[arXiv:2108.11868]

Precise calculation of charged Higgs boson decays in two Higgs doublet models

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ILC camp, online

Introduction

THDMs: two Higgs doublet models

- So far, the standard model (SM) is successful theory that describes electroweak symmetry breaking.

- However, the structure of the Higgs sector has not been clarified.
    - Extended Higgs sectors.

      $$\Phi + \Phi \text{ (Doublet)}, \quad \Phi + S \text{ (Doublet)}, \quad \Phi + \Delta \text{ (Triplet)}, \text{ etc.}$$

    - They appear in variety of New Physics (NP) models and scenarios.

      SUSY, WIMP dark matter, generation of neutrino mass, electroweak baryogenesis, …

    → We can pursue NP by investigating Higgs sector.

This talk: Radiative corrections to charged Higgs boson ($H^{\pm}$) decays in THDMs.

- Importance and quantitative size of the radiative corrections to $H^{\pm}$ decays.
- How can we separate 4 types of THDMs by decay patterns of $H^{\pm}$?

Two Higgs doublet models (THDMs)

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

$$\Phi_i = \begin{pmatrix} w_i^\pm \\ \frac{1}{\sqrt{2}}(v_1 + h_i + z_i) \end{pmatrix} \quad (i = 1, 2)$$

- Z_2 symmetry is imposed : $\Phi_1 \to +\Phi_1, \quad \Phi_2 \to -\Phi_2$

	Type-I	Type-II	Type-X	Type-Y
Z_2 charge for $(u_R,\ d_R,\ \ell_R)$:	$(-,\ -,\ -)$,	$(-,\ +,\ +)$,	$(-,\ -,\ +)$,	$(-,\ +,\ -)$

→ 4 types of Yukawa interactions.

$$\mathcal{L}_Y = -Y_u\bar{Q}_L\tilde{\Phi}_u u_R - Y_d\bar{Q}_L\Phi_d d_R - Y_e\bar{L}_L\Phi_e e_R + \text{h.c.}$$

$\Phi_{u,d,e} : \Phi_1 \text{ or } \Phi_2$

→ Flavor changing neutral current (FCNC) is prohibited at tree level.

- Mass eigenstates:

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

$$R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

H, A, H⁺, H⁻ :additional Higgs bosons, *h* : SM-like Higgs boson

- Input parameters: m_H, m_A, $m_{H^\pm}$, $\sin(\beta-\alpha)$, $\tan\beta$, M^2

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

Alignment limit

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

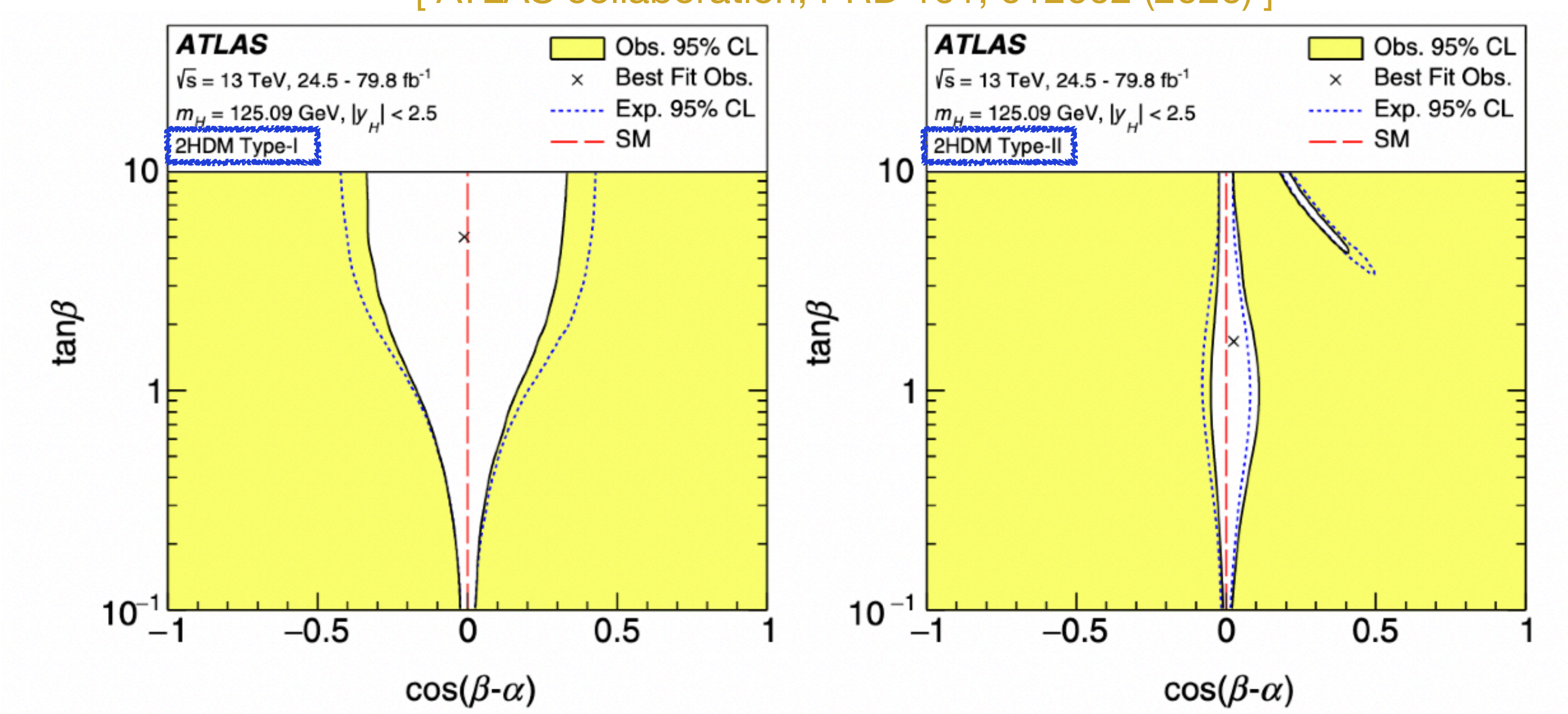
- Higgs boson couplings:

