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

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hep-ph: 2207.01032

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Introduction

Standard Model

We have problems that cannot 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 Φ_1 and Φ_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 is 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, $m_{H^\pm}$, $M^2 = m_{12}^2/(s_\beta c_\beta)$, $\tan\beta$, $s_{\beta-\alpha}$

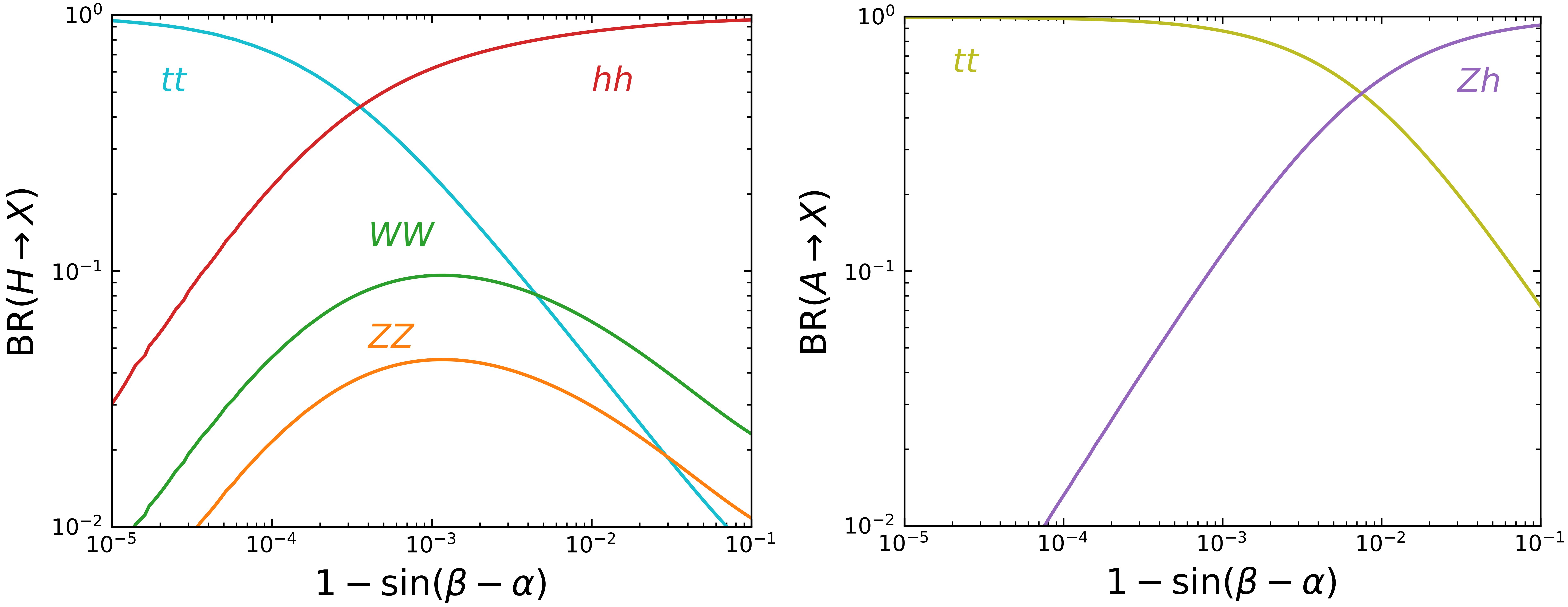
Higgs couplings $g_{hVV} = s_{\beta-\alpha}g_{hVV}^{\rm SM}$, $g_{hff} = (s_{\beta-\alpha} - c_{\beta-\alpha}\zeta_f)g_{hff}^{\rm SM}$ $(\zeta_f = -\tan\beta \text{ or } \cot\beta)$

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

Decay of the additional Higgs bosons (LO)

Decay patterns

Type-I 2HDM: $m_\Phi = m_H = m_A = m_{H^\pm} = 400$ 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)

