Next-to-leading-order corrections to the $e^+e^- \to hZ$ process in extended Higgs models

Based on EPJC 81 11 (2021) [arXiv:2109.02884]

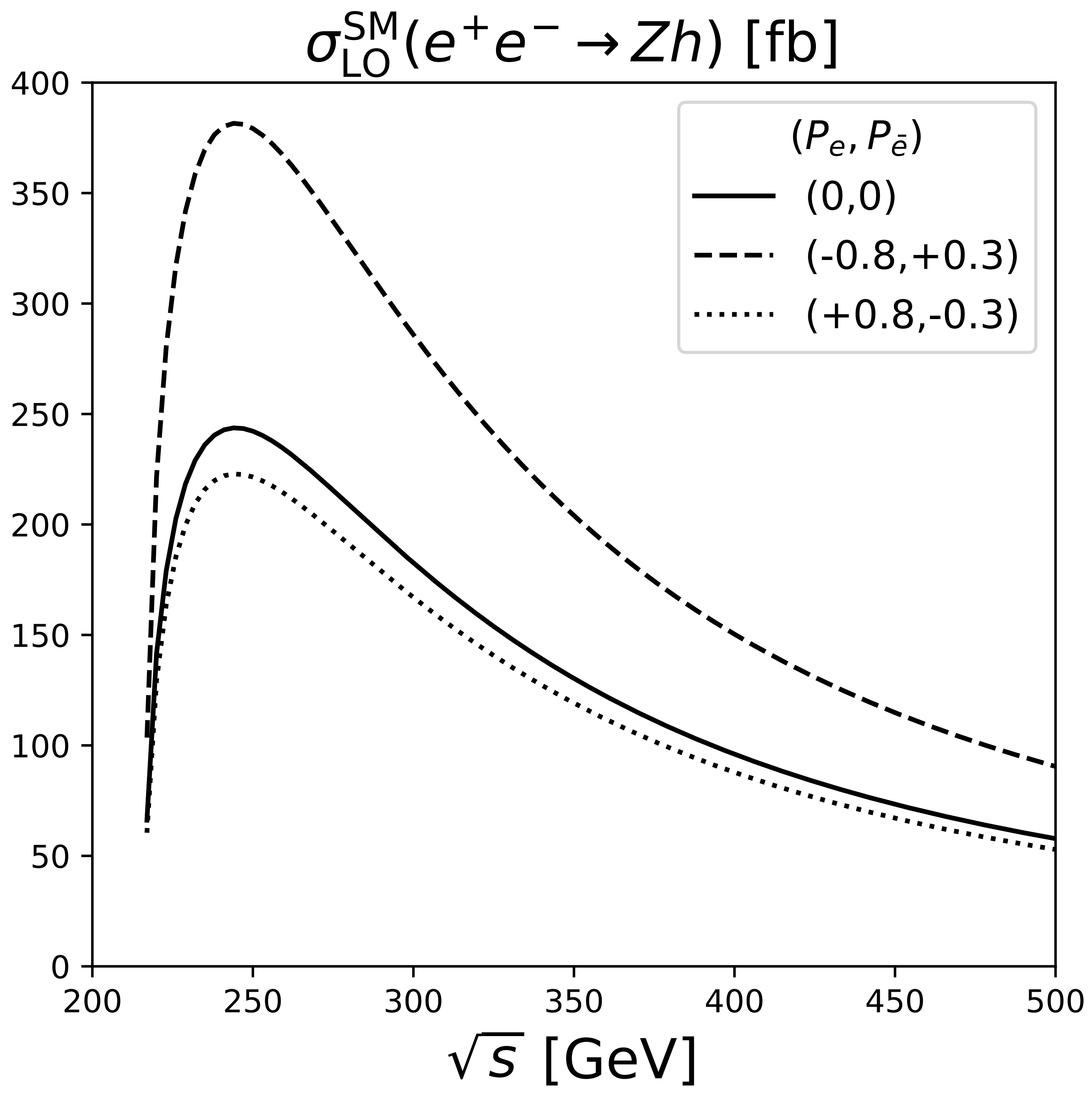
Masashi Aiko (Osaka University → KEK)