$$\kappa_X \equiv g_{hXX}/g_{hXX}^{\rm SM}$$

$$\begin{cases} \kappa_V = \sin(\beta - \alpha) \\ \kappa_f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha) \end{cases} \xrightarrow{\text{Alignment limit}} \begin{cases} \kappa_V = 1 \\ \kappa_f = 1 \end{cases}$$

- Constraint from Higgs signal strength

[ATLAS collaboration, PRD 101, 012002 (2020)]



$\sin(\beta - \alpha)$ should be close to 1.

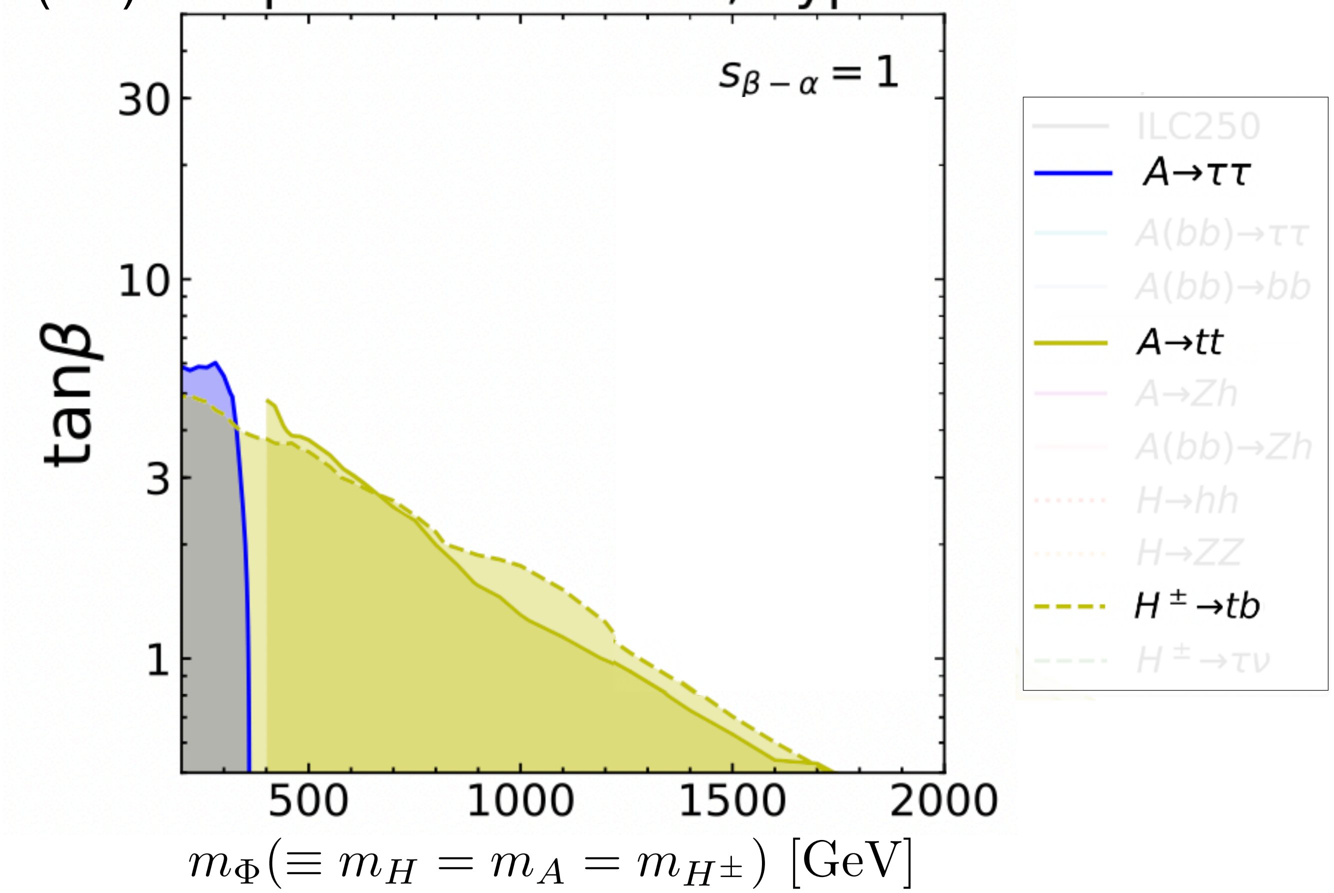
Alignment limit or near alignment scenarios ($\sin(\beta - \alpha) \simeq 1$) are favored.

