Impact of radiative corrections on decays of Higgs bosons in extended Higgs sectors

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In collaboration with Shinya Kanemura (Osaka University), Mariko Kikuchi (Nihon University), Kodai Sakurai (Warsaw University), Kei Yagyu (Osaka University)

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Introduction

Problems in the SM

- Baryon asymmetry of the universe
- Dark matter
- Neutrino tiny mass   etc.

SM must be extended to solve these problems.

Extended Higgs model

The detail of the Higgs sector is still a mystery.

- One $SU(2)_L$ doublet is an assumption in the SM.
  - Additional Higgs fields (singlet, multi-doublets, and higher representations)
- The above problems can be solved.
  - Electroweak baryogenesis, scalar DM, radiative seesaw mechanism etc.

Determination of the Higgs sector is one of the central interests in high-energy physics

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 currents. 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), $\tan\beta$, $s_{\beta-\alpha}$, m_H, m_A, $m_{H^\pm}$, $M^2 = m_{12}^2/(s_\beta c_\beta)$

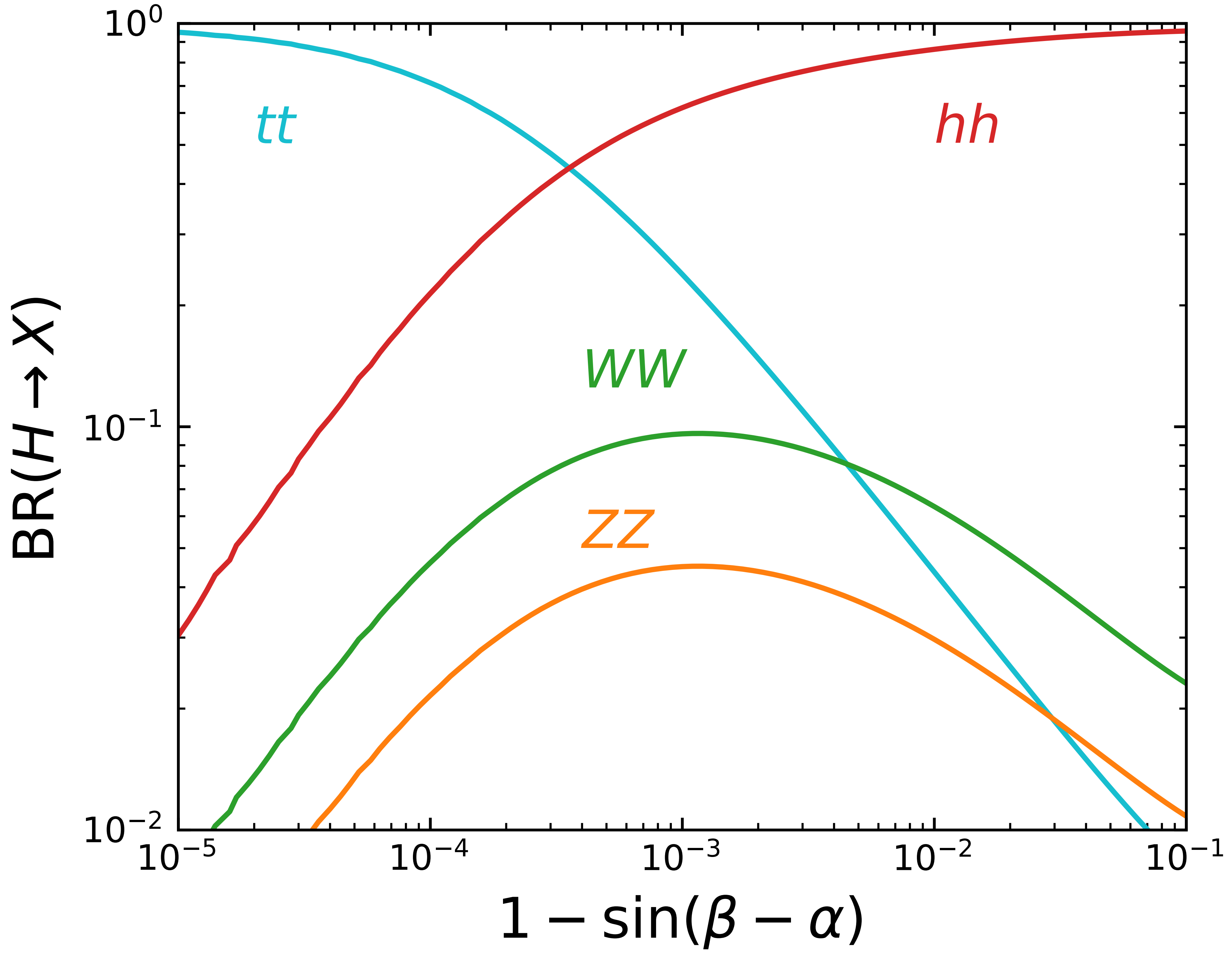
Higgs couplings $g_{hVV} = s_{\beta-\alpha}g_{hVV}^{\mathrm{SM}}$, $g_{hff} = (s_{\beta-\alpha} - c_{\beta-\alpha}\zeta_f)g_{hff}^{\mathrm{SM}}$ $(\zeta_f = -\tan\beta$ or $\cot\beta)$

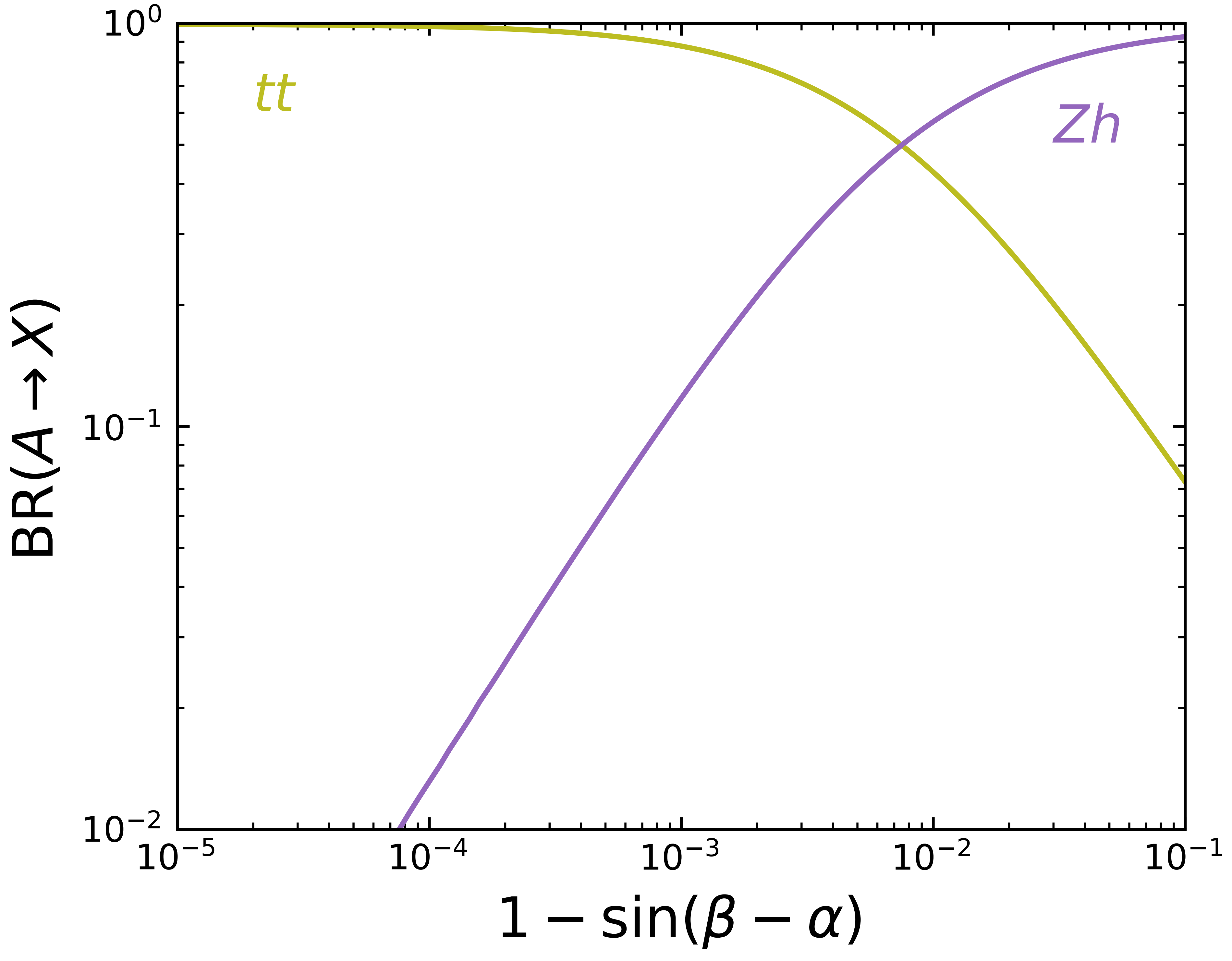
- Alignment limit : $s_{\beta-\alpha} \to 1$ (tree-level Higgs couplings take SM-values.) Gunion, Haber, PRD67 (2003)
- LHC data indicate $s_{\beta-\alpha} \simeq 1$. ATLAS, Nature 607 (2022) CMS, Nature 607 (2022)

