# Impact of radiative corrections on decays of the charged and CP-odd Higgs bosons

Based on

Nucl. Phys. B973 (2021) 115518 [hep-ph: 2108.11868] and work in progress

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Physics in LHC and Beyond （2022/05/13 Matsue, Shimane）

# Introduction

## Standard Model

We have problems that can't be explained within the SM.

Baryon asymmetry of the universe, Dark matter, Neutrino's tiny mass, etc.

SM must be extended to solve these problems.

## Extended Higgs model

- One $SU(2)_L$ doublet is a theoretical assumption in the SM.
- The above problems can be solved.

The structure of the Higgs sector is still a mystery.

# Two Higgs doublet model (2HDM)



The model with two scalar doublet $\Phi_1$ and $\Phi_2$ with $Y = 1/2$

$$V(\Phi_1,\ \Phi_2) = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right],$$

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

Softly-broken $Z_2$ symmetry suppresses flavor-changing neutral current. Glashow, Weinberg, PRD15 (1977) Paschos, PRD15 (1966)

- 2HDM can be classified into Type-I, II, X and Y. Barger et al. PRD41 (1990) Aoki et al. PRD80 (2009)

**Scalar paricles** $h$ (SM-like Higgs boson), $H$, $A$, $H^\pm$

**Parameters** $v$ (=246 GeV), $m_h$ (=125 GeV), $m_H$, $m_A$, $m_{H^\pm}$, $M^2 = m_{12}^2/(s_\beta c_\beta)$, $\tan\beta$, $s_{\beta-\alpha}$

**Higgs couplings** $g_{hVV} = s_{\beta-\alpha}g_{hVV}^{\rm SM}$, $g_{hff} = (s_{\beta-\alpha} - c_{\beta-\alpha}\zeta_f)g_{hff}^{\rm SM}$ $(\zeta_f = -\tan\beta \text{ or } \cot\beta)$

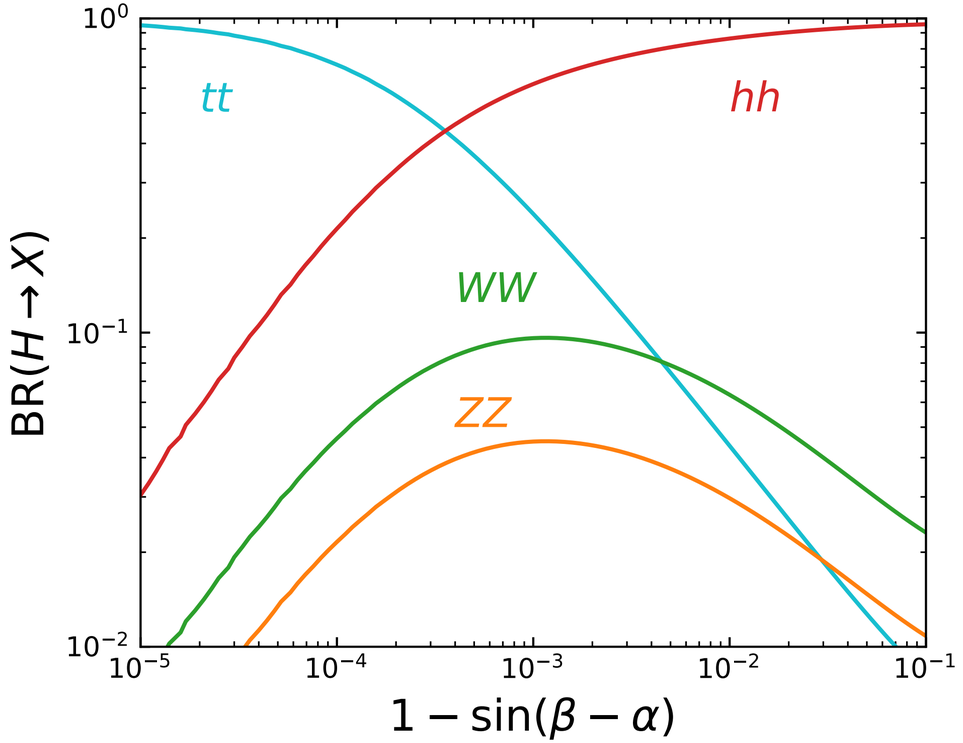
- **Alignment limit** : $s_{\beta-\alpha} \to 1$ (tree-level Higgs couplings take SM-values.)
- LHC data indicate $s_{\beta-\alpha} \simeq 1$. G. Aad et al. PRD101 (2020)