Synergy between direct and indirect searches[1/3]

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

[M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB 966 (2021) 115375]

(Ex.): Expected exclusion; Type-I at HL-LHC



$s_{\beta-\alpha}:\ \sin(\beta-\alpha)$

$c_{\beta-\alpha}:\ \cos(\beta-\alpha)$

$$\Gamma(A\to f\bar{f}) \propto \frac{m_A}{\tan^2\beta}$$

$$\Gamma(H^+\to t\bar{b}) \propto \frac{m_{H^\pm}}{\tan^2\beta}$$

Direct searches : Lower bounds for m_Φ and $\tan\beta$ are given.

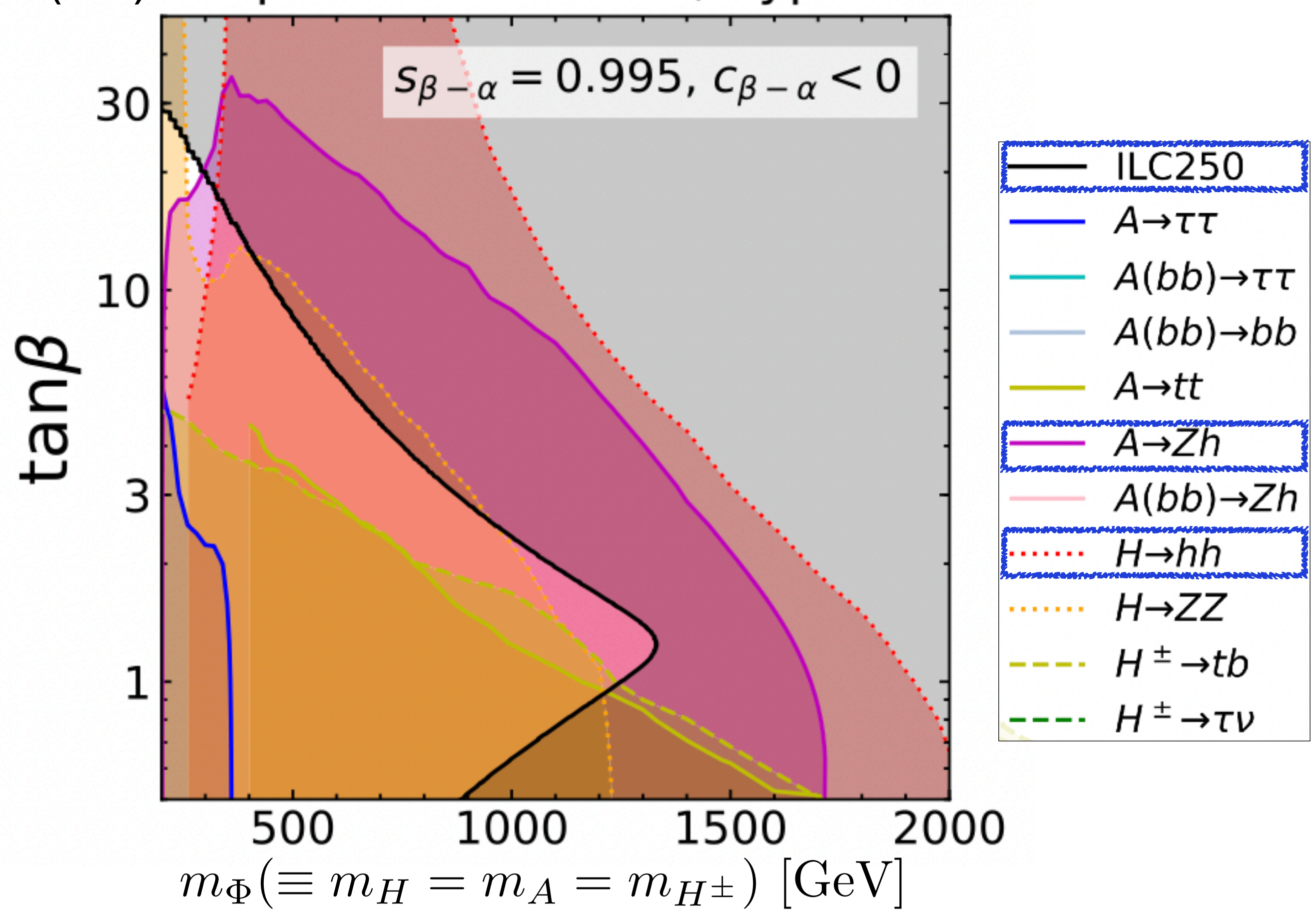
Indirect searches : No sensitivity since Higgs couplings do not deviate.