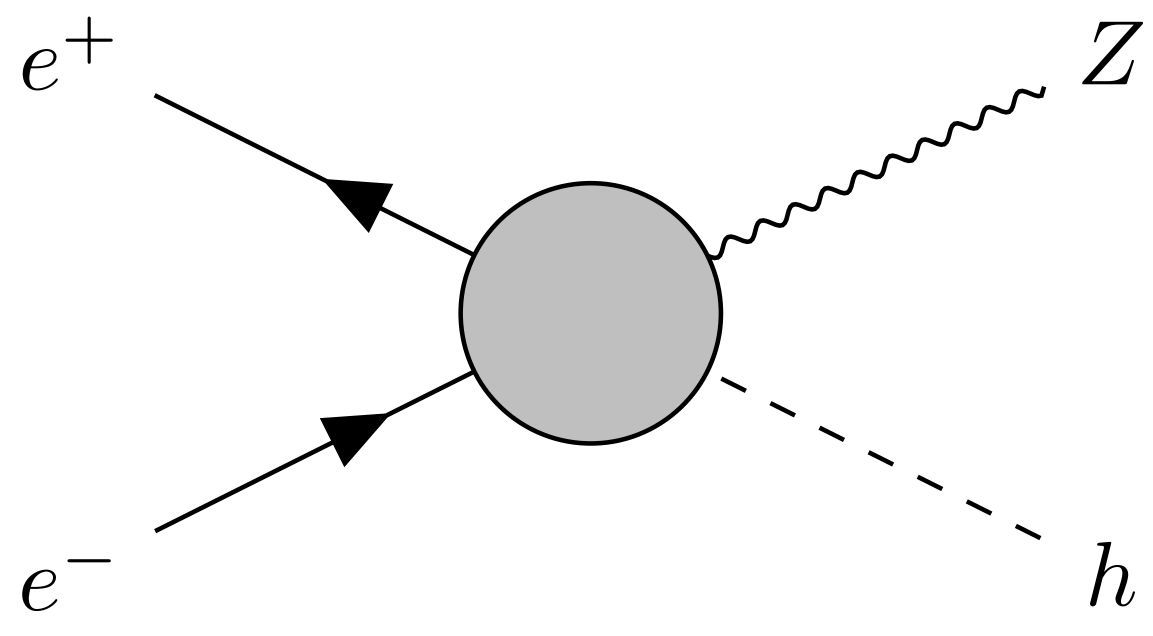
Collaborators: **Shinya Kanemura** (Osaka Univ.) **Kentarou Mawatari** (Iwate Univ.)

OSAKA UNIVERSITY
School of Science
Graduate School of Science

mini-workshop on BSM at ILC（2022/02/28 Online）

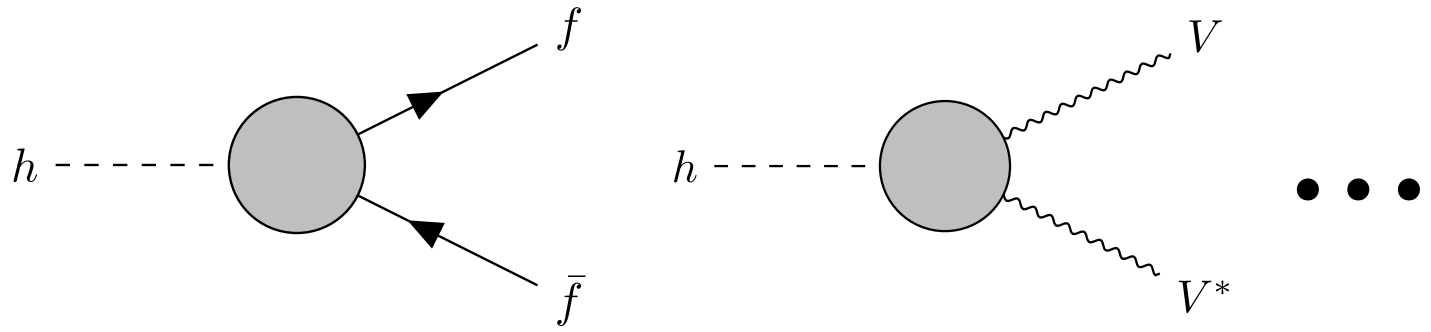
We analyze the cross-section for $e^+e^- \to hZ$ at the full next-to-leading order in various extended Higgs models.