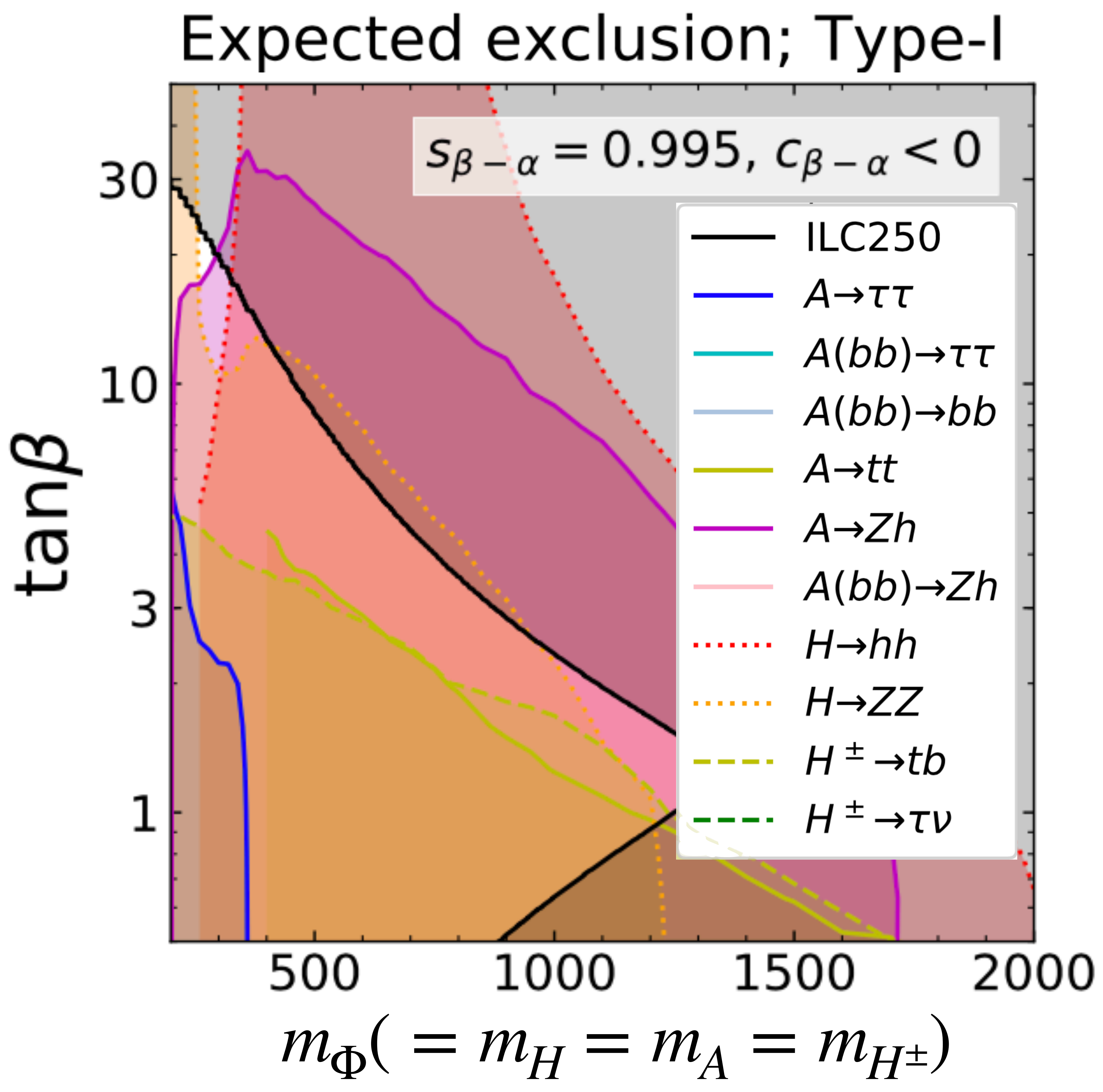
Direct search

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

Indirect search

- If the SM-like Higgs boson couplings deviate from those in the SM, an upper bound on m_Φ can be deduced.

We can explore the non-alignment scenario.



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Need of higher-order calculations

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

SM-like Higgs boson

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

c.f. other public tools
2HDECAY; Krause, Mühlleitner, Spira, CPC246 (2020)
Prophecy4f; Denner, Dittmaier, Mück, CPC254 (2020)

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

Krause, Mühlleitner JHEP04 (2020)
Kanemura, Kikuchi, Yagyu 2203.08337

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

Higher-order calculation

Decay modes of A

MA, Kanemura, Sakurai, 2207.01032

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

Decay modes of $H^{\pm}$

MA, Kanemura, Sakurai, NPB973 (2021)

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

Improved on-shell scheme

Kanemura, Kikuchi, Sakurai, Yagyu, PRD96 (2017)
See also Krause, Lorenz, Muhlleitner, Santos, Ziesche, JHEP09 (2016)

- UV divergences are renormalized in the on-shell scheme.
- Gauge dependencies are removed by the pinch technique. Papavassiliou, PRD50, 5958
- Infrared divergences are removed by adding real photon emission.
- For $A \to t\bar{t}$ and $H^{\pm} \to tb$ 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 $A \to Zh$ and $H^{\pm} \to W^{\pm}h$.

Impact of NLO corrections

$A \to Zh$

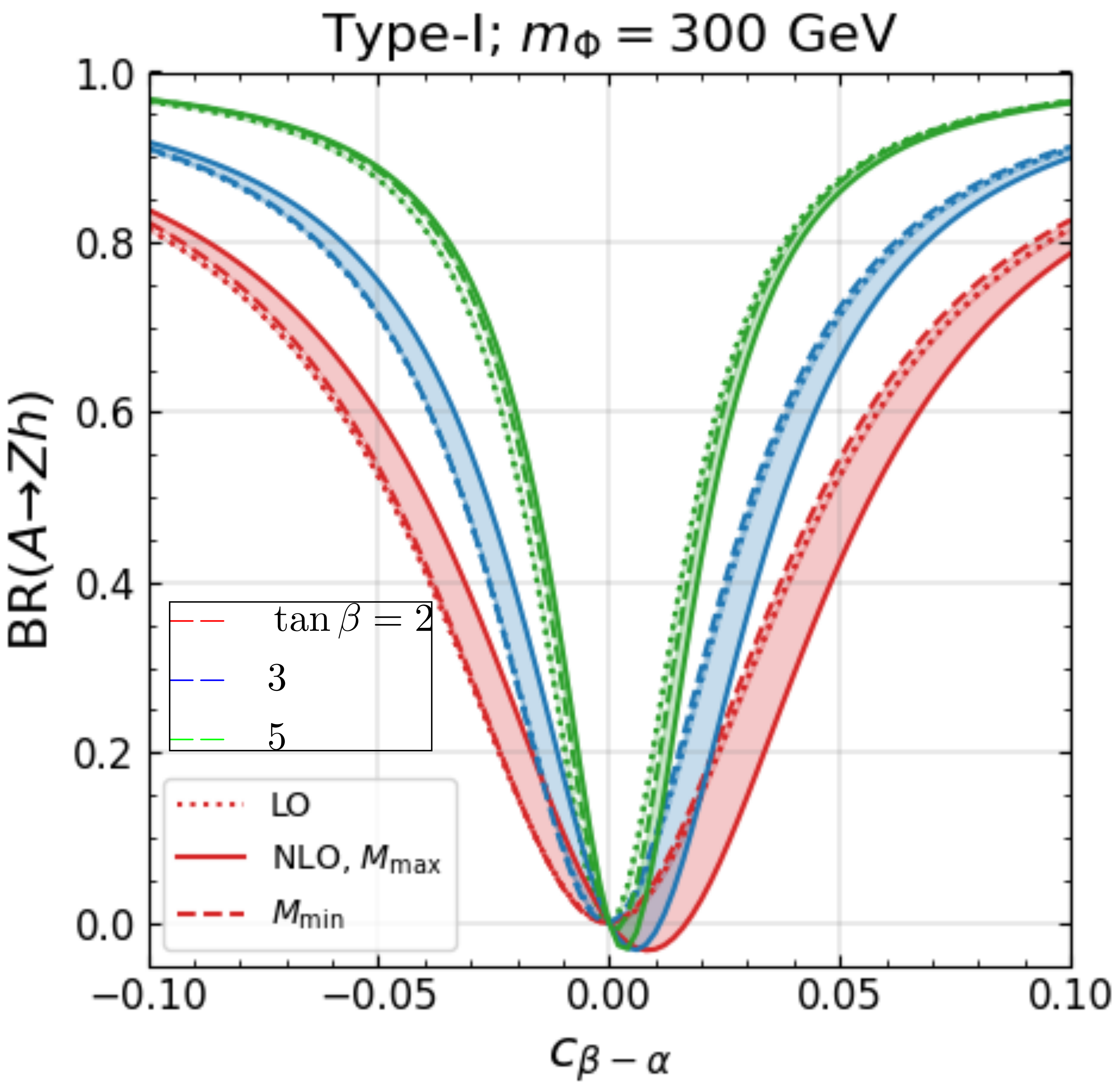
- When $\tan\beta$ is small, we have $\mathcal{O}(10)\,\%$ corrections.