Synergy between direct and indirect searches[2/3]

Near alignment scenario: $\sin(\beta-\alpha)=0.995$

[M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB 966 (2021) 115375]

(Ex.): Expected exclusion; Type-I at HL-LHC



$s_{\beta-\alpha}:\ \sin(\beta-\alpha)$

$c_{\beta-\alpha}:\ \cos(\beta-\alpha)$

$$\Gamma(A\to Zh)\propto\cos(\beta-\alpha)^2\frac{m_A^3}{16\pi v^2}$$

$$\Gamma(H\to hh)\sim\cos(\beta-\alpha)^2\frac{m_H^3}{16\pi v^2}$$

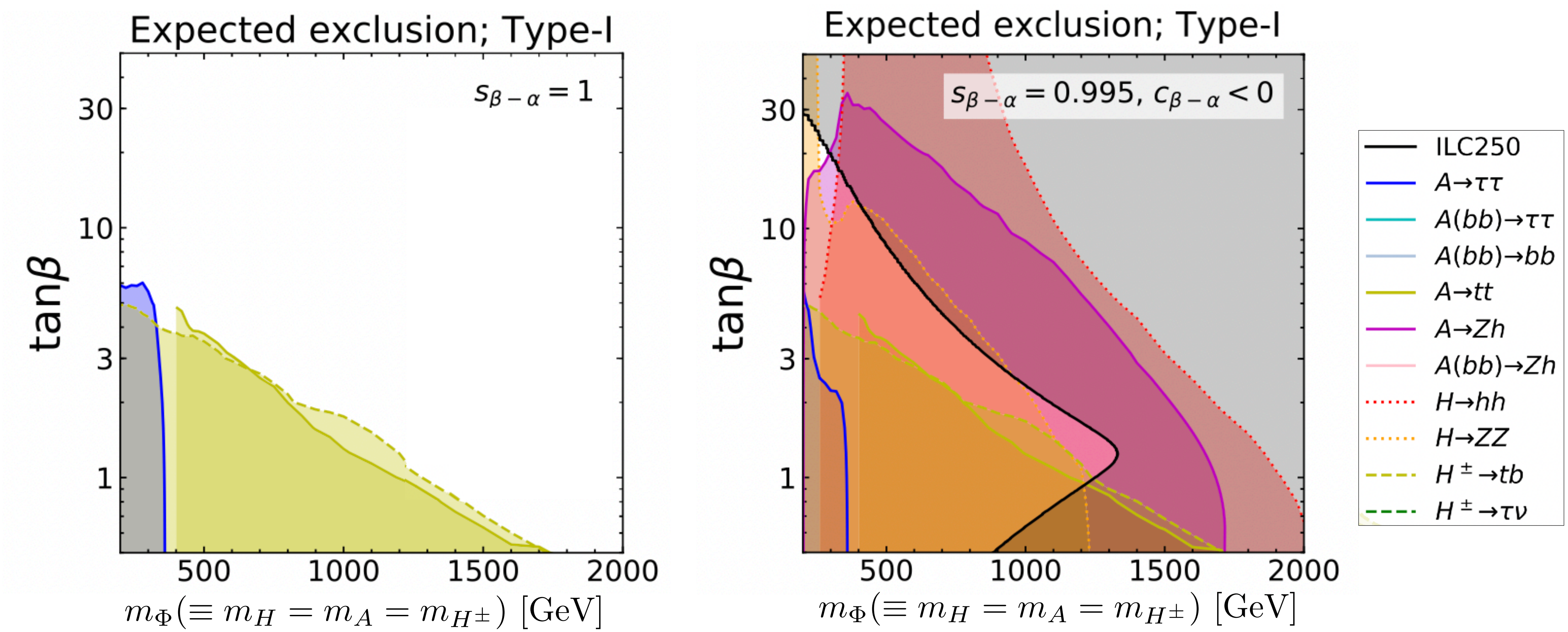
Direct searches : $A\to Zh$ and $H\to hh$ give wider sensitivity regions for $(m_\Phi,\ \tan\beta)$ plane.

Indirect searches : If a deviation in *hZZ* founds, the upper bounds for m_Φ are given.

→ Most parameter space can be surveyed.

Synergy between direct and indirect searches[3/3]

[M. Aiko, S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB 966 (2021) 115375]



→ Sensitivity regions by direct searches are drastically changed by $\sin(\beta-\alpha)$.

Radiative corrections to Heavy Higgs decays can be significant in alignment scenarios.

- $H^\pm$ decays (this talk)
- *H* decays (talk by Mariko Kikuchi on 21st Sep. (Tue.))
- *A* decays (future work)

Radiative corrections to Higgs boson decays

- Radiative corrections to SM-like Higgs boson *h*

  - Higgs boson couplings (one-loop EW)

    $$hf\bar{f},\ hVV\ ,hhh$$

    [S. Kanemura, Y. Okada, E. Senaha, C. Yuan, PRD70 (2004) 115002]
    [S. Kanemura, M. Kikuchi, K. Yagyu, PLB 731 (2014) 27]
    [S. Kanemura, M. Kikuchi, K. Yagyu, NPB896 (2015) 80]

  - Higgs boson decays (NLO EW, NNLO QCD)

    $$h \to f\bar{f},\ h \to VV^* \to Vf\bar{f}$$

    [S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, PLB783 (2018) 140]
    [S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu, NPB949 (2019) 114791]

H-COUP calculates these processes.

[Kanemura, Kikuchi, KS, Yagyu, CPC 233 (2018) 134]

[Kanemura, Kikuchi, KS, Mawatari, Yagyu, CPC257(2020) 107512]

Other tools:

2HDECAY [M. Krause, M. Mühlleitner, M. Spira, CPC. 246 (2020) 106852]

Prophecy4f [L. Altenkamp, S. Dittmaier, H. Rzehak, JHEP 1803 (2018) 110]

  - Production process at ILC (NLO EW, NLO QCD)

    $e^+e^- \to Zh$ talk by Masashi Aiko on 21st Sep (Tue.).