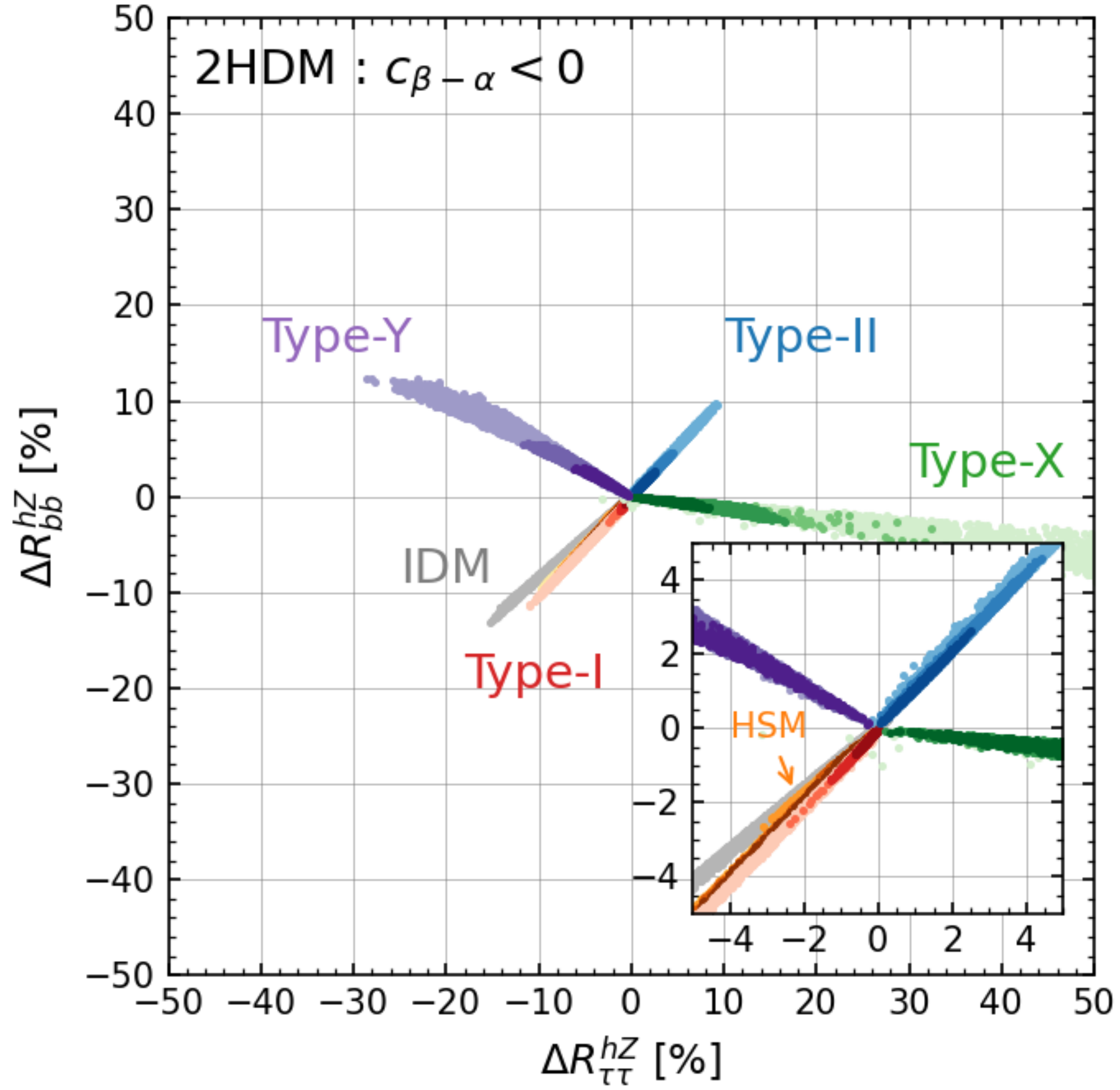


This work

×



H-COUP ver.2



Precision measurement at the ILC250

Discrimination of the extended Higgs models

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

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

Determination of the Higgs sector is important.

How to determine