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)

Synergy between direct and indirect searches 5

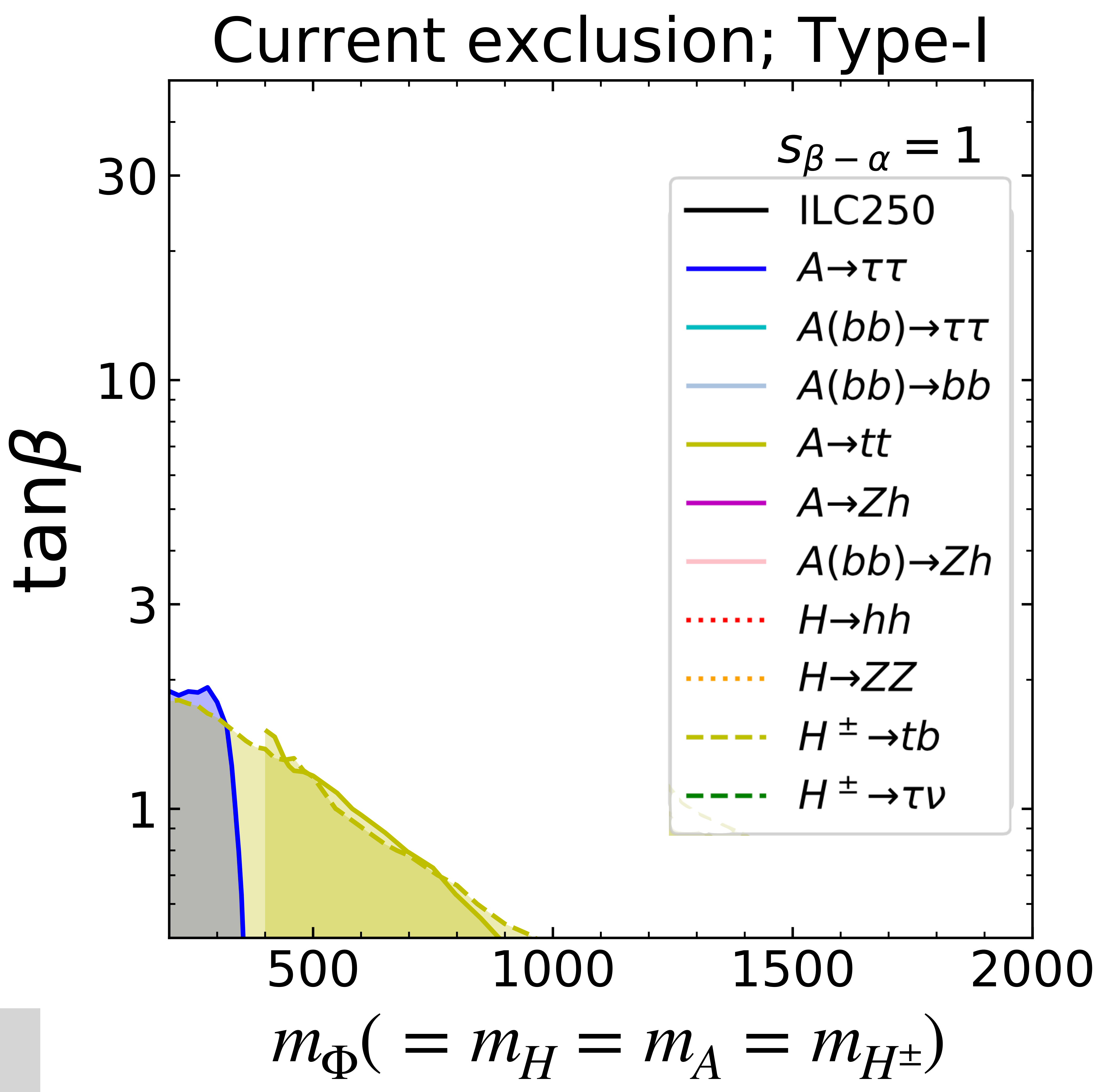
Direct search

- Direct searches give 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.

The non-alignment scenario can be explored comprehensively.