    $e^+e^- \to \gamma h$ [S. Kanemura, K. Mawatari, KS, PRD 99 (2019) 035023]

→ Loop effects in Higgs observables have been studied.

Calculation of one-loop corrections to charged Higgs decays

- We calculated NLO EW and NLO QCD corrections to the following process:

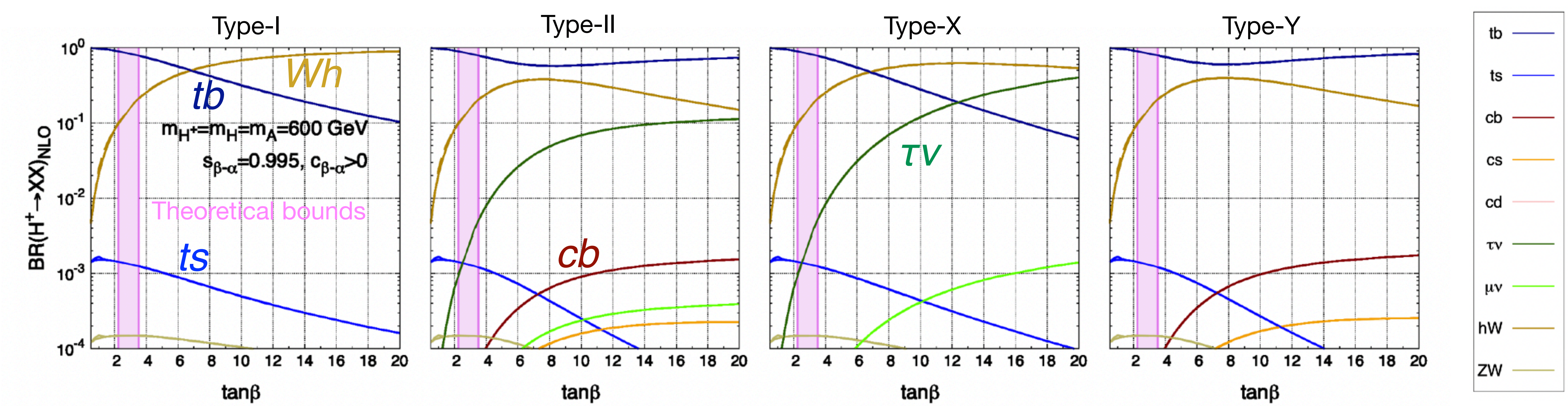
$$H^{\pm} \to f f', \quad H^{\pm} \to W\phi \ (\phi = h, H, A), \quad H^{\pm} \to WV(V = Z, \gamma)$$

For UV divergence : improved on-shell scheme (same scheme as **H-COUP**)

For IR divergence : adding real photon emission contributions

- Analytical expressions will be implemented in **`H-COUP ver. 3`**.

- Behavior of branching ratios for H^+ for near alignment scenario, $\sin(\beta - \alpha) = 0.995$