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

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

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

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



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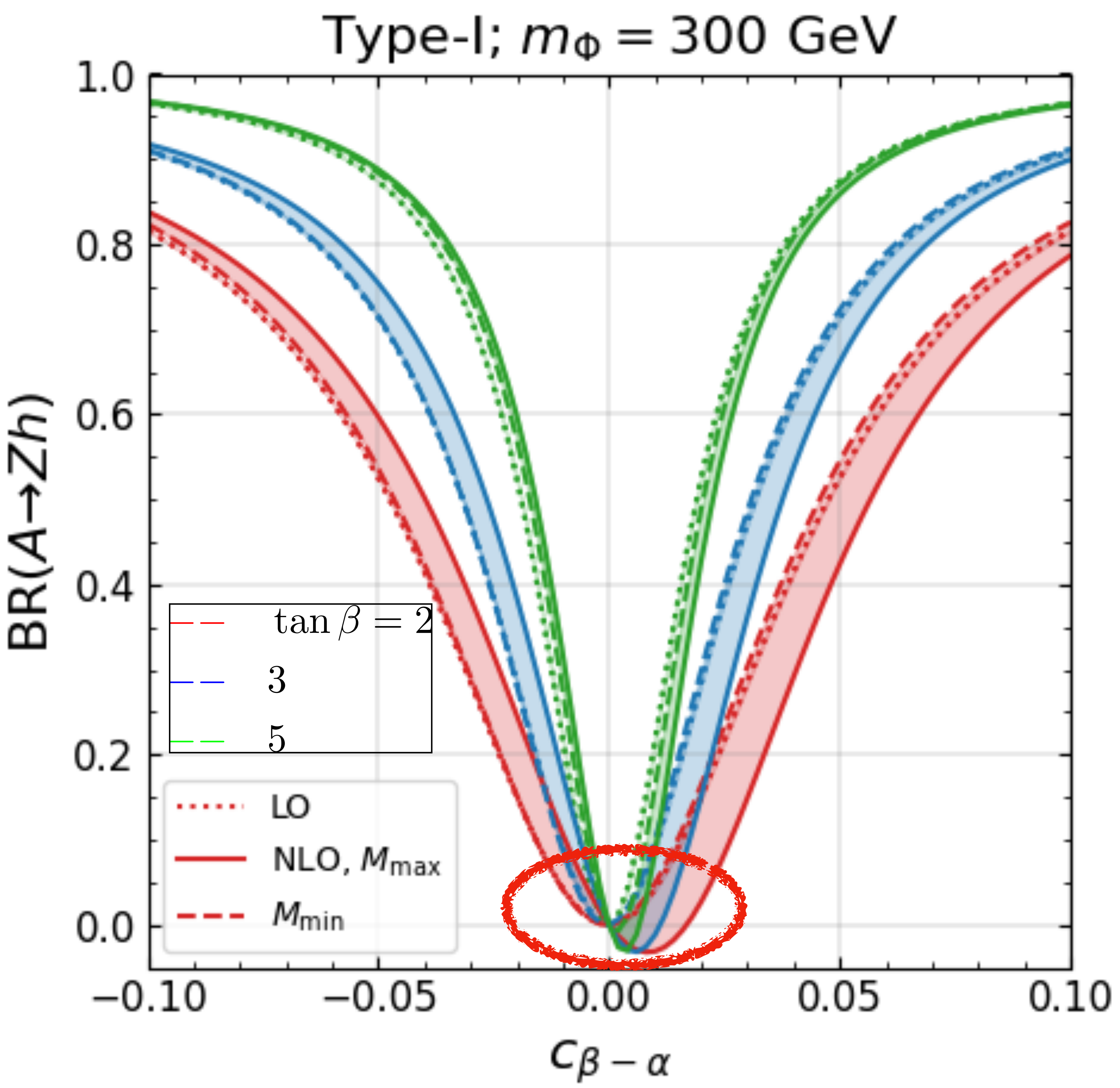