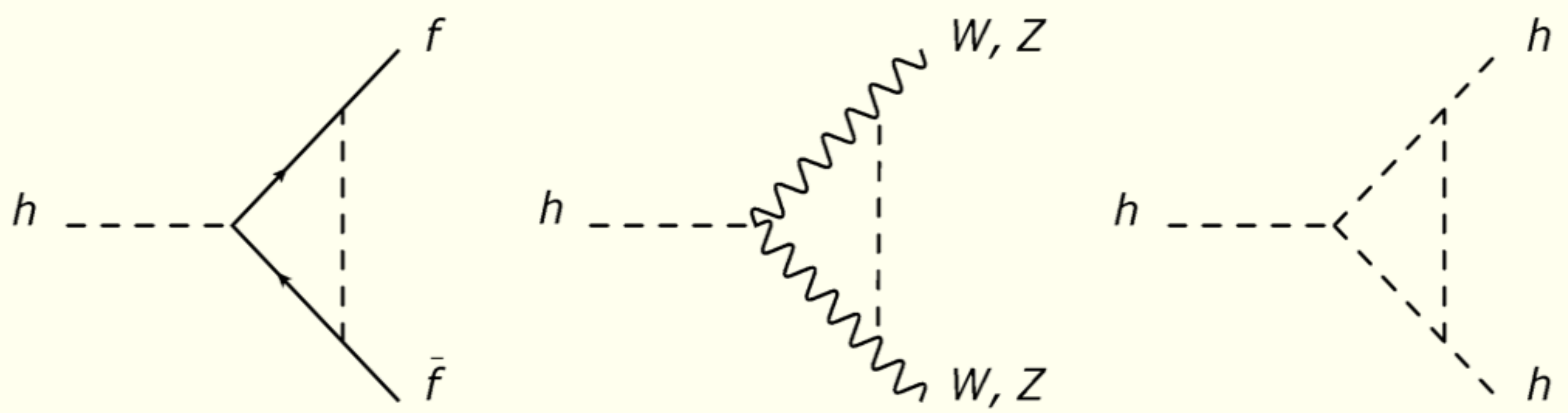
The properties of SM-like Higgs boson are different from those in the SM.

Such deviations can be measured with **a few percent accuracies** at future lepton colliders. → **Precision calculations** are essentially important.

H-COUP: tool for precision calculation

http://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.