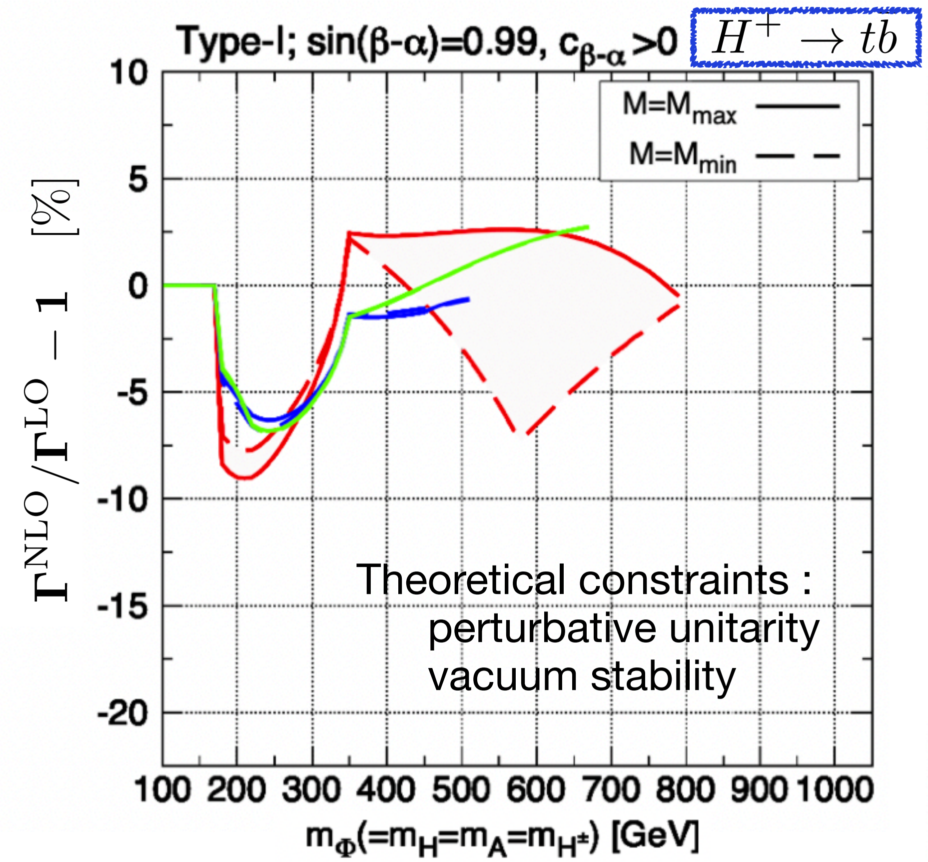


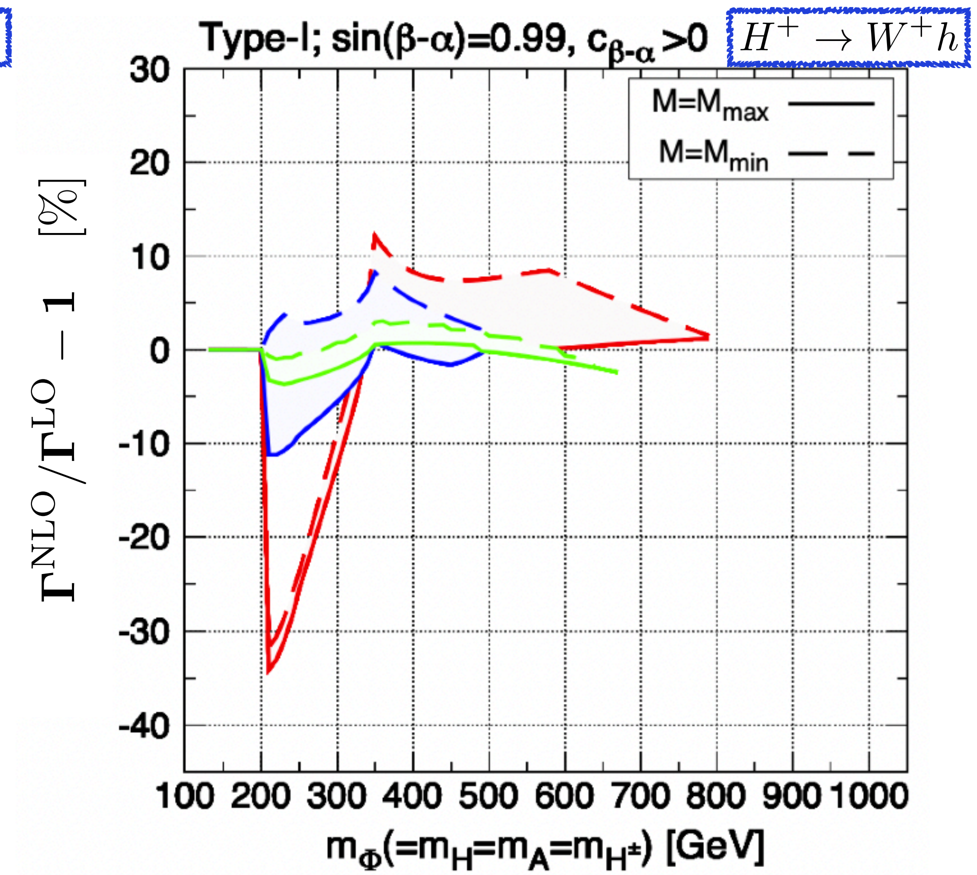
Low $\tan\beta$ regions : $H^+ \to t\bar{b}$ is dominant without depending on types of THDMs.

High $\tan\beta$ regions : difference among types of THDMs can appear.

Effects of scalar loop corrections to charged Higgs decays

- red line: $\tan\beta = 1$
- blue line: $\tan\beta = 3$
- green line: $\tan\beta = 5$





Most sizable corrections :

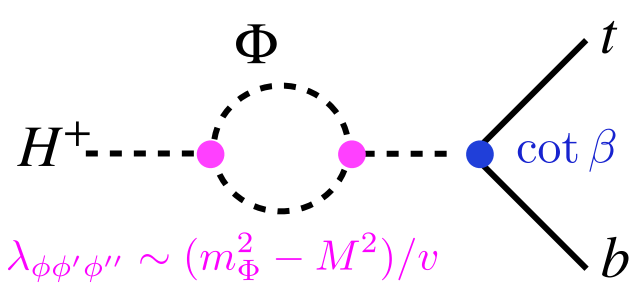
When $m_\Phi \lesssim 400$ GeV,

thresholds of 1PI diagrams

can enhance the corrections.