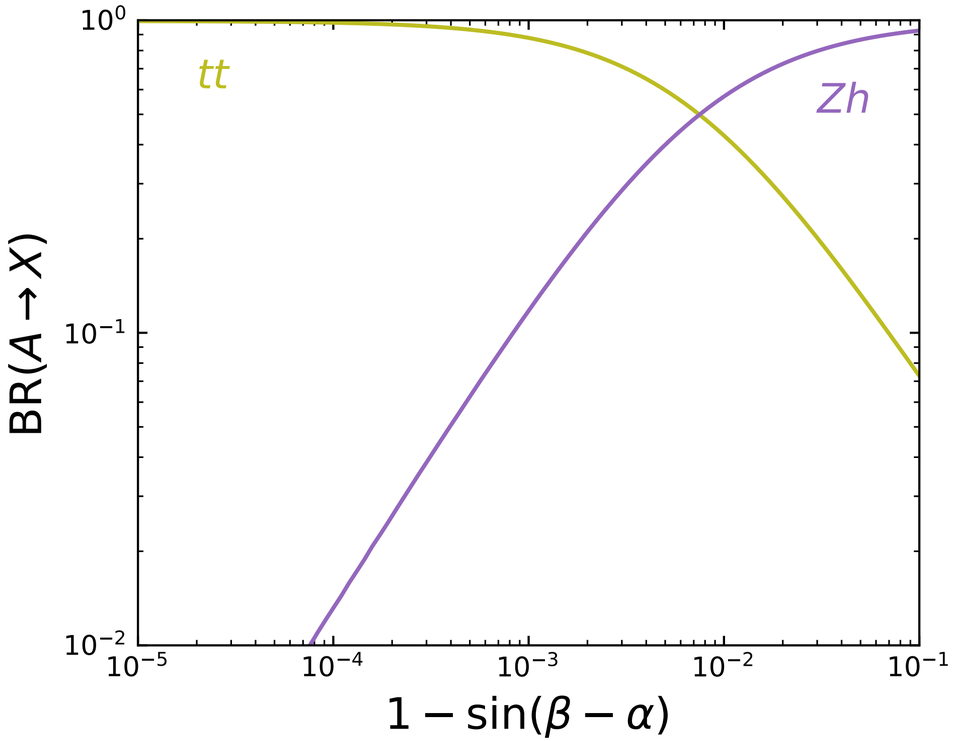
# Decay of the additional Higgs bosons (LO)



## Decay patterns

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




Higgs-to-Higgs decays can be dominant if $s_{\beta-\alpha} \neq 1$

MA, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB966 (2021)