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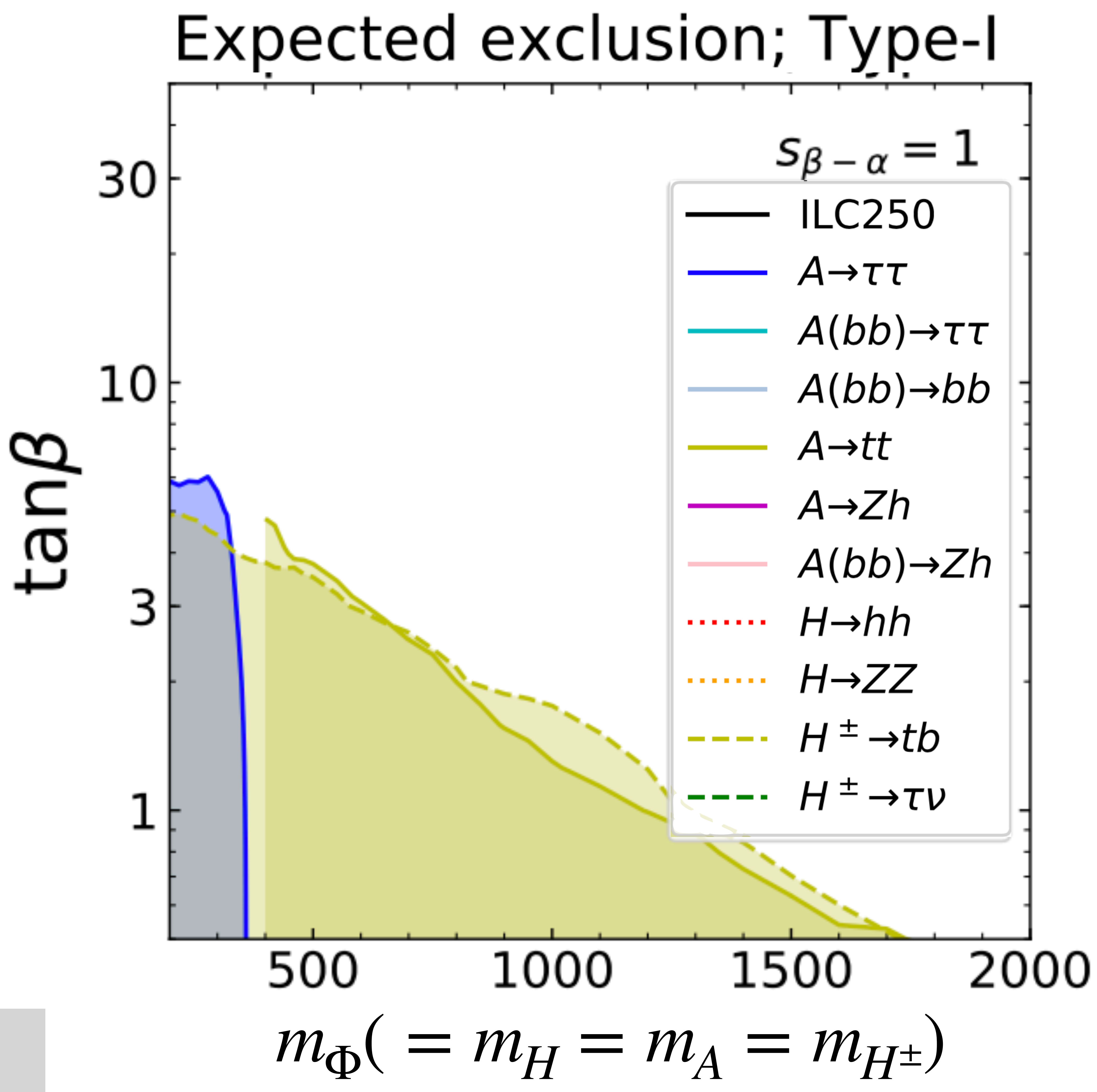

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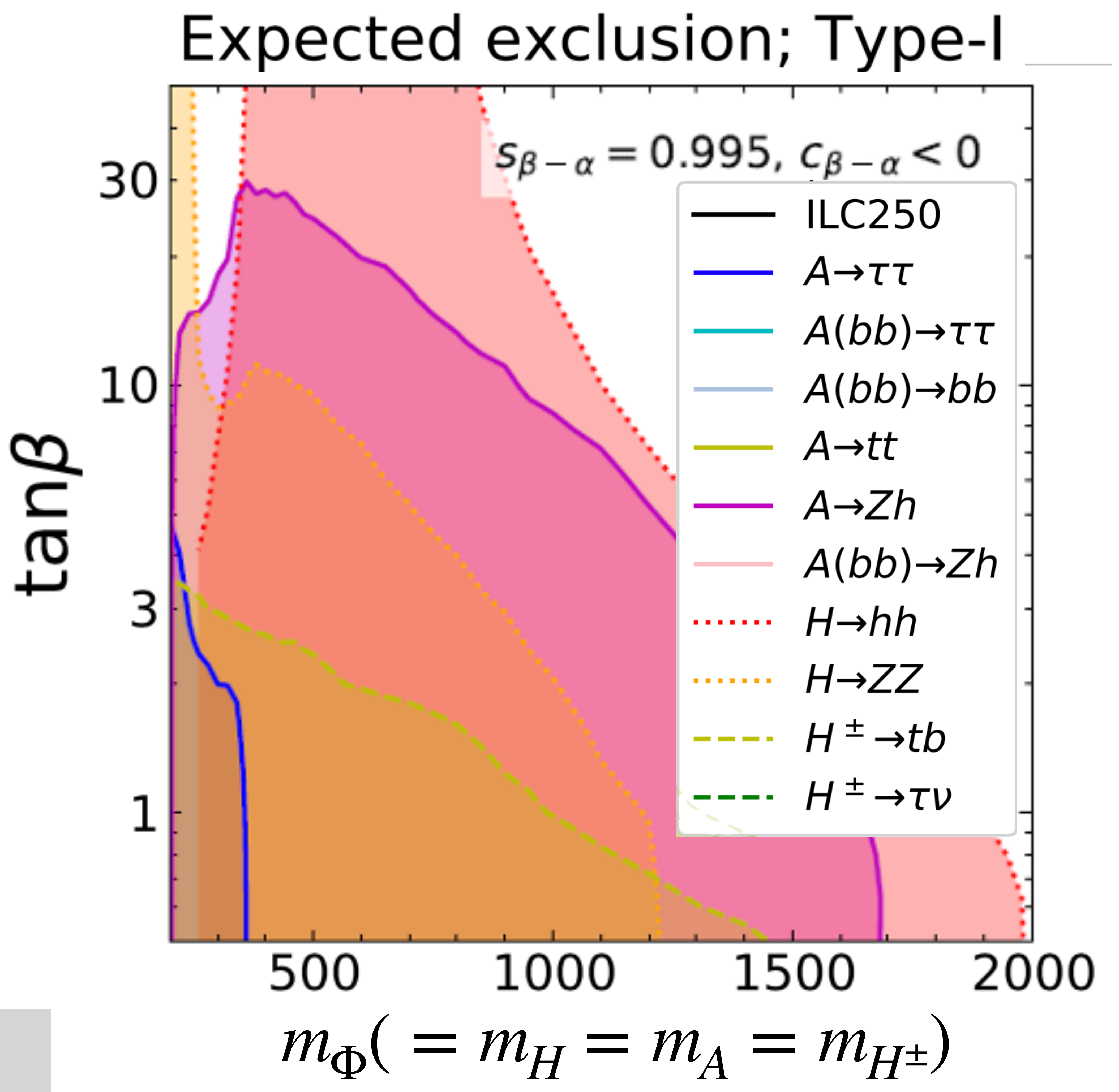