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

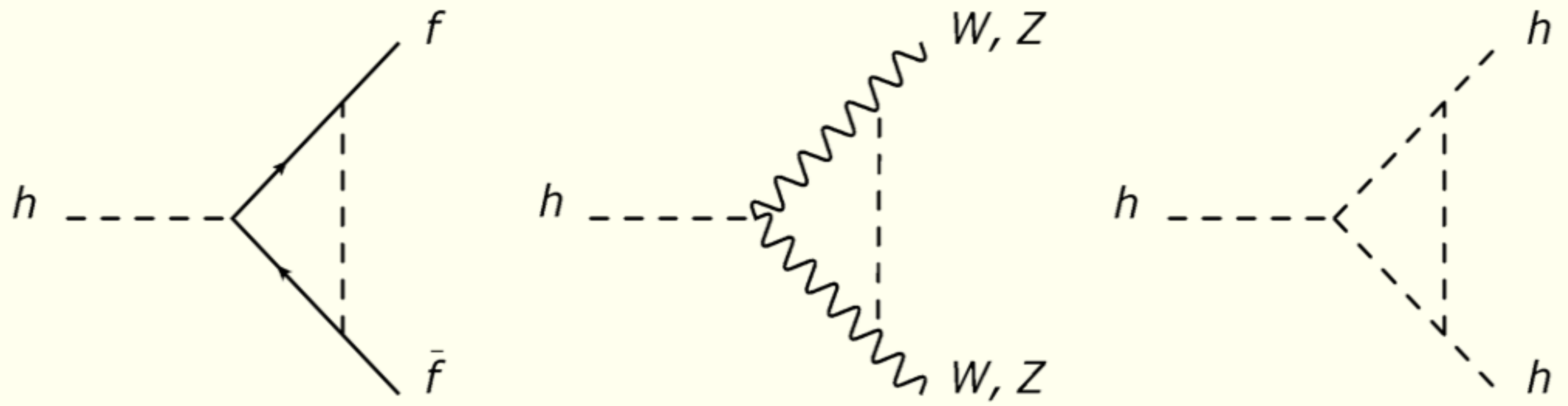
The manual for H-COUP version 2 can be taken on arXiv:1910.12769 [hep-ph].

H-COUP: tool for precision calculation

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

H-COUP Extension

- **Production cross-section**
- Decays of additional Higgs bosons



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.

I focus on 2HDM in this talk

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

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

The model with two scalar doublet Φ_1 and Φ_2 with $Y = 1/2$

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

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

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)

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

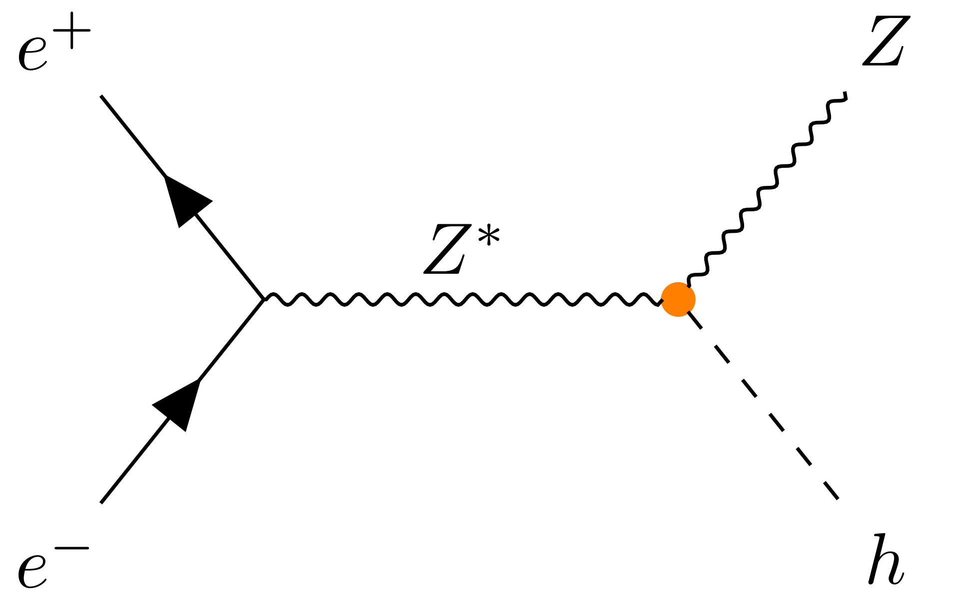
- **Alignment limit** : $s_{\beta-\alpha} \to 1$ (tree-level Higgs couplings take SM-values.)
- LHC data are consistent with the SM prediction $\to s_{\beta-\alpha} \simeq 1$ G. Aad et al. PRD101 (2020)

Why higher-order calculations are needed?