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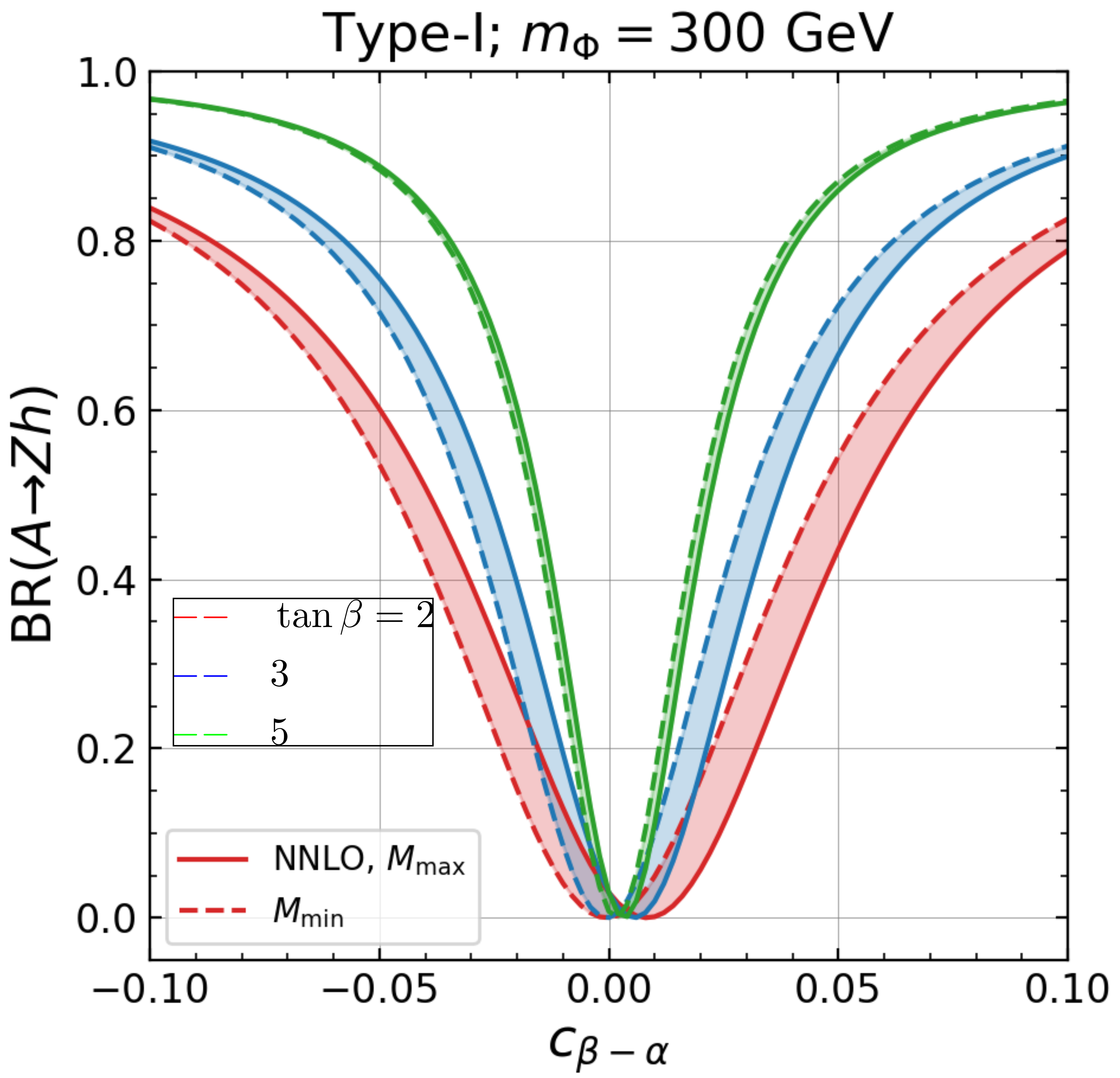

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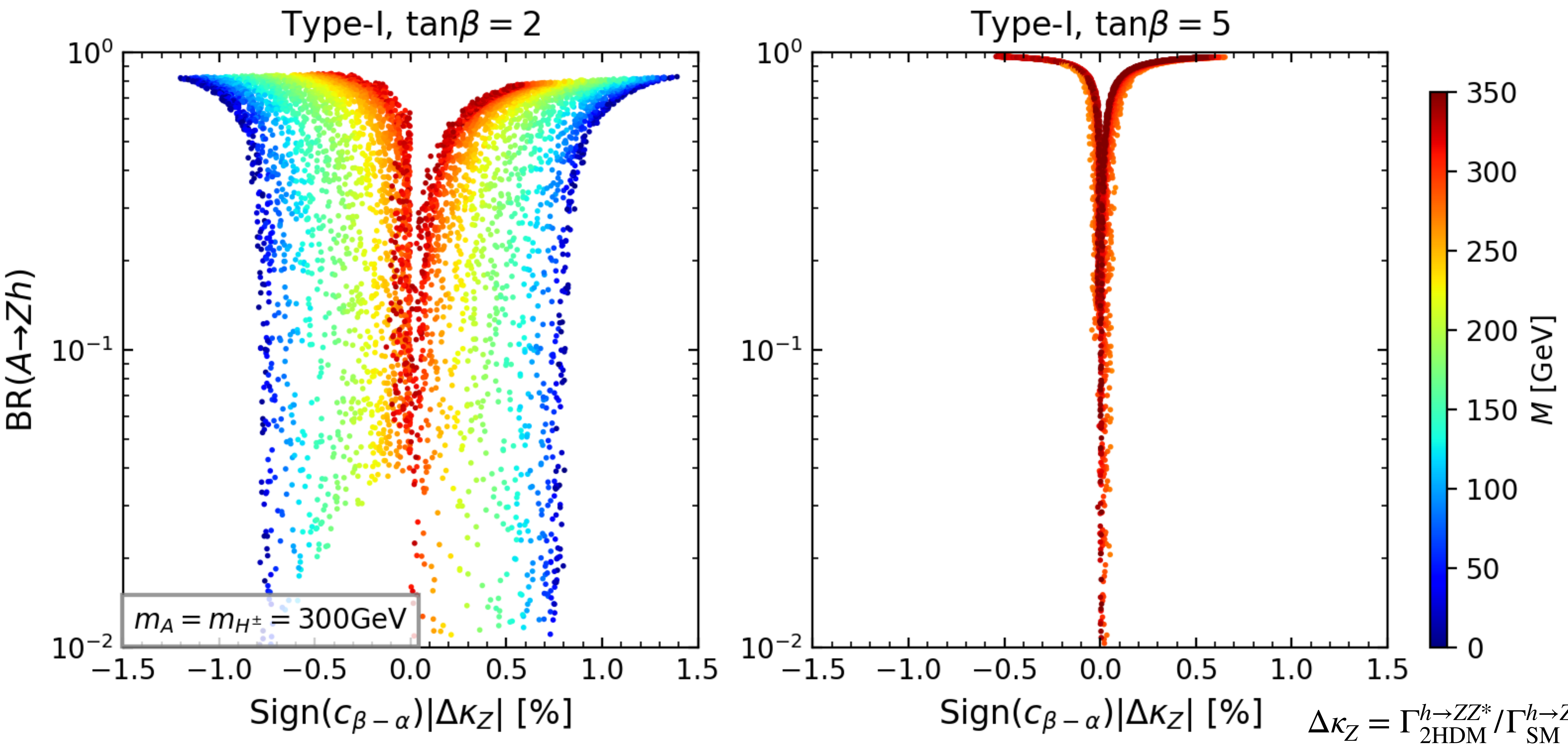
BR($A \to Zh$) vs $\Delta\kappa_Z$ at NLO

