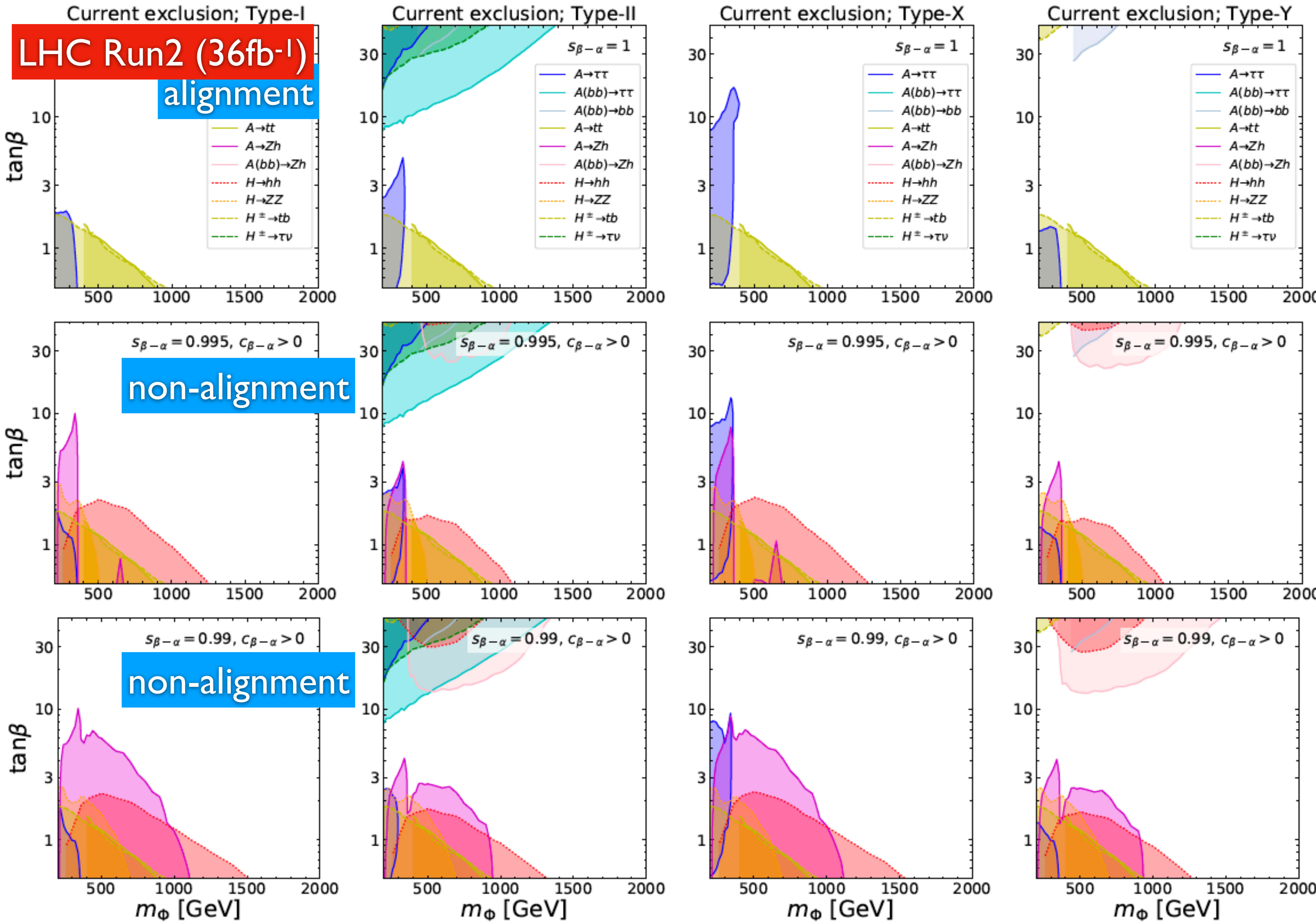




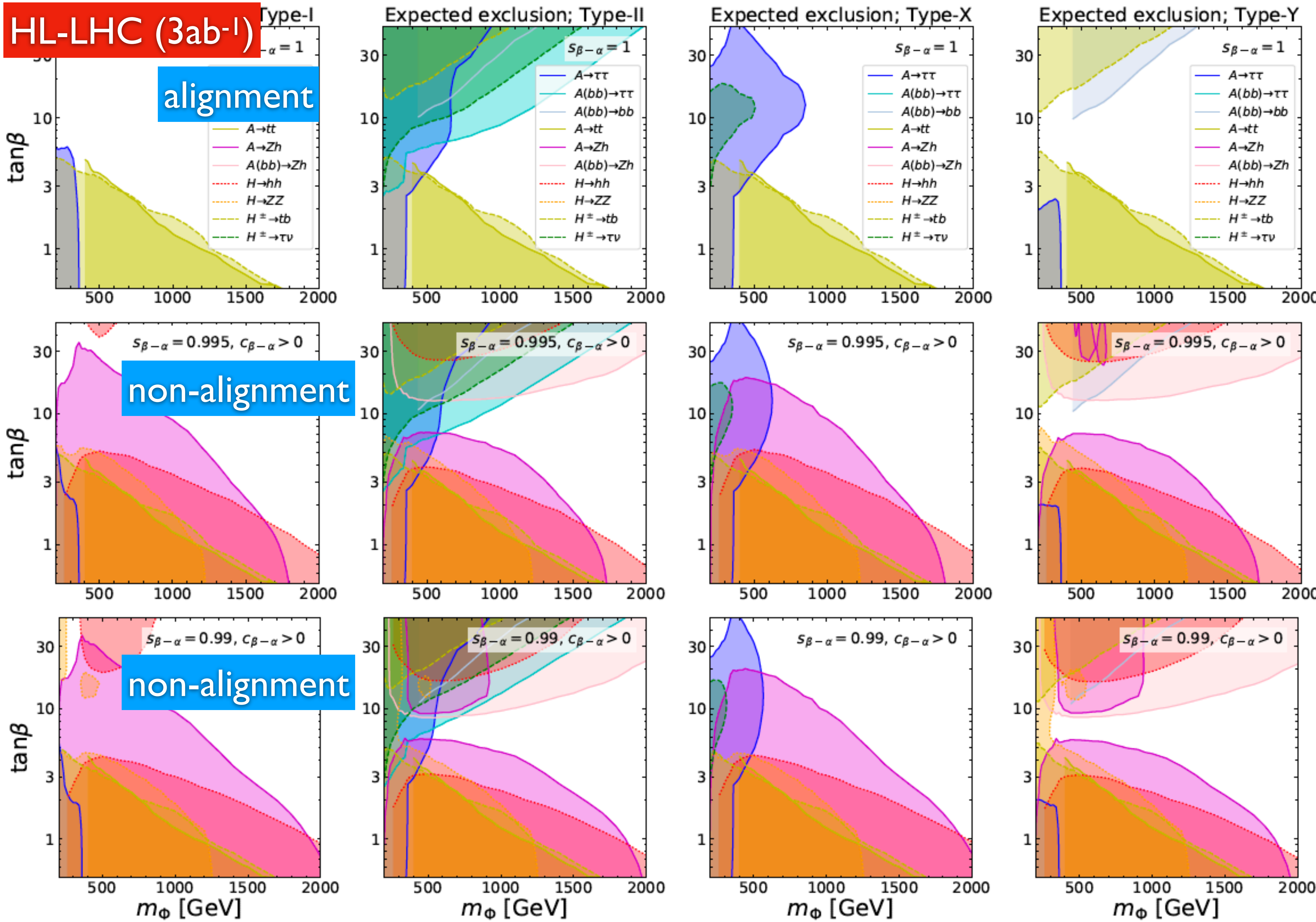
Exclusion region (e.g. Type-II, non-alignment)