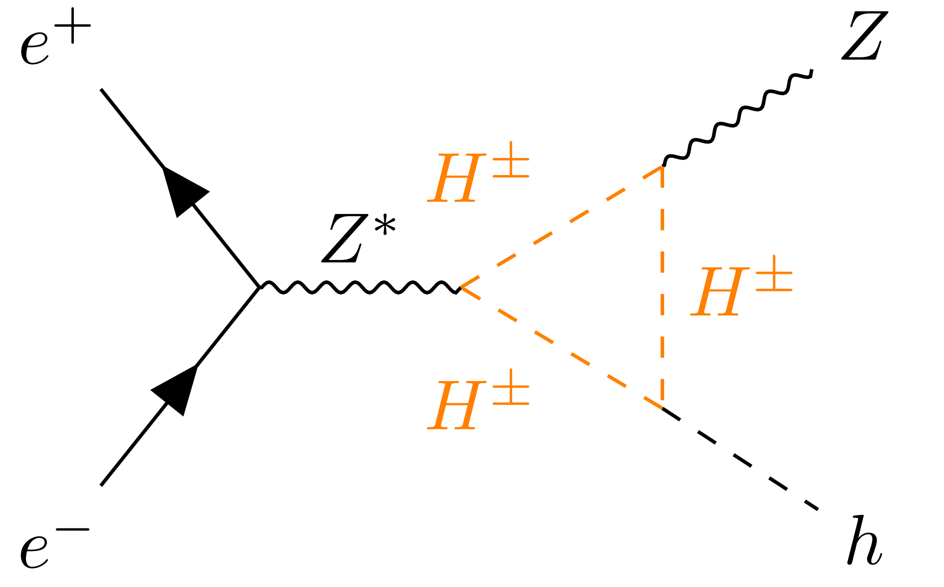
LO $\sigma_{\rm LO}^{\rm 2HDM} = s_{\beta-\alpha}^2 \sigma_{\rm LO}^{\rm SM} \to$ The deviation is $\mathcal{O}(1)\,\%$

- LHC data indicate a SM-like scenario $s_{\beta-\alpha} \approx 1$.

NLO Loop corrections → The deviation is $\mathcal{O}(1)\,\%$



Each size of correction is comparable.



Experimental accuracy

$$\Delta\sigma(e^+e^- \to hZ) = 2\,\% \ (0.7\%) \ \text{ at ILC } 250\text{fb}^{-1} \ (2 \text{ ab}^{-1})$$