# Synergy between direct and indirect searches 5

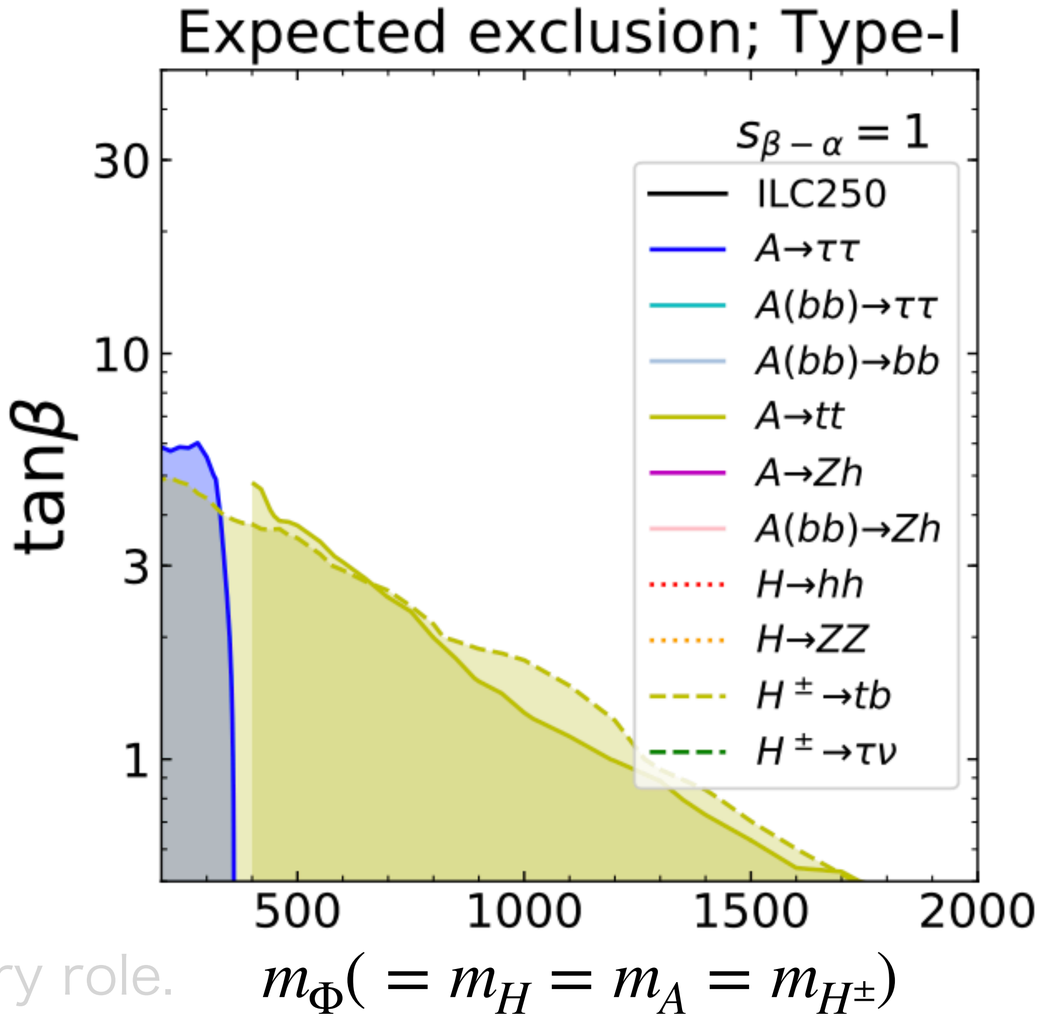
**Direct search**

- HL-LHC gives lower bounds on $m_\Phi$.
- $H \to hh$, $A \to Zh$ decays exclude wide parameter region

**Indirect search**

- If the Higgs boson couplings deviate from those in the SM, an upper bound on $m_\Phi$ can be deduced.

Direct and indirect searches play a complementary role.
Non-alignment scenarios can be explored in detail




MA, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB966 (2021)