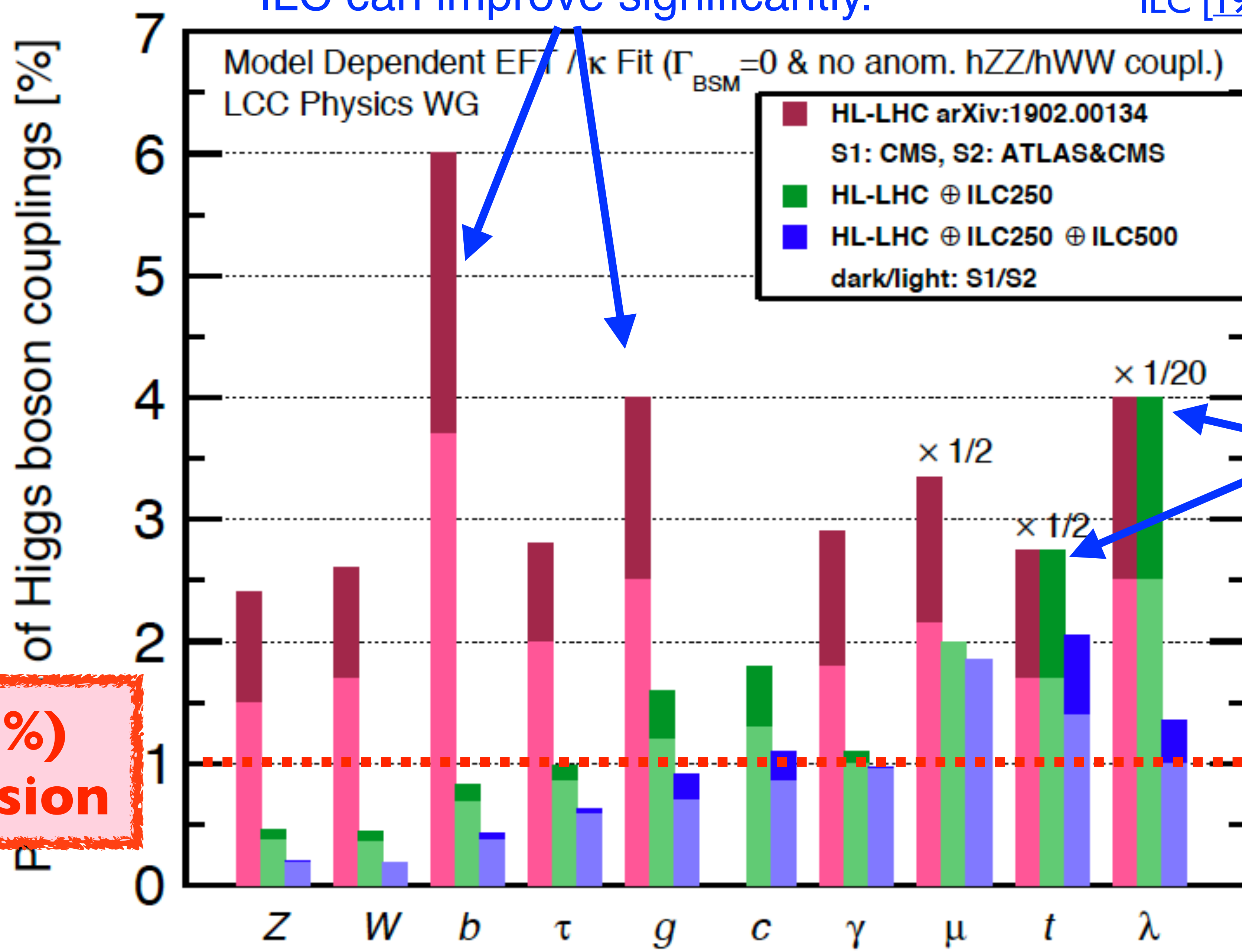
LHC Run2 (36fb-1)
alignment
non-alignment
non-alignment
Current exclusion; Type-I
Current exclusion; Type-II
Current exclusion; Type-X
Current exclusion; Type-Y
$s_{\beta-\alpha}=1$
$s_{\beta-\alpha}=0.995,\ c_{\beta-\alpha}>0$
$s_{\beta-\alpha}=0.99,\ c_{\beta-\alpha}>0$
A→ττ
A(bb)→ττ
A(bb)→bb
A→tt
A→Zh
A(bb)→Zh
H→hh
H→ZZ
H±→tb
H±→τν
tanβ
m_Φ [GeV]


HL-LHC (3ab-1)
alignment
non-alignment
non-alignment
Type-I
Expected exclusion; Type-II
Expected exclusion; Type-X
Expected exclusion; Type-Y
$s_{\beta-\alpha}=1$
$s_{\beta-\alpha}=0.995,\ c_{\beta-\alpha}>0$
$s_{\beta-\alpha}=0.99,\ c_{\beta-\alpha}>0$
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]

Higgs precision measurements @ HL-LHC + ILC

ILC can improve significantly.

ILC [1903.01629]



180M Higgs (HL-LHC)
+ 0.6M (ILC250)

ILC500 is necessary.

O(1%) precision

What can we learn from the Higgs precision measurements ?

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

relatively clean even at the LHC. Only ILC can measure.