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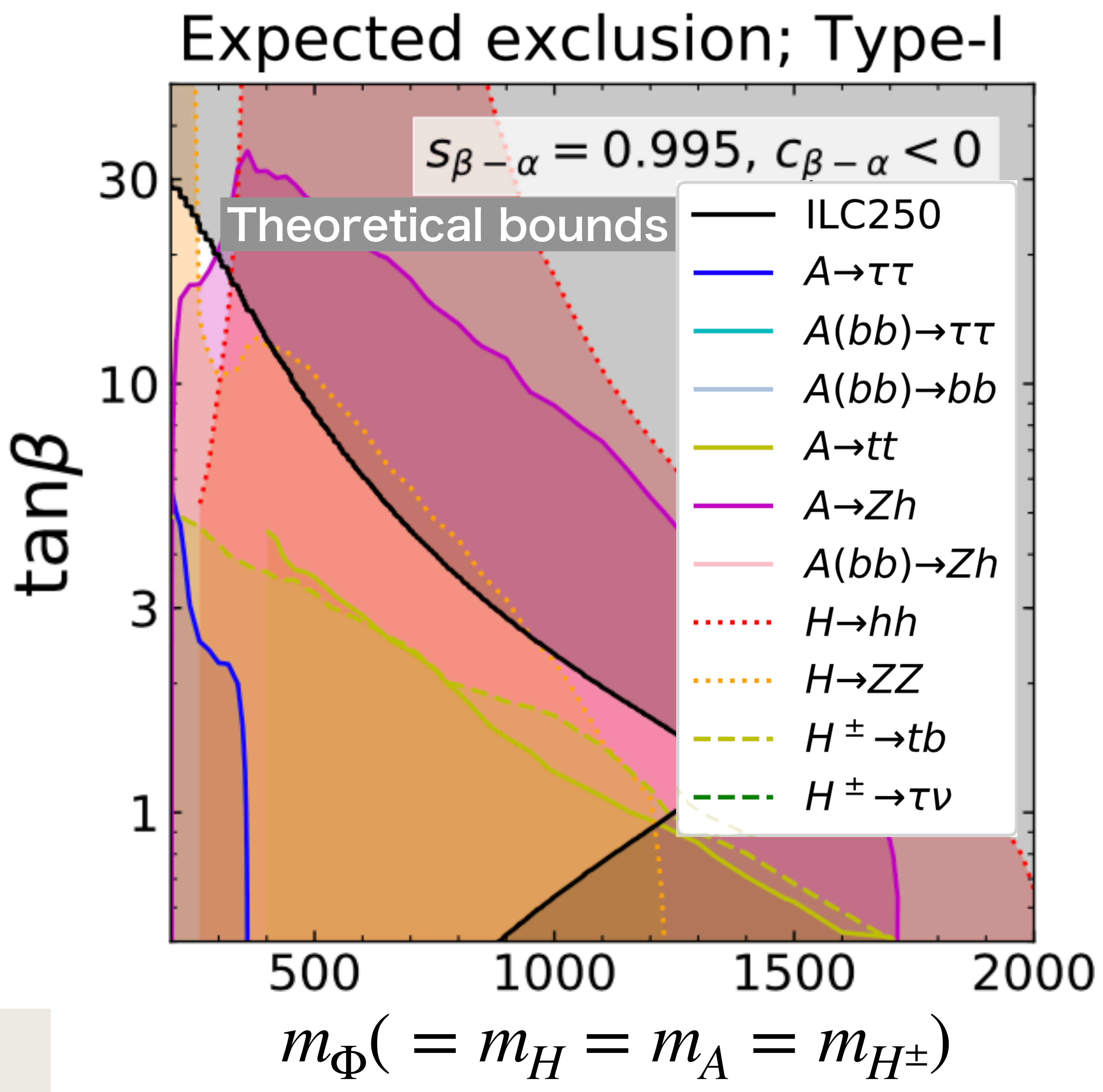

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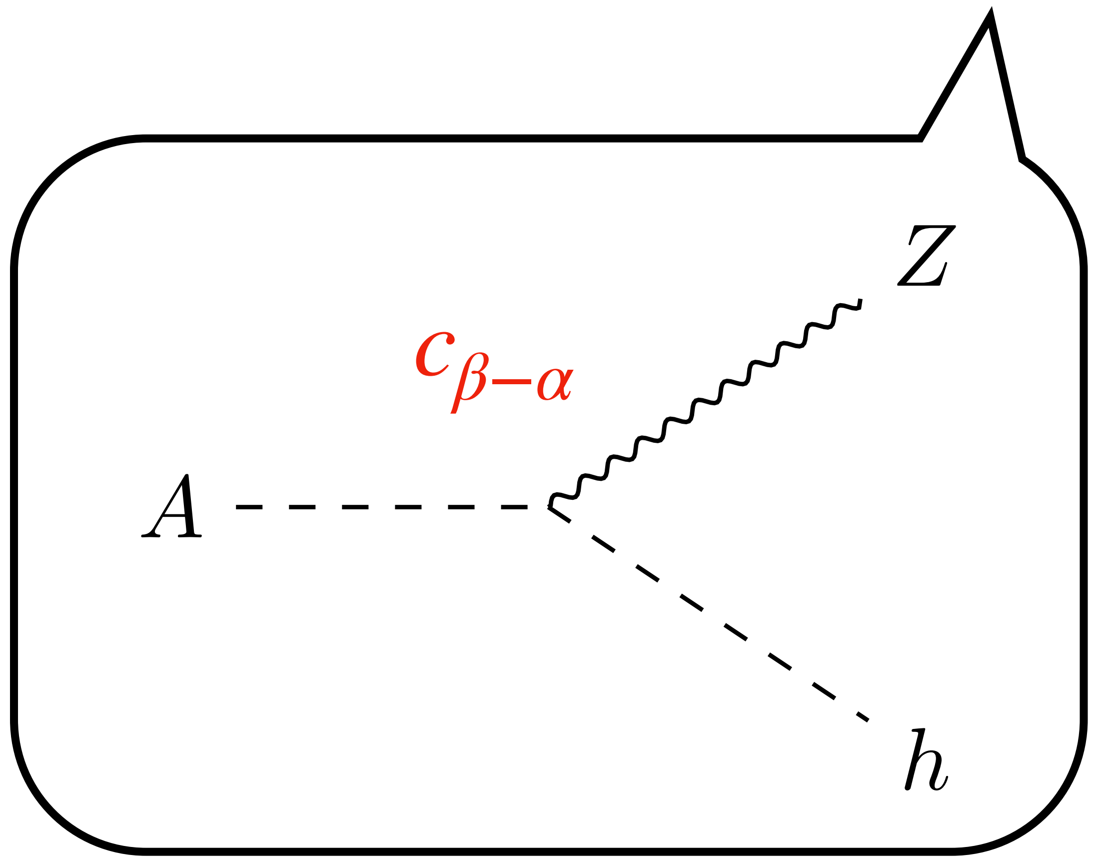
Need of higher-order calculations

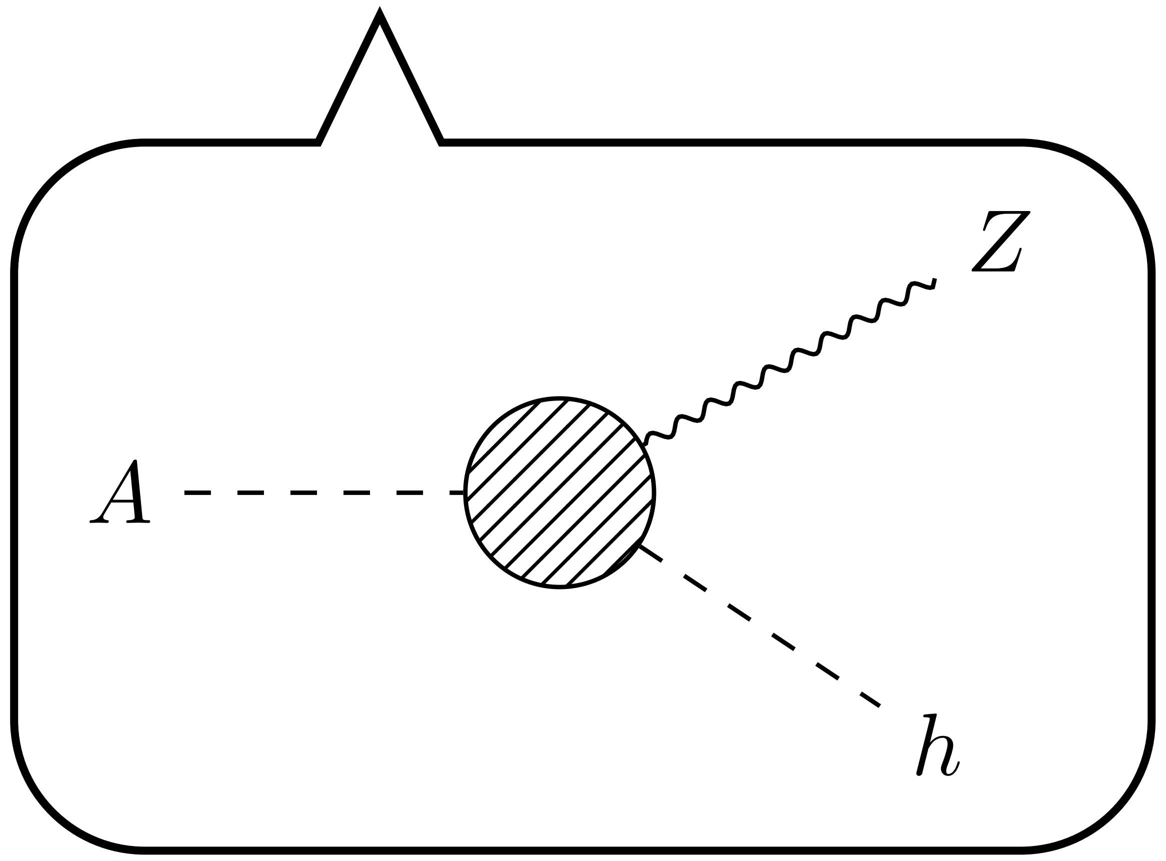
H decay : Kanemura, Kikuchi, Yagyu NPB983 (2022)
$H^{\pm}$ decay : MA, Kanemura, Sakurai, NPB973 (2021)
A decay : MA, Kanemura, Sakurai, NPB986 (2023)