$A \to Zh$

$\Gamma(A \to Zh) \propto c^2_{\beta-\alpha}$, $\Delta\kappa_Z \propto c^2_{\beta-\alpha}$ at LO, $\lambda_{\phi\phi'\phi''} \propto (m^2_\Phi - M^2)/v^2$ MA, Kanemura, Sakurai, 2207.01032



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

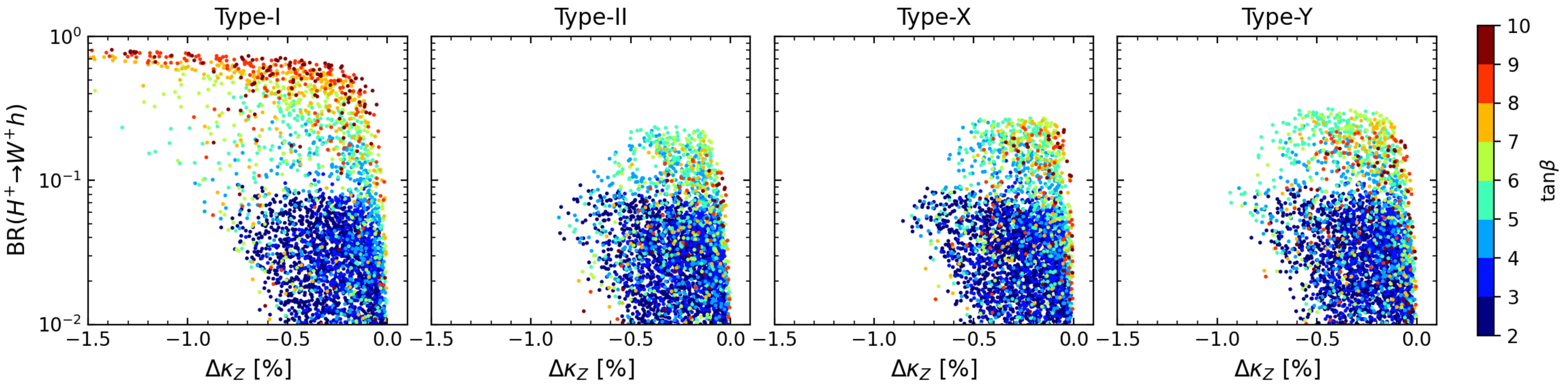
BR($A \to Zh$) can be small while $\Delta\kappa_Z$ is sizable to detect.

$\mathrm{BR}(H^+ \to W^+ h)$ vs $\Delta\kappa_Z$ at NLO

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

  → The additional Higgs bosons almost decouple ($s_{\beta-\alpha} \simeq 1$)

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



MA, Kanemura, Sakurai, NPB973 (2021)

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

H-COUP ver.3

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

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

MA, Kanemura, Mawatari, EPJC 81 (2021)

MA, Kanemura, Sakurai, 2207.01032

MA, Kanemura, Sakurai, NPB973 (2021)

Summary

Motivation

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

New points

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

What we found

- Branching ratios of $A \to Zh$ and $H^{\pm} \to W^{\pm}h$ 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.