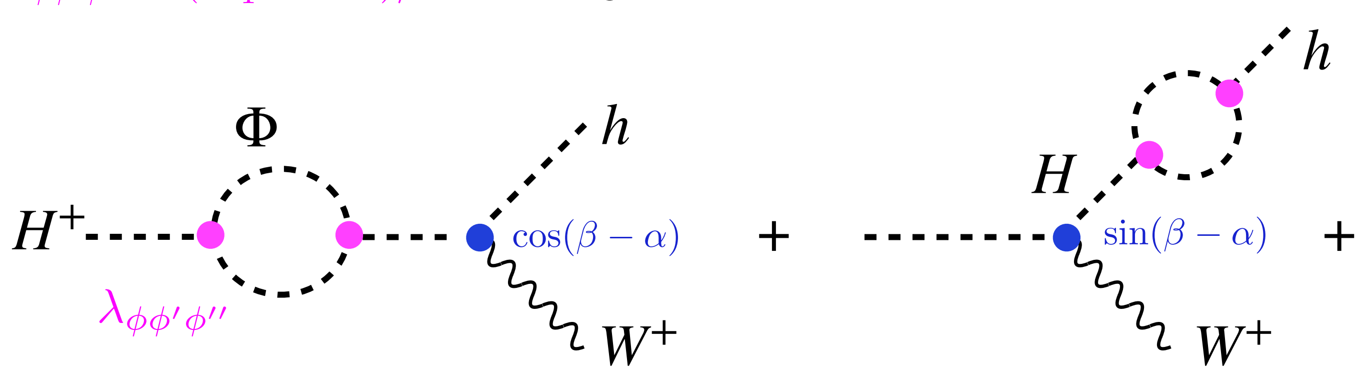
Dominant contributions at m_Φ ~600 GeV with tanβ=1:

$\mathcal{M}^{\text{1-loop}}_{H^+\to t\bar{b}} \simeq$



$+ \ldots$ ⇒ (NLO correction)~ -7%

$\mathcal{M}^{\text{1-loop}}_{H^+\to W^+h} \simeq$

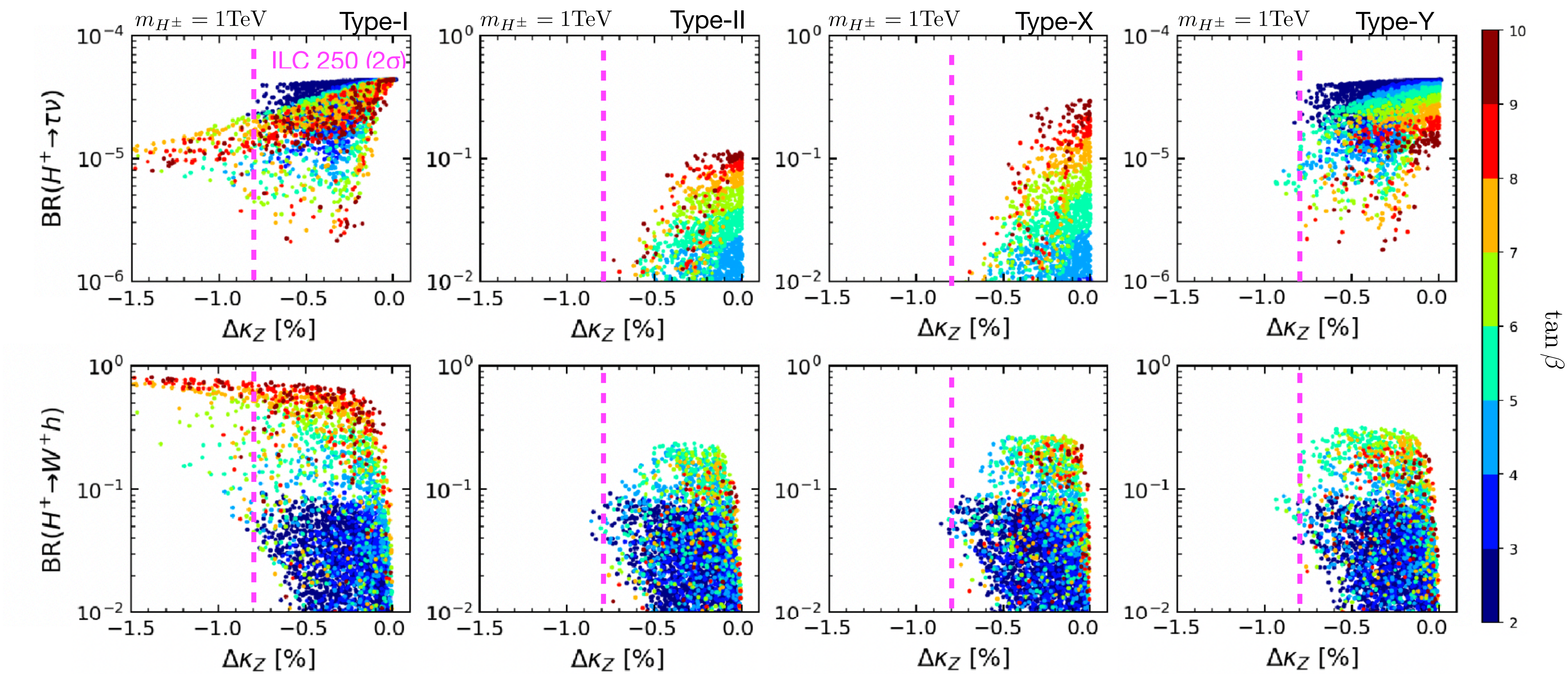


$+ \ldots$ ⇒ (NLO correction)~ +7%

Discrimination of THDMs by decays of $H^{\pm}$

We discuss how 4 types of THDMs can be distinguished in alignment regions, $\Delta\kappa_Z \lesssim 0.76\%$. ←*hZZ* (ILC): 0.38%
[K. Fujii, et al., 1710.07621]

[M. Aiko, S. kanemura, KS]



- $\mathrm{BR}(H^+ \to \tau^+\nu) \gtrsim 10\%$ is predicted only in Type-X.
- In Type-I $\mathrm{BR}(H^+ \to W^+ h)$ can be maximally 60%.