Higgs-to-Higgs decays

Higgs-to-Higgs decays ($H \to hh$, $A \to Zh$, $H^{\pm} \to W^{\pm}h$) are sensitive to $c_{\beta-\alpha}$.

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





Ex. $c_{\beta-\alpha} = 0.1$ when $s_{\beta-\alpha} = 0.995$

NLO corrections do not vanish even with $c_{\beta-\alpha} \to 0$

We need to take into account NLO corrections in a nearly alignment case.

H-COUP is a calculation tool composed of a set of Fortran codes to evaluate full one-loop corrections to the Higgs bosons' observables.

SM-like Higgs boson

ver. 1: Kanemura, Kikuchi, Sakurai, Yagyu, CPC233 (2018)
ver. 2: Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu CPC257 (2020)

- **2HDM**
- **Inert doublet model**
- **Higgs singlet model**

Two and three-body decays of $h(125)$ with NLO EW and higher-order QCD (ver.2)

Additional Higgs bosons

MA, Kanemura, Kikuchi, Sakurai, Yagyu in preparation

Two-body decays of additional Higgs bosons with NLO EW and higher-order QCD (ver.3)

Improved on-shell scheme

Kanemura, Kikuchi, Sakurai, Yagyu, PRD96 (2017)
Krause et al. JHEP09 (2016), Denner, et al. JHEP09 (2016)

- UV divergences are renormalized in the on-shell scheme.
- Gauge dependencies are removed by the pinch technique.
- IR divergences are removed by adding real photon emission.

Papavassiliou, PRD50, 5958
Denner 0709.1075
Goodsell, Liebler, Staub, EPJC77 (2017)

c.f. other public tools
2HDECAY; Krause et al. CPC246 (2020), Prophecy4f; Denner et al. CPC254 (2020)

H-COUP ver.3

✔ : H-COUP ver.2 { **2HDM**, **Inert doublet model (IDM)**, **Higgs singlet model (HSM)** }

✔ : Our works

H decay : Kanemura, Kikuchi, Yagyu NPB983 (2022)
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125GeV Higgs		CP-even		CP-odd		Charged	
$h \to ff$	✔	$H \to ff$	✔	$A \to ff$	✔	$H^{\pm} \to ff'$	✔
$h \to VV^*$	✔	$H \to VV$	✔	$A \to Z\, h/H$	✔	$H^{\pm} \to W^{\pm}\, h/H$	✔
$h \to \gamma\gamma/Z\gamma/gg$	✔	$H \to hh$	✔	$A \to W^{\pm}H^{\mp}$	✔	$H^{\pm} \to W^{\pm}\, A$	✔
		$H \to AA/H^+H^-$	✔	$A \to VV$	✔	$H^{\pm} \to W^{\pm}\, Z/\gamma$	✔
		$H \to ZA/W^{\pm}H^{\mp}$	✔				

Additional Higgs decays in IDM and HSM will be also included.

We focus on the EW corrections to $A \to Zh$

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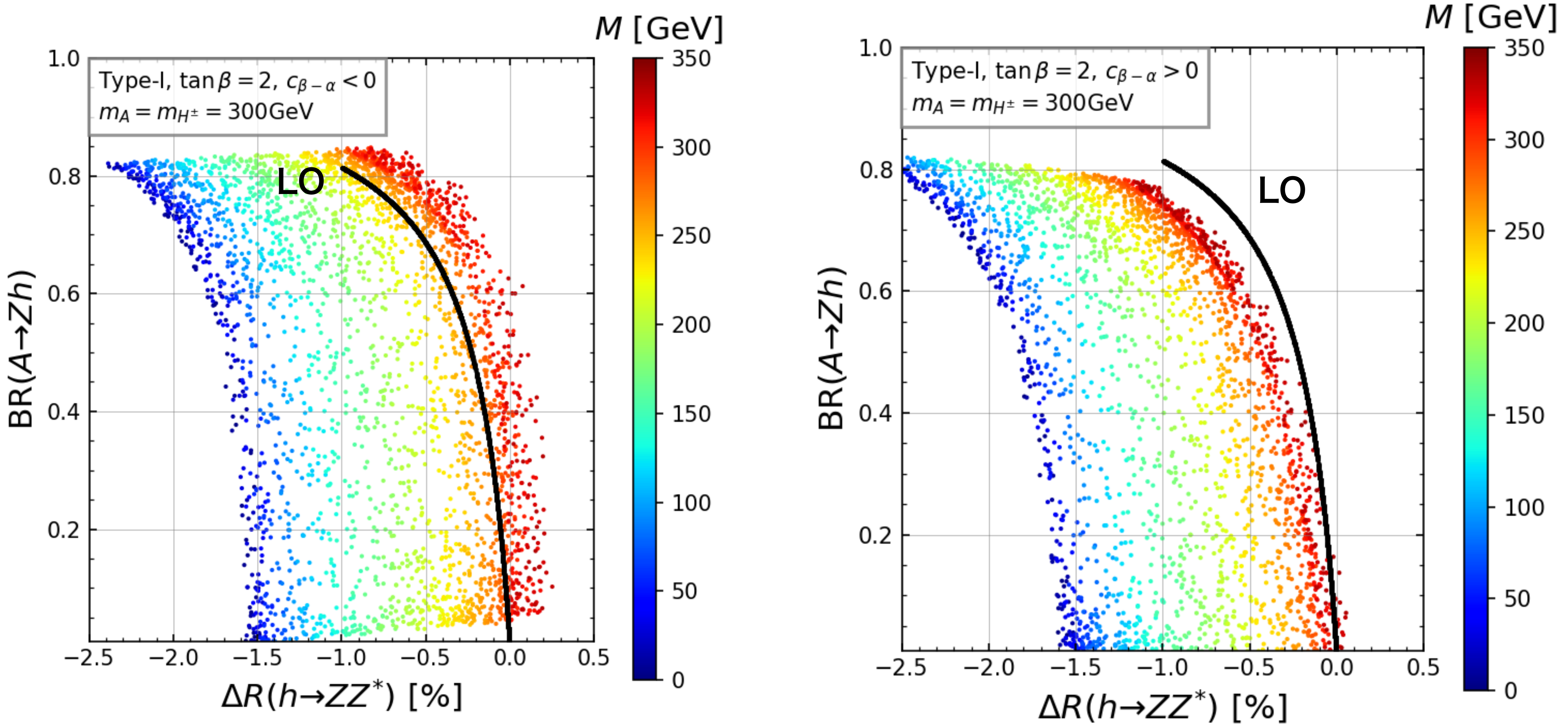
BR($A \to Zh$) vs $\Delta R(h \to ZZ^*)$ at NLO