Backup

Synergy between direct and indirect searches

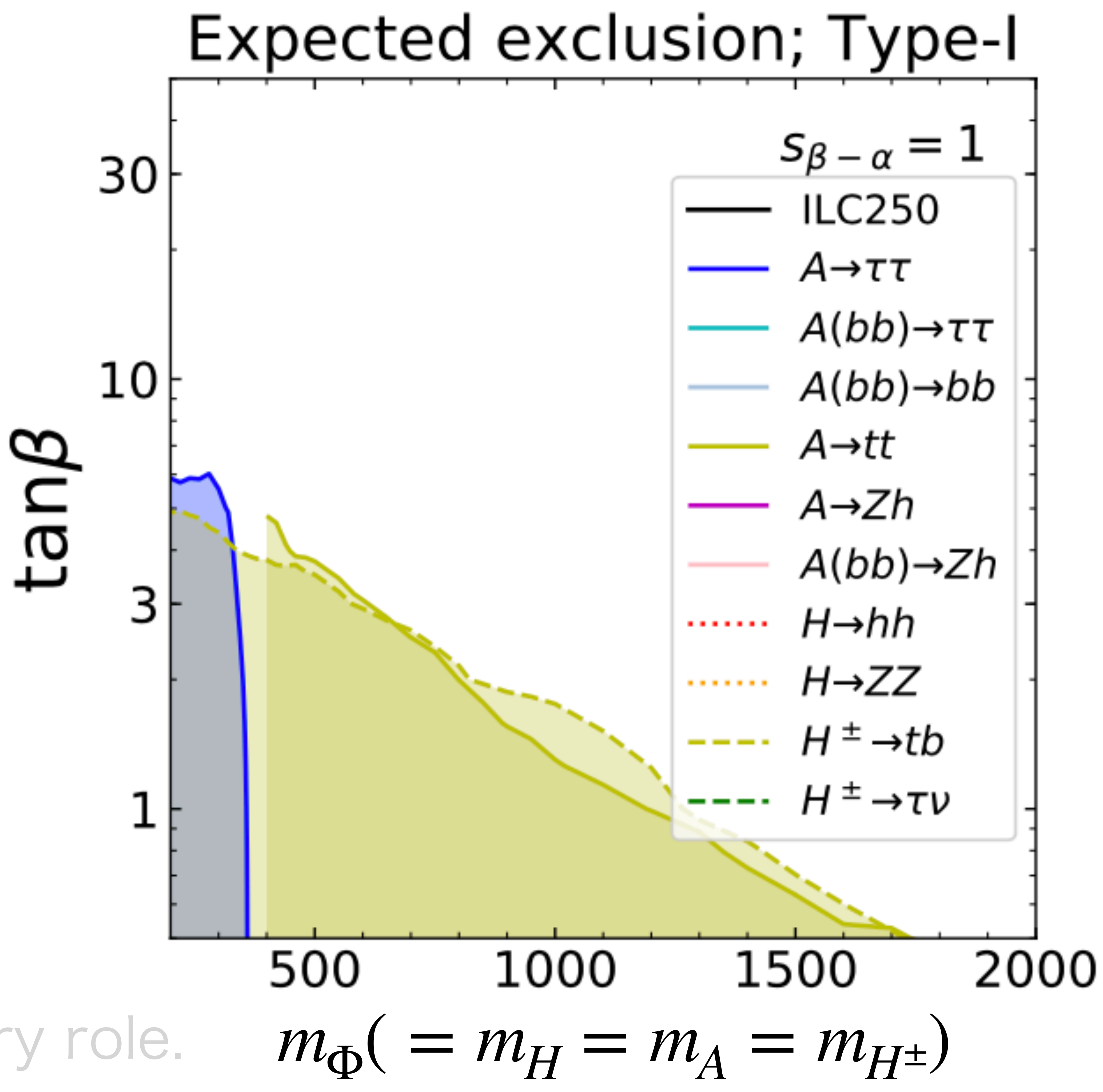
Direct search

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

Indirect search

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

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



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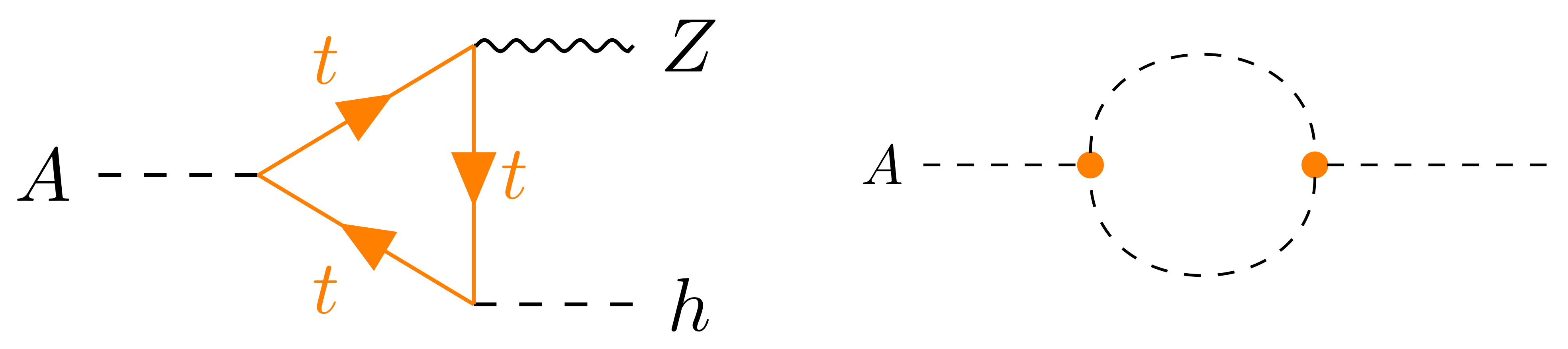
Behavior of NLO Electroweak correction