(Type-II and Y can be identified by $\mathrm{BR}(H^+ \to c\bar{b})$ and $\mathrm{BR}(H^+ \to \tau^+\nu)$.) -> Back up slide

Summary

- Constraints from direct searches of additional Higgs bosons are drastically changed depending on $\sin(\beta-\alpha)$.

  → Radiative corrections to heavy Higgs boson decays can be significant in alignment scenarios, $\sin(\beta-\alpha) \simeq 1$.

- We investigated impact of radiative corrections to charged Higgs boson decays.

  - Magnitude of NLO corrections to $\Gamma(H^+ \to t\bar{b})$ and $\Gamma(H^+ \to W^+h)$ can become 10-30%

- We found that 4 types of THDMs can be distinguished by H^+ decays.

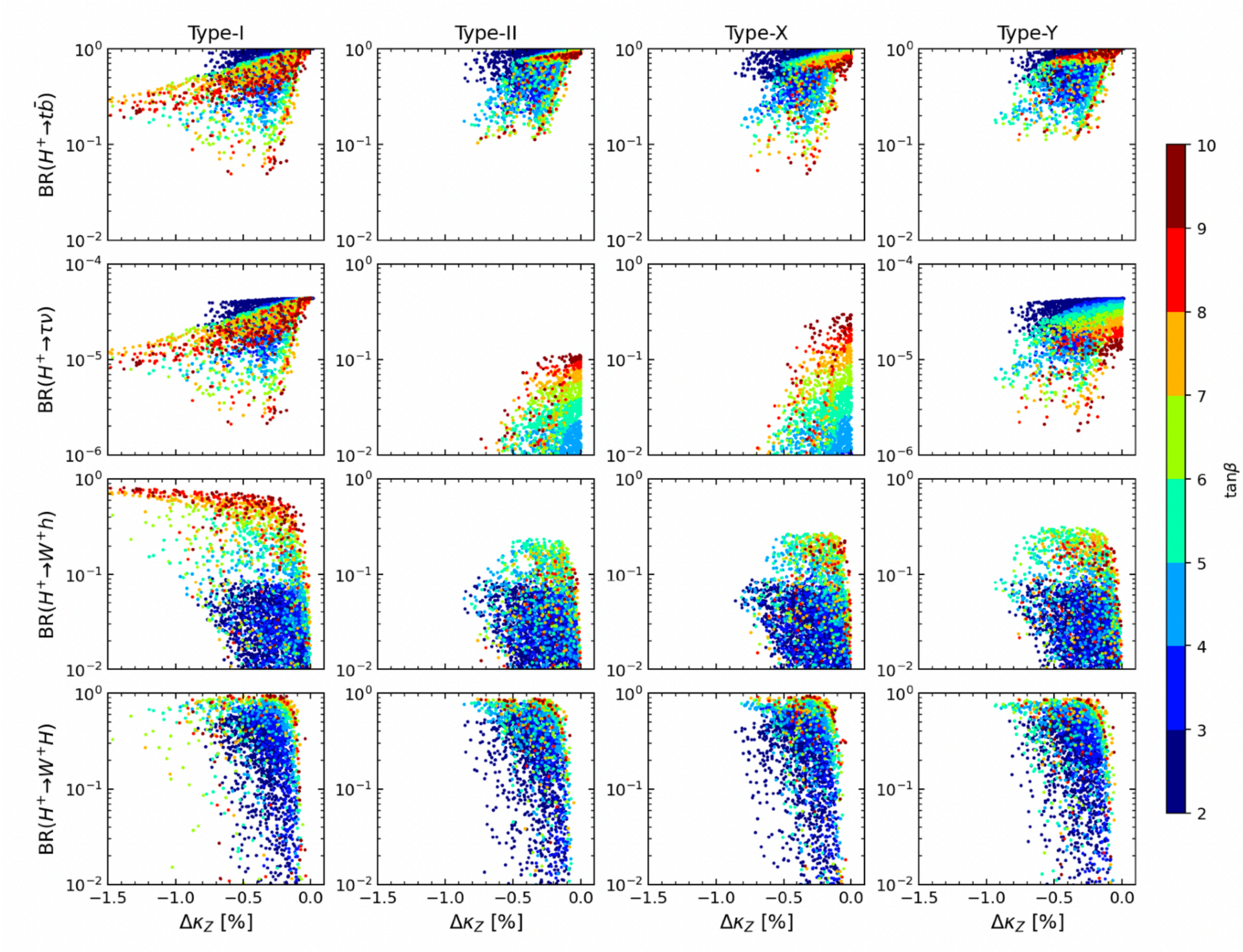
  Type-I : maximum of $\mathrm{BR}(H^+ \to w^+h)$ is ~60%.

  Type-X : $\mathrm{BR}(H^+ \to \tau^+\nu) \gtrsim 10\,\%$.

  Type-II and-Y: characteristic predictions in correlation between $\mathrm{BR}(H^+ \to \tau^+\nu)$ and $\mathrm{BR}(H^+ \to c\bar{b})$.

Buck up

Branching ratios in near alignment senarios



Correlation between $H^+ \to c\bar{b}$ and $H^+ \to \tau^+\nu$