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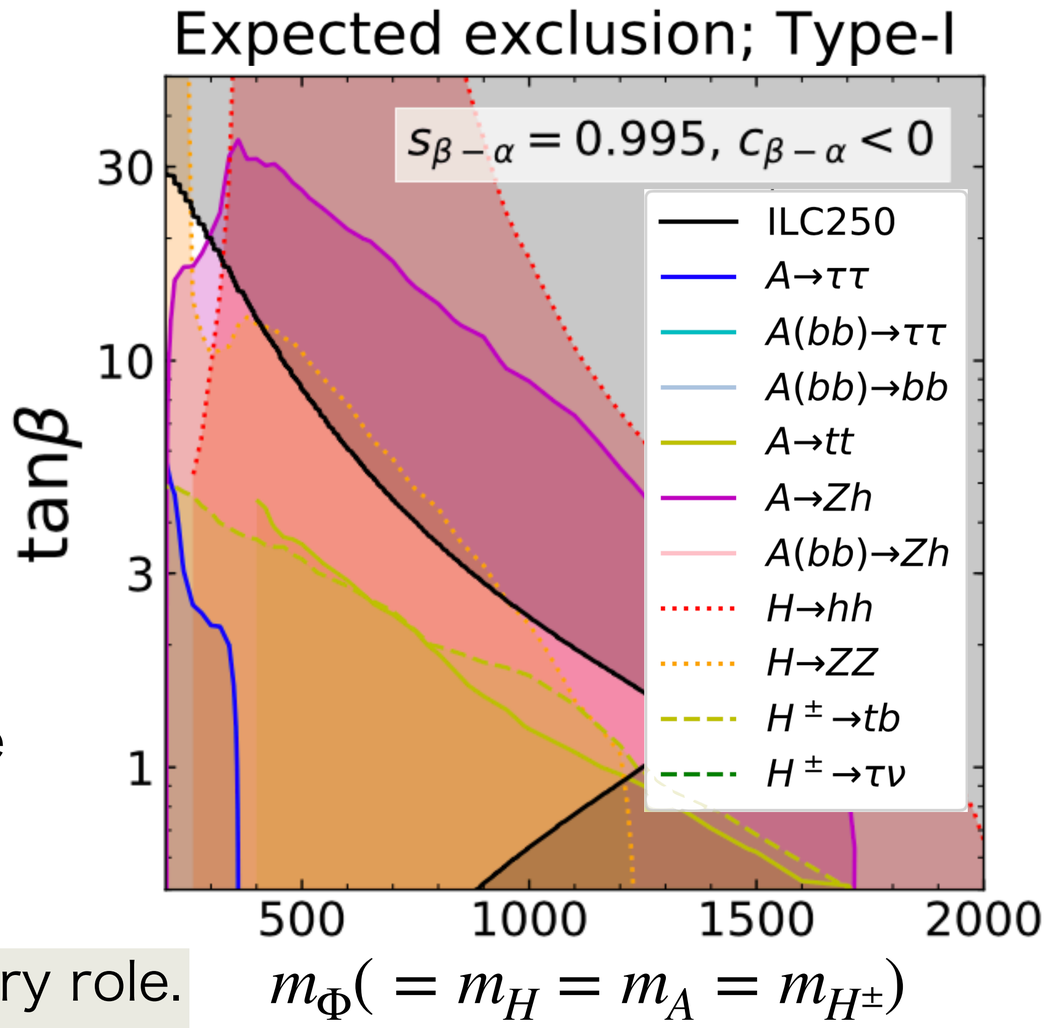



MA, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, NPB966 (2021)

# Need of higher-order calculations



Higher-order corrections would sizably modify tree-level analysis especially in $s_{\beta-\alpha} \approx 1$.

**125 GeV Higgs boson**

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu
NPB949 (2019), CPC257 (2020)

c.f. other public tools
2HDECAY, M. Krause, M. Mühlleitner, M. Spira
Prophecy4f, A. Denner, D. Dittmaier, A. Mück

- Expected accuracies in future experiments are $\mathcal{O}(1)\,\%$
  - H-COUP ver.2 : Two and Three-body decays of $h(125)$ with NLO EW and QCD

**Additional Higgs bosons** H-COUP ver.3

- Higgs-to-Higgs decays ($H \to hh$, $H^\pm \to W^\pm h$, $A \to Zh$) are quite sensitive $c_{\beta-\alpha}$.
  - Decays of additional CP-even Higgs boson $H$ with NLO EW.

Kanemura, Kikuchi, Yagyu 2203.08337
See Kikuchi-san's talk

We discuss the impact of radiative corrections on decays of $H^\pm$ and $A$.