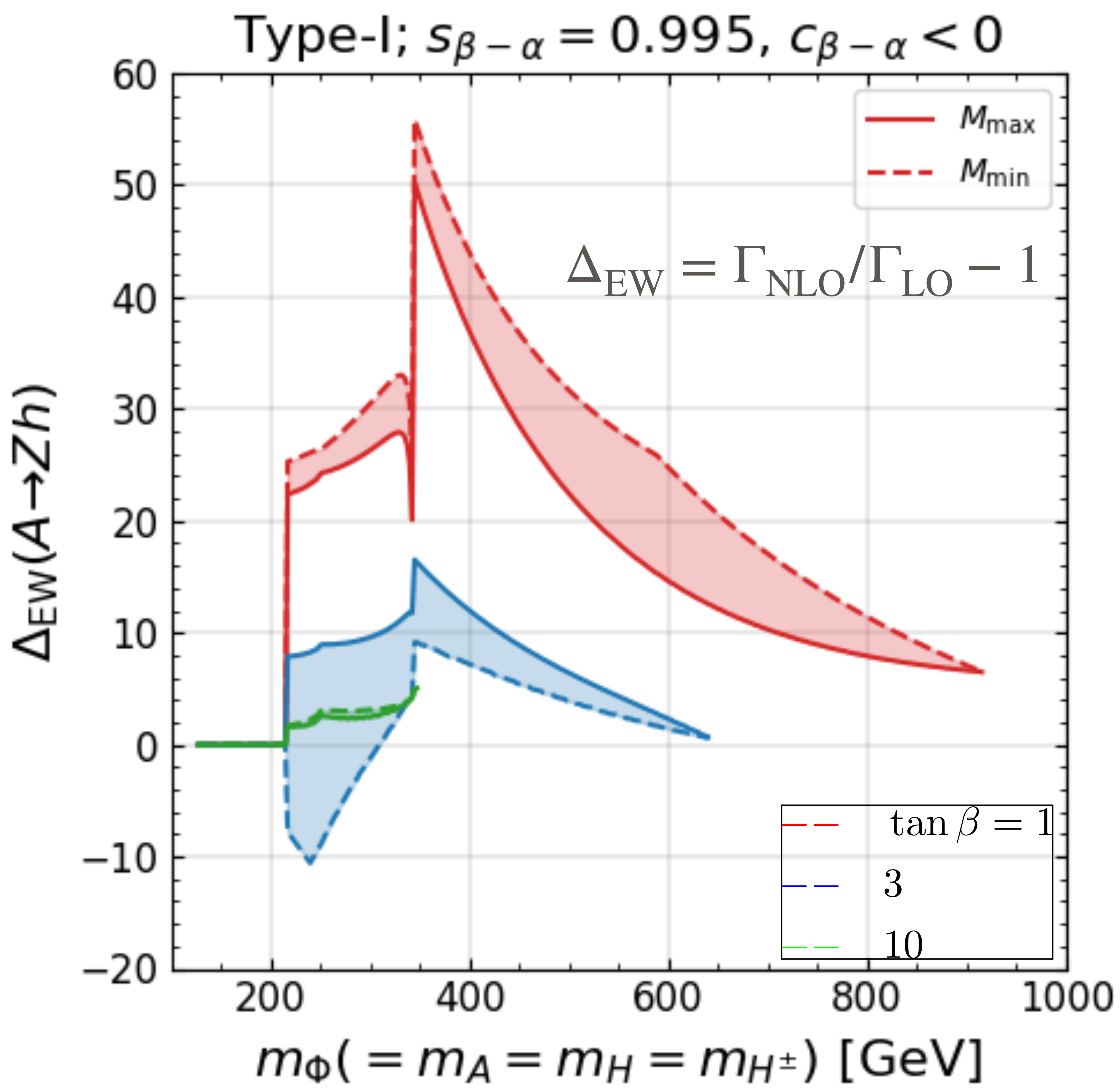
$A \to Zh$

- LO partial decay width is proportional to $c^2_{\beta-\alpha}$.
- The top-quark triangle diagram gives large threshold correction at $m_A \simeq 2m_t$
- When m_Φ is large, δZ_A and $\delta\beta$ gives $\mathcal{O}(\lambda^2_{SS'S''})$ corrections, and they give dominant effects.



δZ_A: Wave-function renormalization constant of A

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



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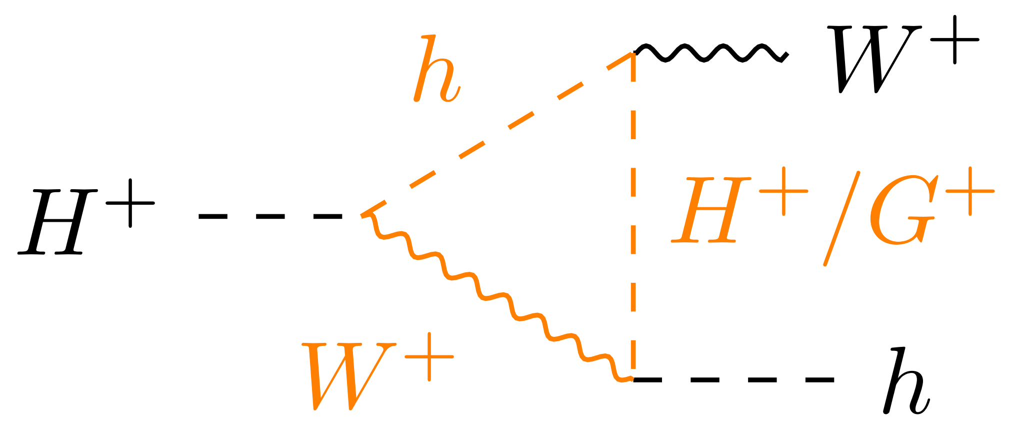
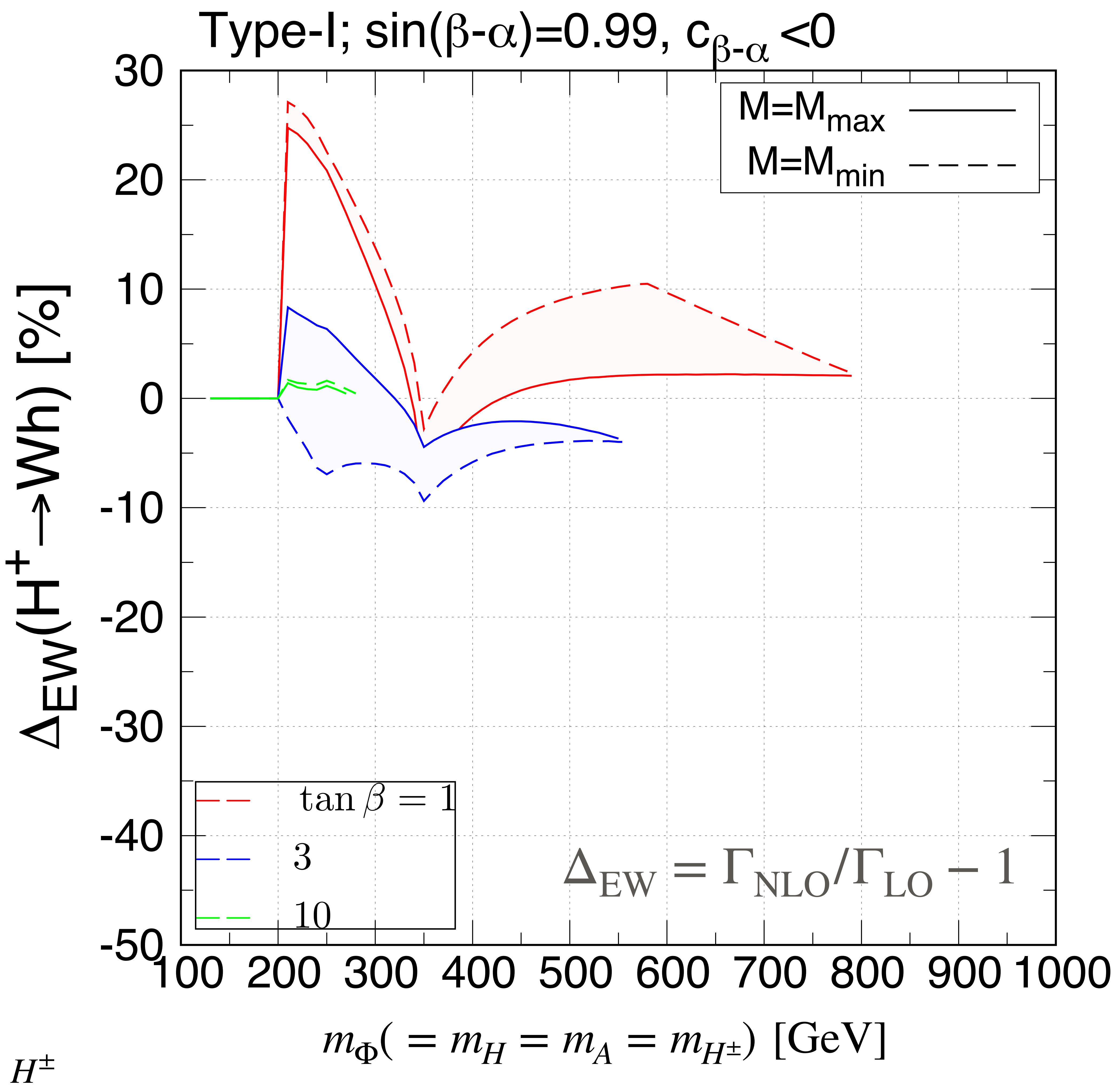
Behavior of NLO Electroweak correction