MA, Kanemura, Sakurai, NPB986 (2023)

$A \to Zh$

LO: $\Gamma(A \to Zh) \propto c_{\beta-\alpha}^2$, $\Delta R(h \to ZZ^*) \propto c_{\beta-\alpha}^2$, $\lambda_{\phi\phi'\phi''} \propto (m_\Phi^2 - M^2)/v^2$



$\Delta R(h \to ZZ^*) = \Gamma_{\rm 2HDM}^{h \to ZZ^*}/\Gamma_{\rm SM}^{h \to ZZ^*} - 1$

Correlation between BR($A \to Zh$) and $\Delta R(h \to ZZ^*)$ is significantly changed.

Summary

Motivation

- The phenomenology of the additional Higgs bosons is drastically changed whether $s_{\beta-\alpha}=1$ or not. $\Longrightarrow$ What is the impact of NLO corrections? **H-COUP ver.3**

New points

- Decays of additional Higgs bosons are comprehensively analyzed.
- Correlation between the decay branching ratios and $\Delta R(h \to ZZ^*)$ are studied including the higher-order corrections.

What we found

- Branching ratios of $A \to Zh$ receive $\mathcal{O}(10)$ % corrections if $\tan\beta \simeq 2$.
- Correlation between BR($A \to Zh$) and $\Delta R(h \to ZZ^*)$ is significantly changed from LO.

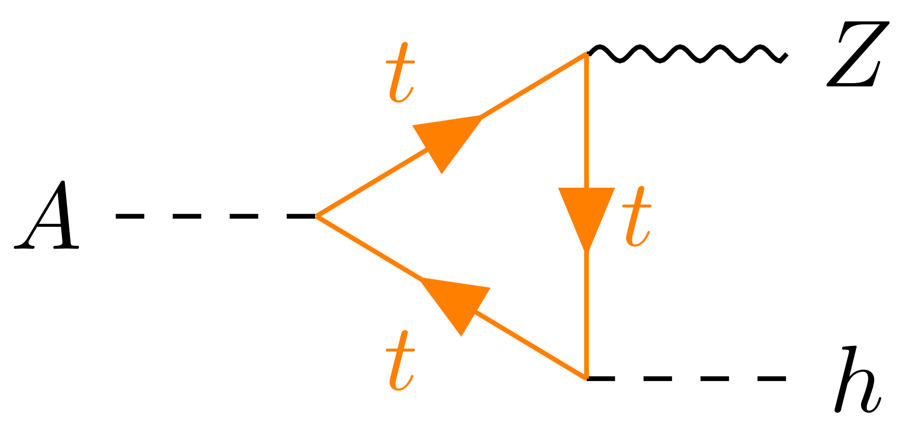
NLO corrections are important for direct searches of the additional Higgs bosons.

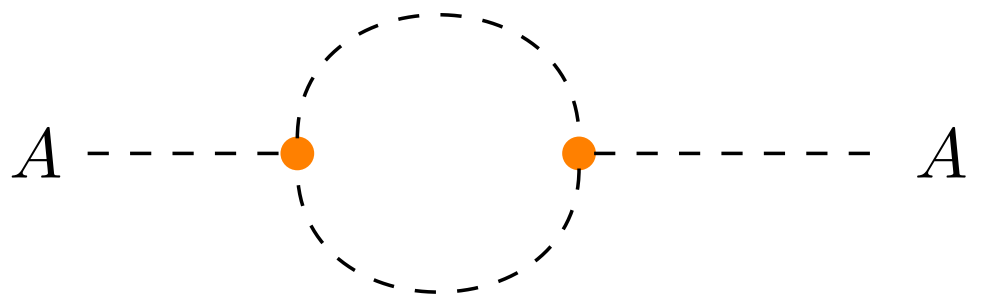
Backup

MA, Kanemura, Sakurai, NPB986 (2023)

$A \to Zh$

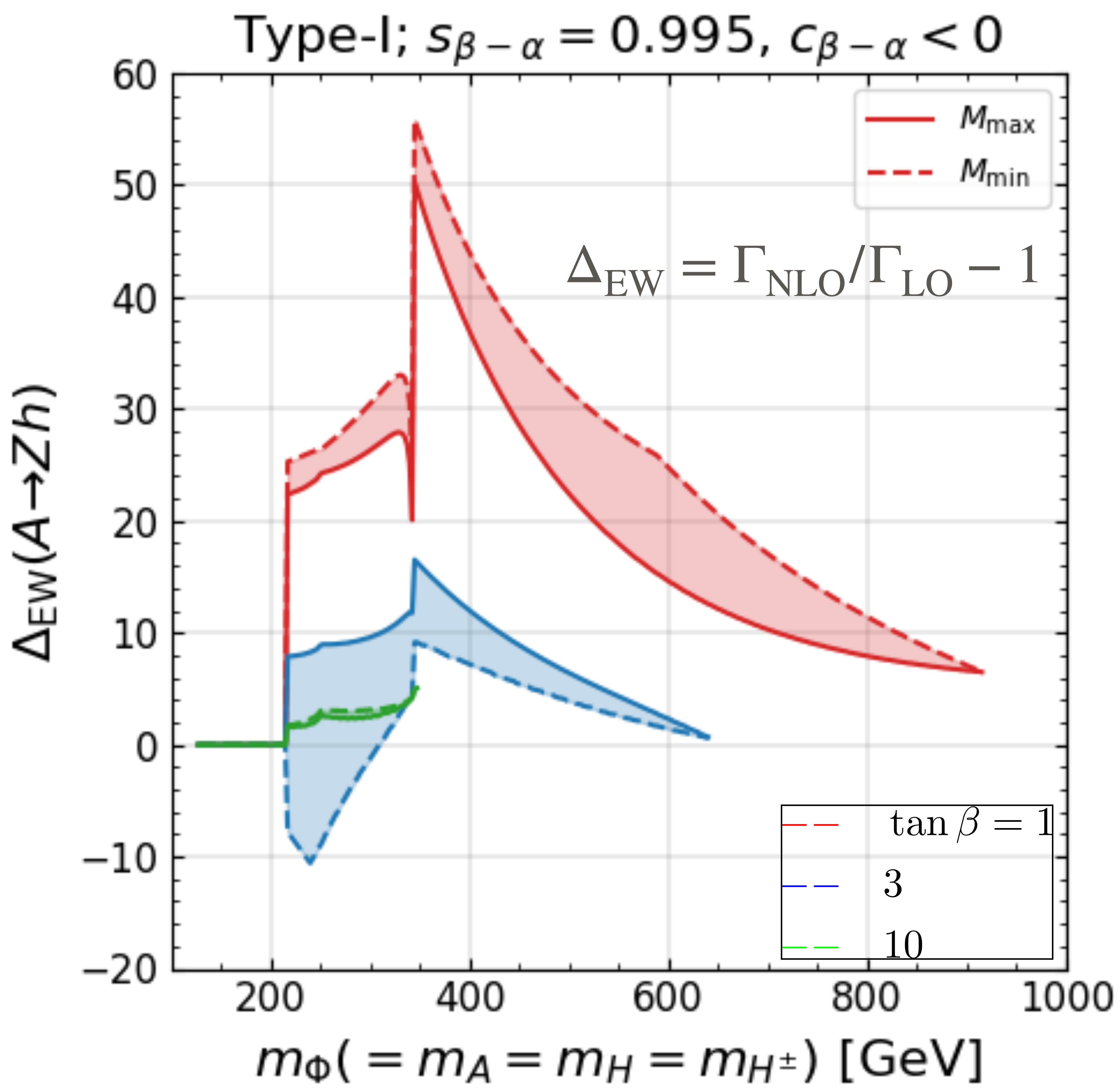
- The top-quark triangle diagram gives large threshold correction at $m_A \simeq 2m_t$
- When m_Φ is large, δZ_A and $\delta\beta$ give $\mathcal{O}(\lambda^2_{SS'S''})$ corrections, and they give dominant effects.