# Higher-order calculation



## Decay modes of $H^\pm$

$$H^+ \to t\bar{b},\ c\bar{s},\ \bar{\tau}\nu \quad H^+ \to W^+h/H/A, \quad H^+ \to W^+Z \text{ and } W^+Z\gamma \text{ (loop-induced)}$$

## Decay modes of $A$

$$A \to f\bar{f} \quad (f = q, \ell), \quad A \to Zh/H\ W^\pm H^\mp, \quad A \to W^+W^-,\ ZZ,\ Z\gamma,\ \gamma\gamma \text{ and } gg \text{ (loop-induced)}$$

## Improved on-shell scheme

M. Krause, R. Lorenz, M. Muhlleitner, R. Santos, H. Ziesche, JHEP09 (2016)

S. Kanemura, M. Kikuchi, K. Sakurai, K. Yagyu, PRD96 (2017)

- UV divergences are renormalized in the on-shell scheme.
- Gauge dependencies are removed by the pinch technique. J. Papavassiliou, PRD50, 5958
- Infrared divergences are removed by adding real photon emission.
- For $H^\pm \to tb$ and $A \to t\bar{t}$ decays, NLO on-shell and NNLO $\overline{\text{MS}}$ QCD corrections are complemented. Djouadi et al. CPC108 (1998)

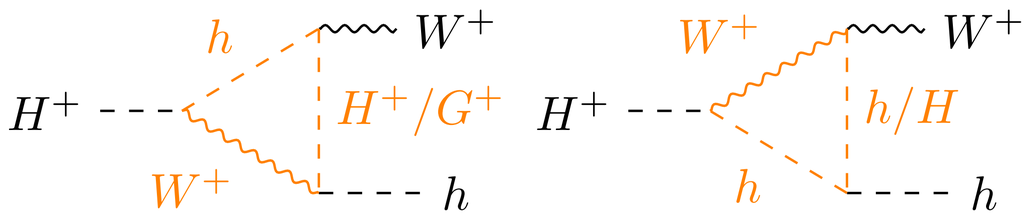
We focus on the EW corrections to $H^\pm \to W^\pm h$ and $A \to Zh$.

# Behavior of NLO Electroweak correction



$H^+ \to W^+h$

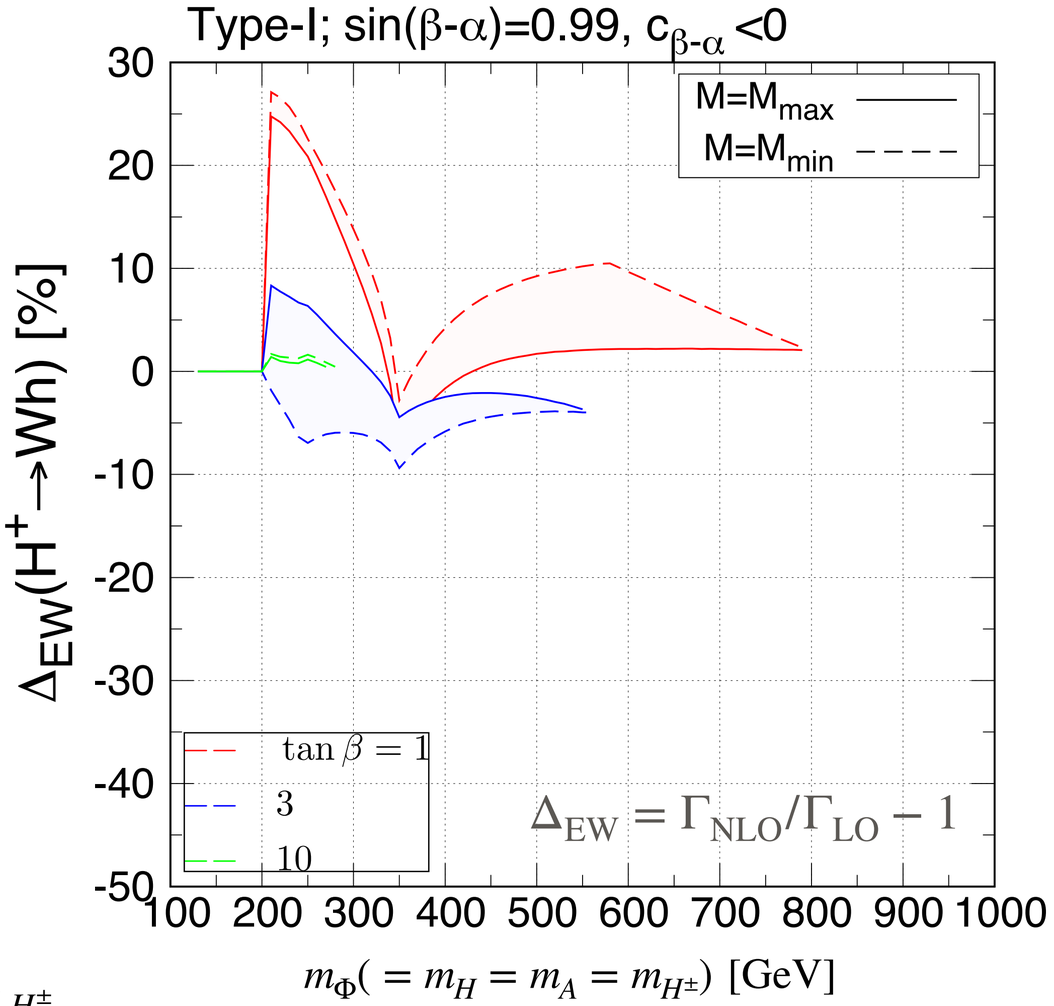
- LO partial decay width is proportional to $c^2_{\beta-\alpha}$.
- Triangle diagrams give large threshold corrections at $m_{H^\pm} \simeq m_h + m_W$ (~30 %).