$H^+ \to W^+ h$

- 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_Φ 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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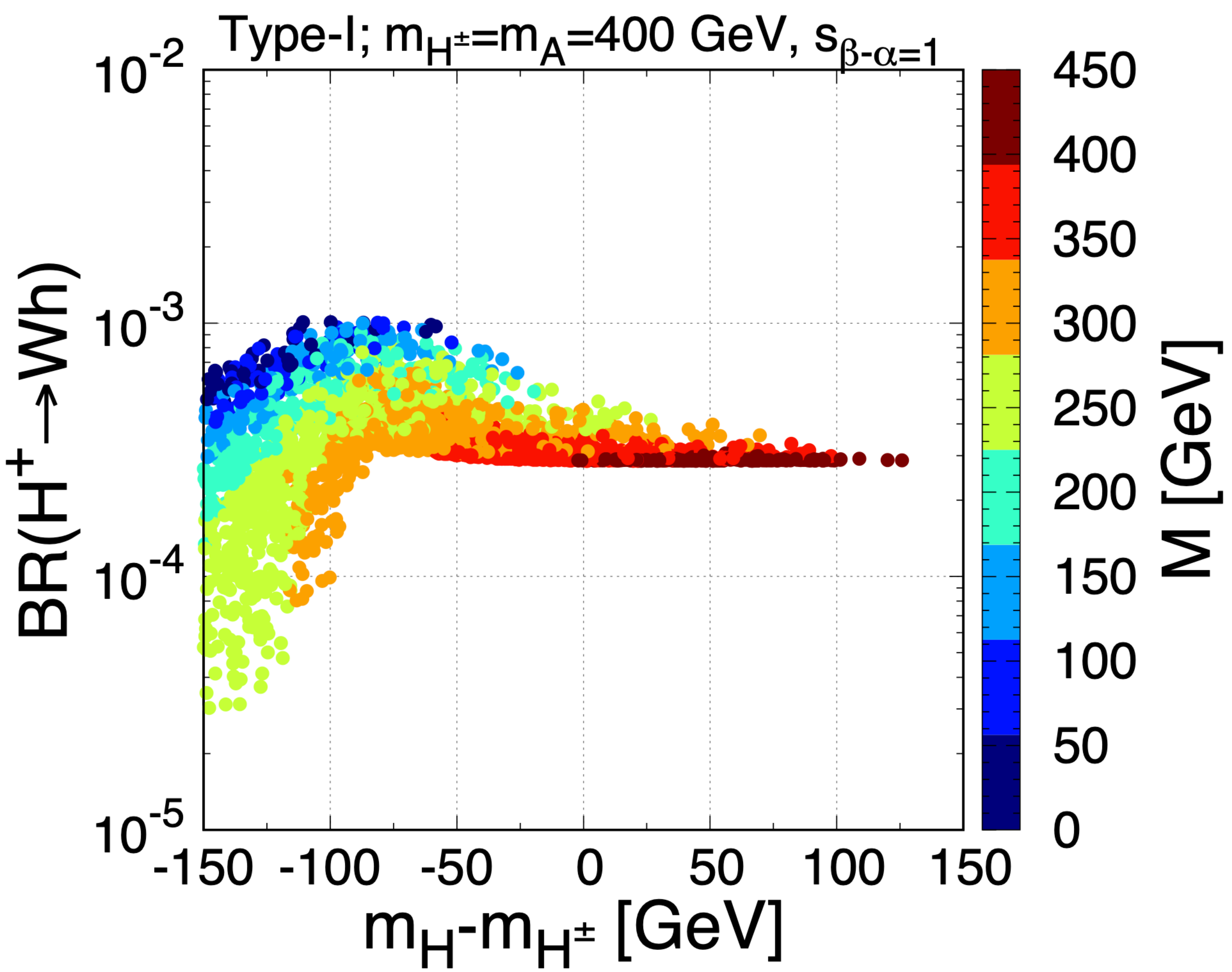
Behavior of NLO Electroweak correction

$H^+ \to W^+ h$

- LO amplitude is proportional to $c_{\beta-\alpha}$, and this process becomes loop-induced if $s_{\beta-\alpha} = 1$.
- In the alignment limit, we have no infrared divergence.
- Decay branching ratio reaches $0.1\,\%$ if M^2 is relatively small.



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