Decoupling without alignment

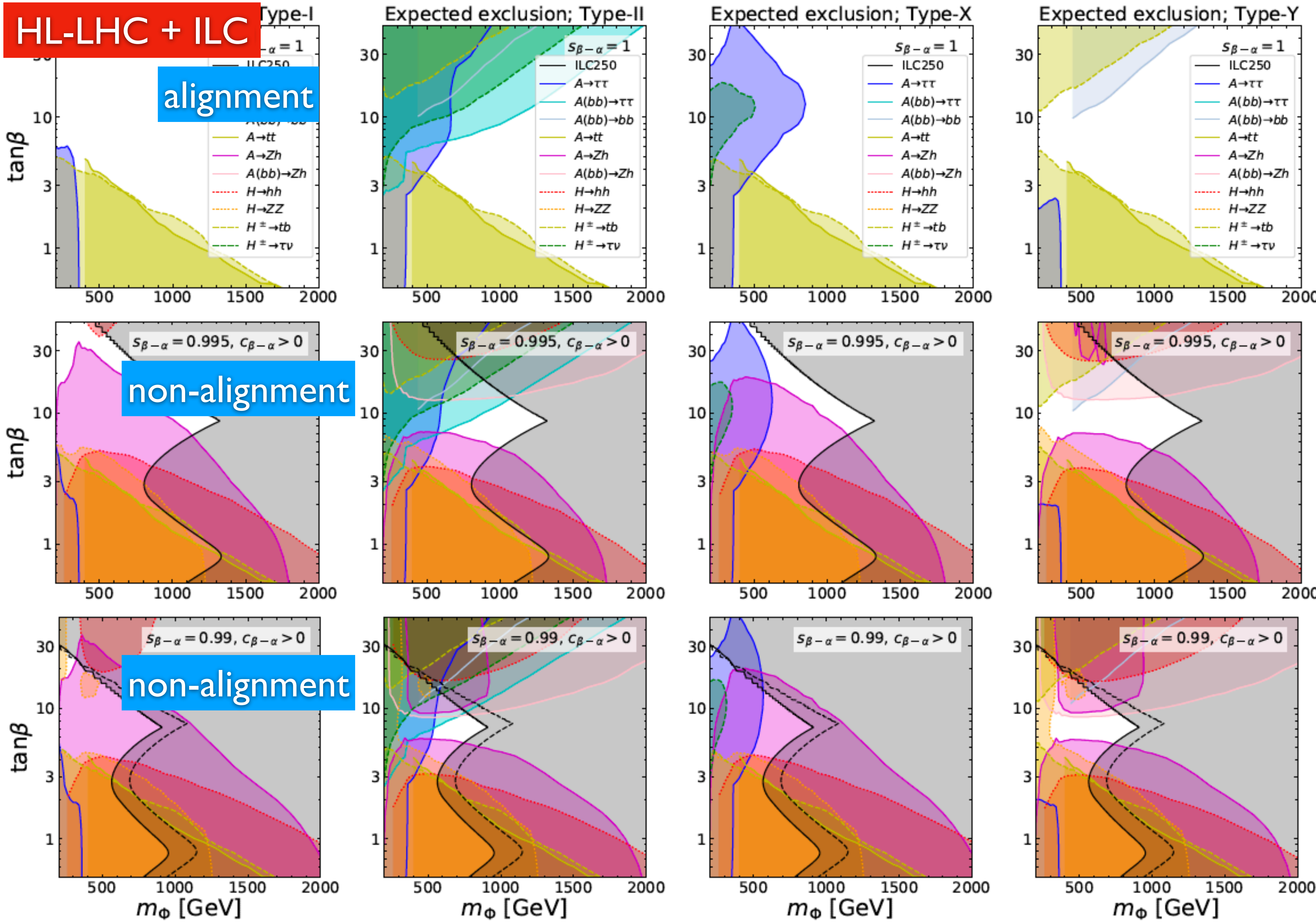
- Can we take M→∞ with sin(β—α)≠1 ?
  - NO ! $m_h^2 = \lambda v^2 + \cos^2(\beta-\alpha)M^2 = (125\ \mathrm{GeV})^2$

➡If sin(β—α)≠1, the upper limit on M is set.