- When $m_\Phi$ is large, $\delta Z_{H^\pm}$ and $\delta\beta$ gives $\mathcal{O}(\lambda^2_{SS'S''})$ corrections, and they give dominant effects.

$\delta Z_{H^\pm}$: Wave-function renormalization constant of $H^\pm$

$\delta\beta$: Counter-term of the mixing angle

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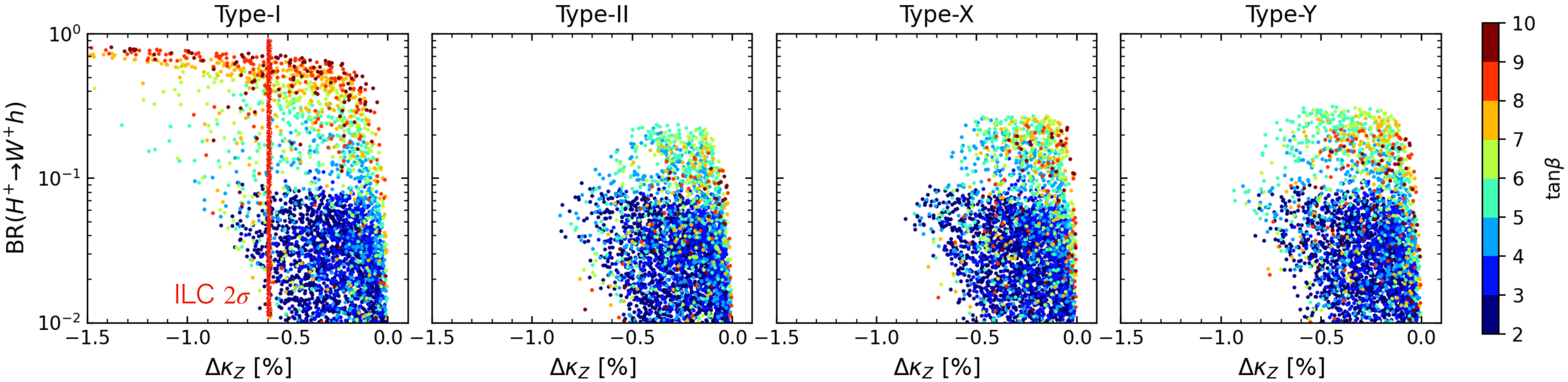
# BR vs $\kappa_Z$ at NLO