δZ_A: Wave-function renormalization constant of A

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



- The sign of $\Delta_{\rm EW}(A \to Zh)$ depends on that of $c_{\beta-\alpha}$.

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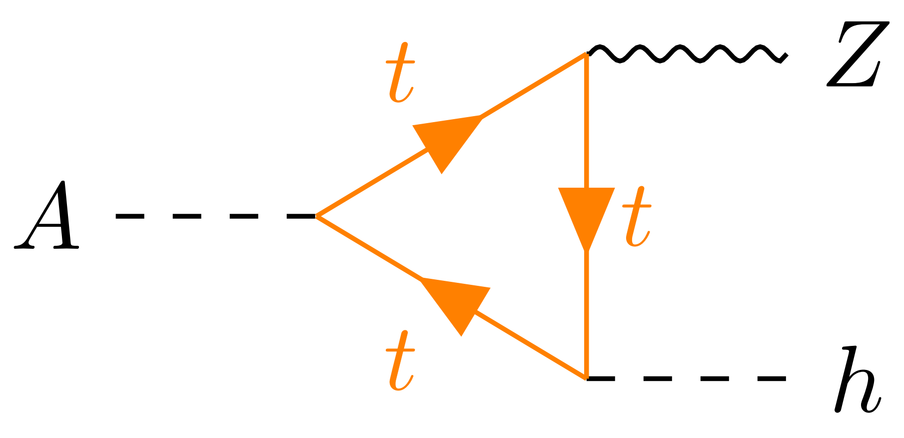

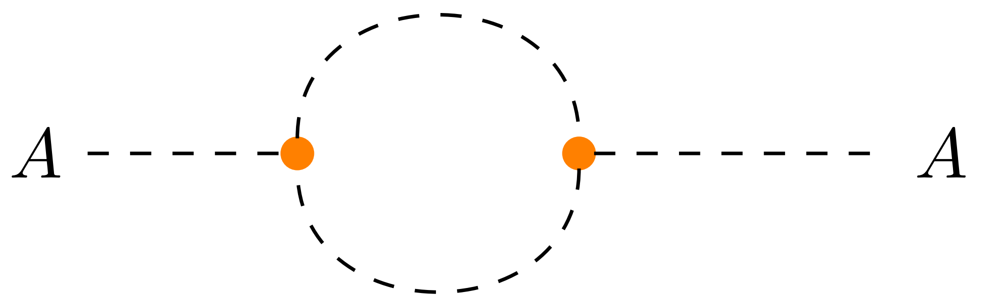

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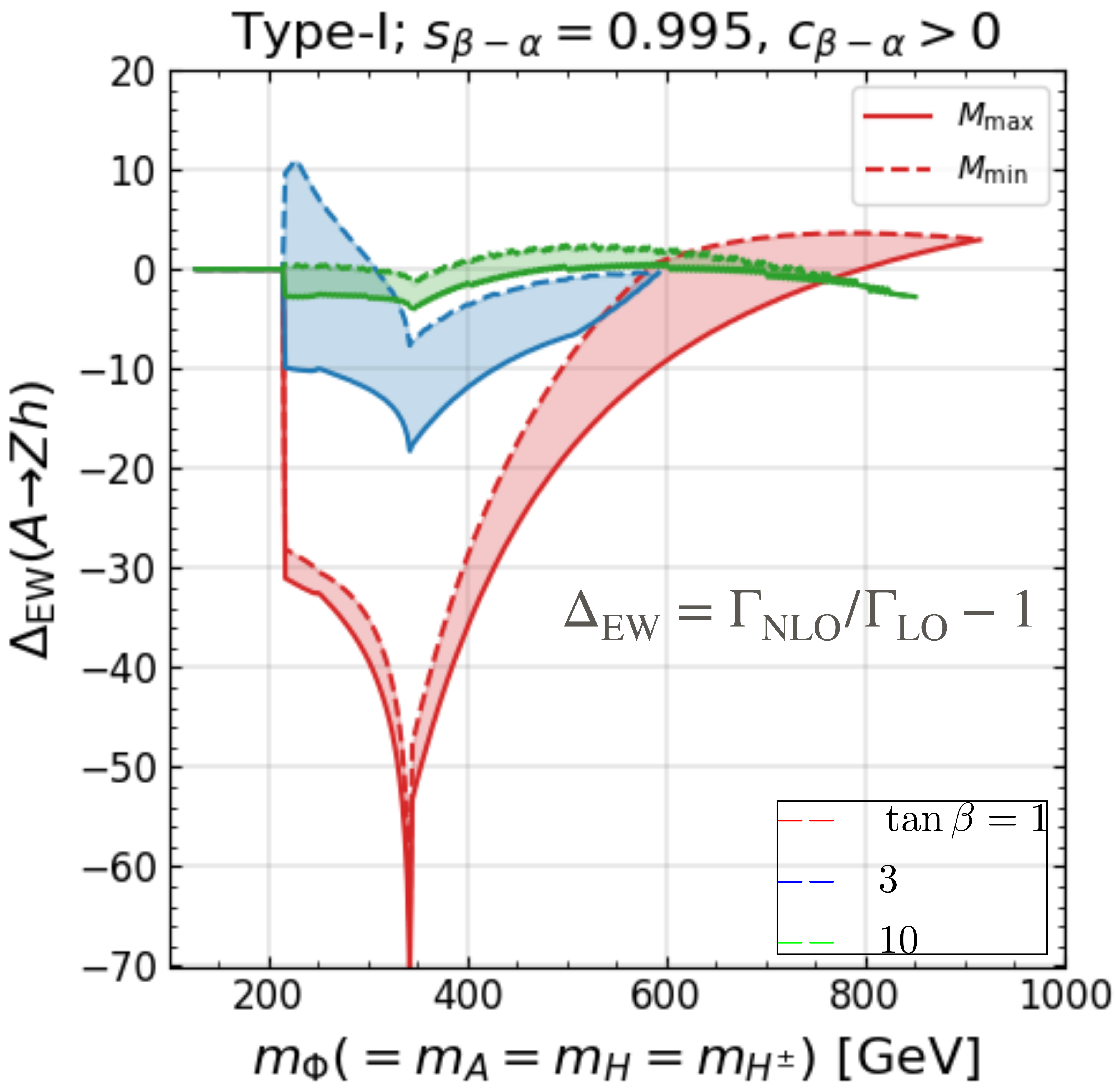