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

ILC [1903.01629]

$$\kappa_V^h = [0.995, 0.99, 0.98] \pm 0.0038\ (0.0076)$$


HL-LHC + ILC
alignment
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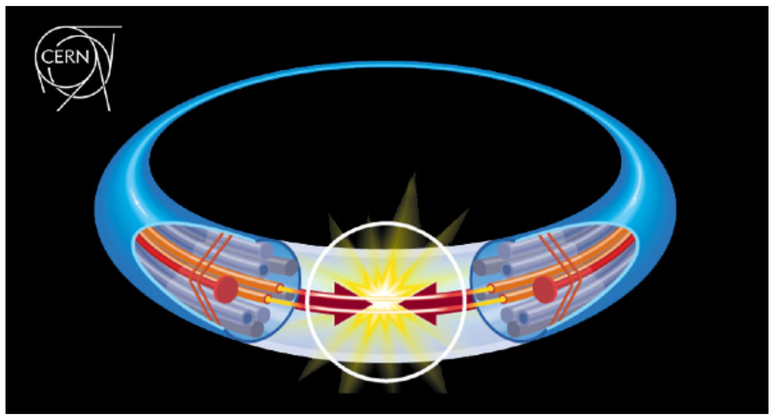
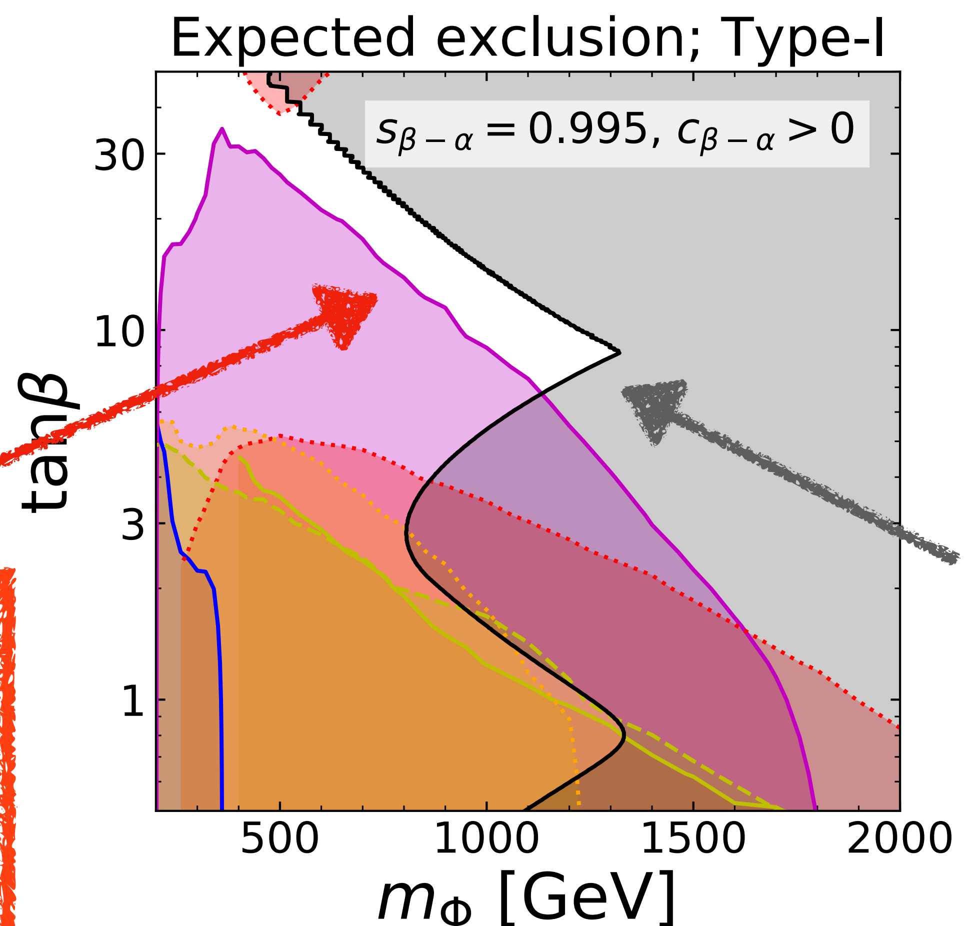
non-alignment
Type-I
Expected exclusion; Type-II
Expected exclusion; Type-X
Expected exclusion; Type-Y
$s_{\beta-\alpha}=1$
$s_{\beta-\alpha}=0.995,\ c_{\beta-\alpha}>0$
$s_{\beta-\alpha}=0.99,\ c_{\beta-\alpha}>0$
ILC250
$A\to\tau\tau$
$A(bb)\to\tau\tau$
$A(bb)\to bb$
$A\to tt$
$A\to Zh$
$A(bb)\to Zh$
$H\to hh$
$H\to ZZ$
$H^\pm\to tb$
$H^\pm\to\tau\nu$
$\tan\beta$
m_Φ [GeV]

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.

@ aiina (next to Morioka station in Iwate)