T. Barklow et al. PRD97 (2018)

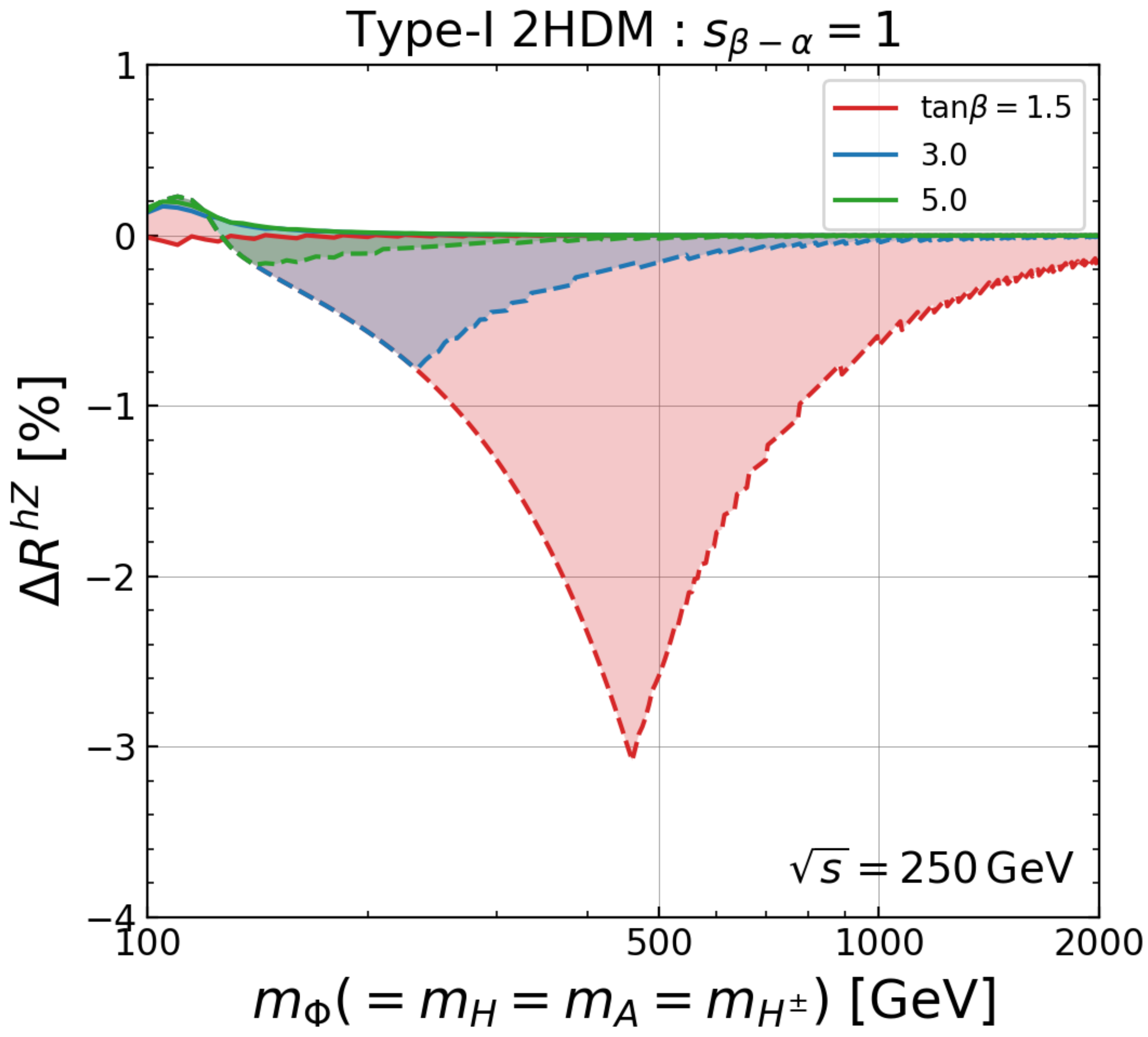
Higher-order calculations are essentially important.

We calculate one-loop corrections based on the renormalization scheme in H-COUP.

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

2HDM with $s_{\beta-\alpha} = 1$

$(P_e, P_{\bar{e}}) = (0,0), \quad \Delta R^{hZ} = \sigma_{\rm NP}/\sigma_{\rm SM} - 1$



M. Aiko, S. Kanemura, K. Mawatari, 2109.02884

LO

- No deviation

Constants

- Vacuum stability
- Perturbative unitarity
- S and T parameter

We find almost no difference among all Types.