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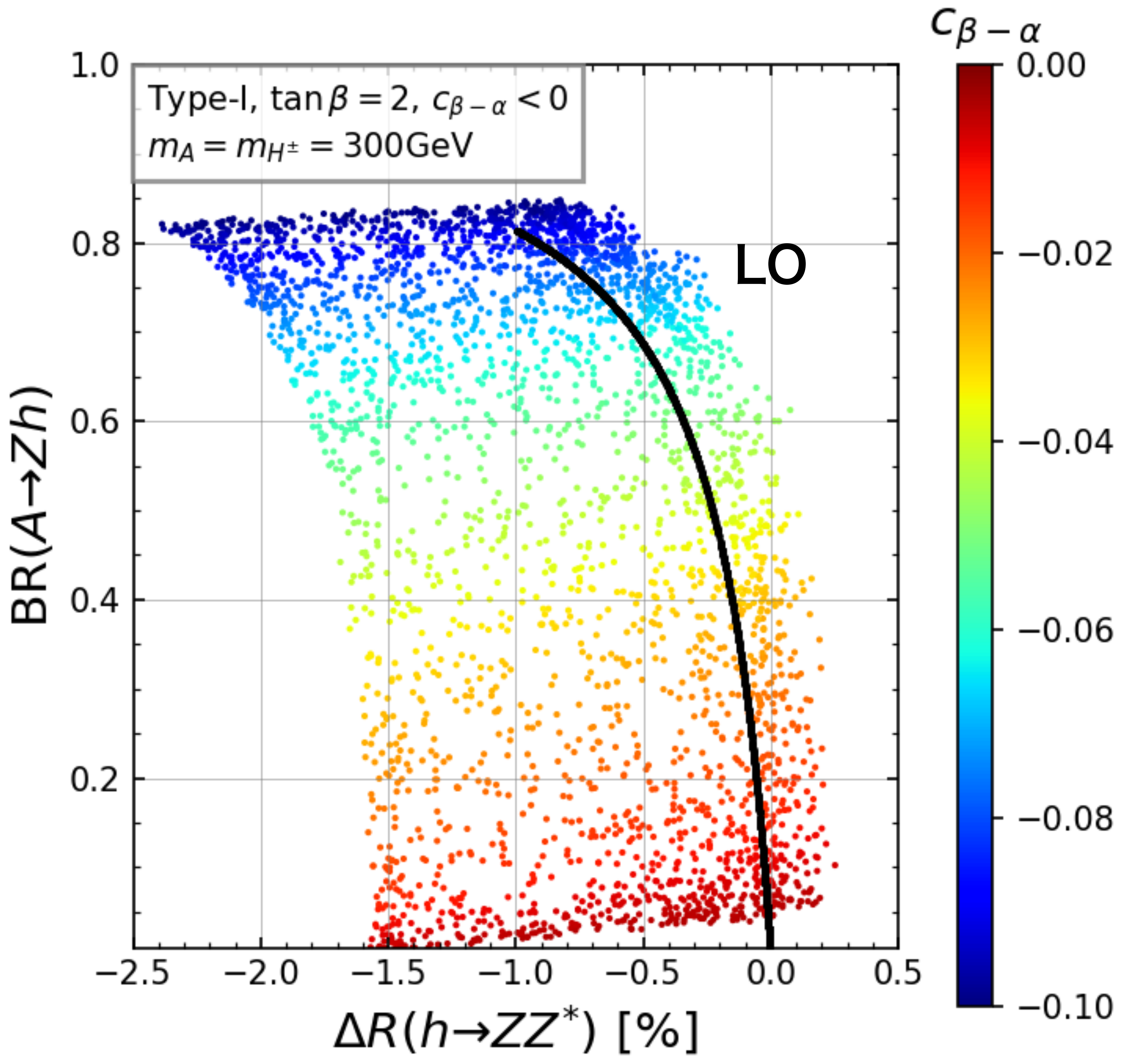

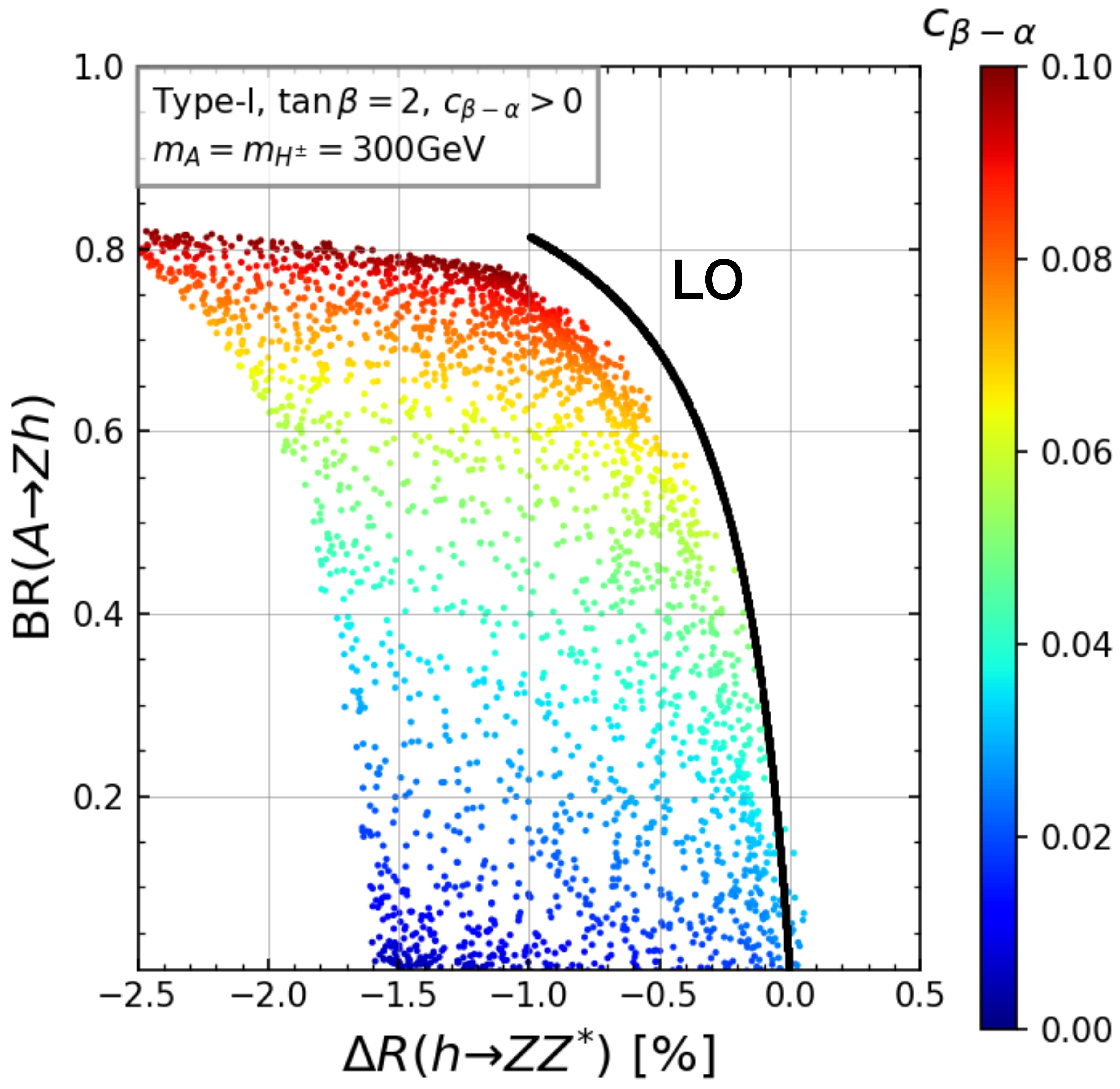

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