- $B \to X_s\gamma$ excludes $m_{H^\pm} \lesssim 800$ GeV in Type-II and Y 2HDMs — Misiak, Steinhauser, JHEP06 (2020)

  → The additional Higgs bosons almost decouple ($s_{\beta-\alpha} \simeq 1$) — Gunion, Haber PRD67 (2003)

$m_{H^\pm} = m_A = 1000$ GeV  Other parameters are scanned

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$\Delta\kappa_Z = \Gamma^{h\to ZZ^*}_{\rm 2HDM}/\Gamma^{h\to ZZ^*}_{\rm SM} - 1$ at NLO

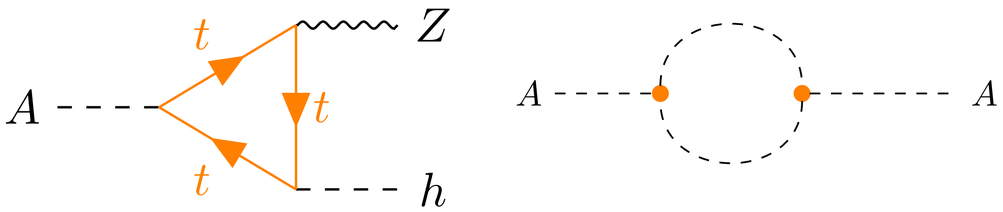
- Even if the additional Higgs bosons are heavy, $H^\pm \to W^\pm h$ can be a dominat decay mode.

# Branching ratio



$A \to Zh$

- When $\tan\beta$ is small, we have $\mathcal{O}(10)\,\%$ corrections.
- When bosonic loops give large corrections, the NLO prediction coincides with the LO one.
  - Fermionic and bosonic loops are canceled.

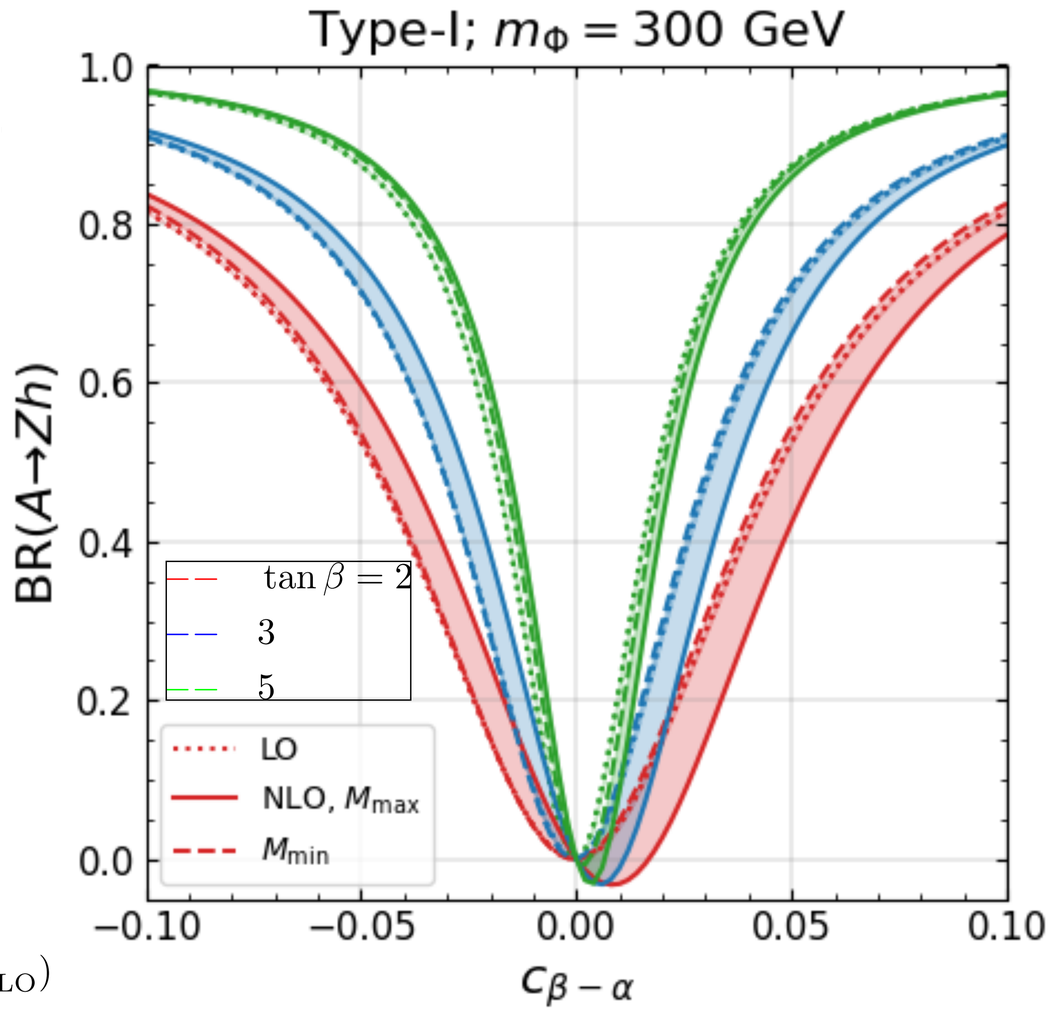



- When $c_{\beta-\alpha} \simeq 0$, NLO corrections become larger than LO corrections $\to \mathrm{Br}(A \to Zh) < 0$

$$|\mathcal{M}|^2 \simeq |\mathcal{M}_{\mathrm{LO}}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO}})$$

- NNLO corrections restore $\mathrm{Br}(A \to Zh) \geq 0$

$$|\mathcal{M}|^2 \simeq |\mathcal{M}_{\mathrm{LO}} + \mathcal{M}_{\mathrm{NLO}}|^2$$




MA, Kanemura, Sakurai, preliminarily

# H-COUP ver.3



✔：H-COUP ver.2　✔：Our works　✔：Kanemura, Kikuchi, Yagyu 2203.08337

| 125GeV Higgs | | CP-even | | CP-odd | | Charged | |
|---|---|---|---|---|---|---|---|
| $h \to ff$ | ✔ | $H \to ff$ | ✔ | $A \to ff$ | ✔ | $H^\pm \to ff'$ | ✔ |
| $h \to VV^*$ | ✔ | $H \to VV$ | ✔ | $A \to Z\,h/H$ | ✔ | $H^\pm \to W^\pm\,h/H$ | ✔ |
| $h \to \gamma\gamma/Z\gamma/gg$ | ✔ | $H \to hh$ | ✔ | $A \to W^\pm H^\mp$ | ✔ | $H^\pm \to W^\pm\,A$ | ✔ |
| $e^+e^- \to hZ$ | ✔ | $H \to ZA$ | ✔ | $A \to \gamma\gamma/Z\gamma/gg$ | ✔ | $H^\pm \to W^\pm\,Z/\gamma$ | ✔ |
| | | $H \to W^\pm H^\mp$ | ✔ | | | | |

MA, Kanemura, Mawatari, EPJC 81 (2021)

MA, Kanemura, Sakurai, in progress

MA, Kanemura, Sakurai, NPB973 (2021)

H-COUP ver.3 will be released soon.

# Summary



## Motivation

- Phenomenology of the additional Higgs bosons drastically changed whether $s_{\beta-\alpha} = 1$ or not.
- NLO EW corrections would play important role especially if $s_{\beta-\alpha} \simeq 1$.

## New points

- Decays of $H^{\pm}$ and $A$ are comprehensively analyzed.
- Correlation between the decay branching ratios and $\kappa_Z$ are exhibited.

## What we found

- Branching ratios of $H^{\pm} \to W^{\pm}h$ and $A \to Zh$ receive $\mathcal{O}(10)$ % corrections if $\tan\beta \simeq 2$.
- Higgs-to-Higgs decay can be dominant decay modes even if $\Delta\kappa_Z$ is small.

NLO corrections are important for direct serches of the additional Higgs bosons.