Results

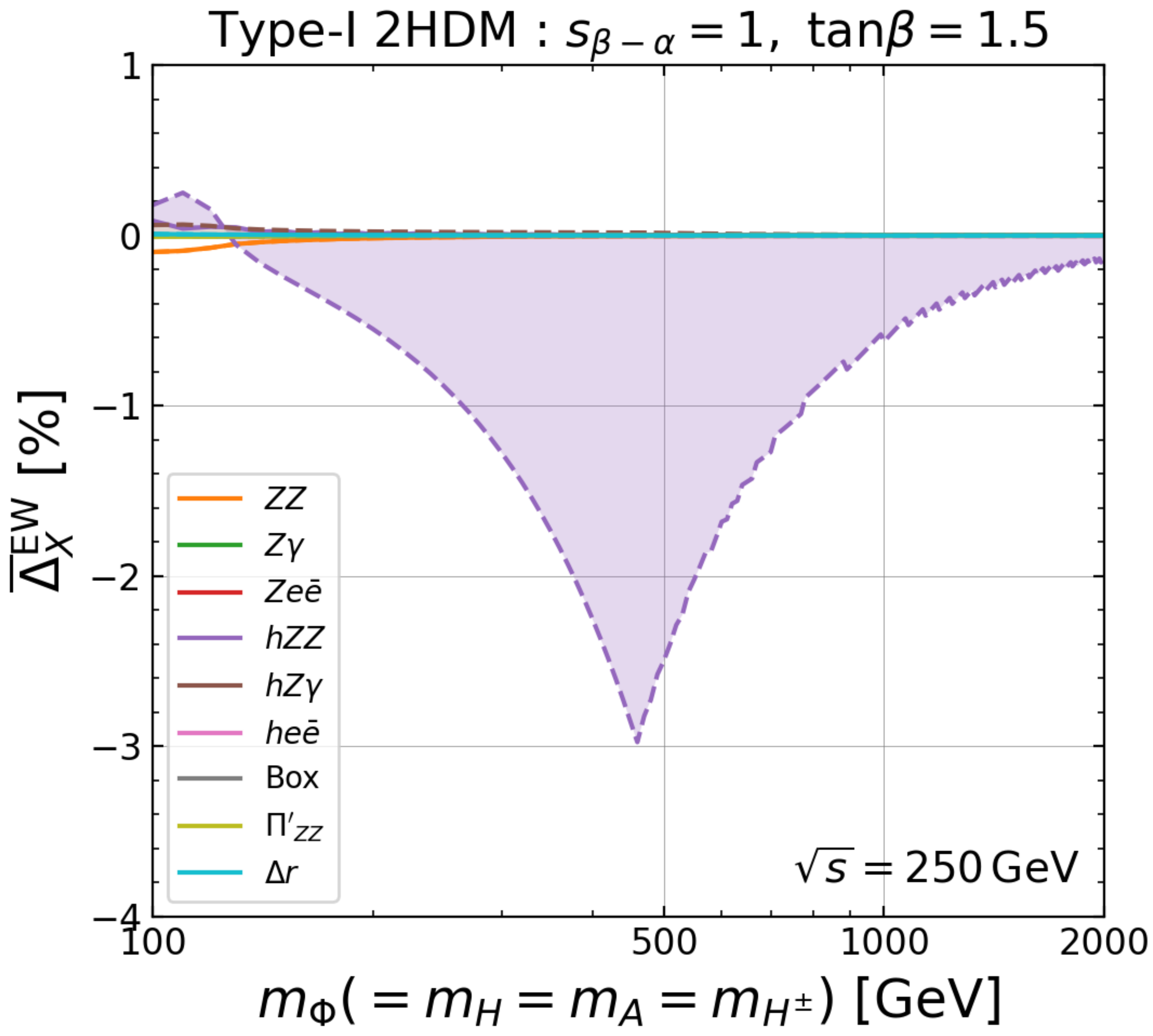
- A few percent deviations
- Decoupling

T. Appelquist, J. Carazzone PRD11 (1975)

- The hZZ vertex gives a dominant contribution

2HDM with $s_{\beta-\alpha} = 1$

$(P_e, P_{\bar{e}}) = (0,0)$, $\overline{\Delta}_X^{\mathrm{EW}}$: Each NP effects



M. Aiko, S. Kanemura, K. Mawatari, 2109.02884

LO

- No deviation

Constant

- Vacuum stability
- Perturbative unitarity
- S and T parameter

We find almost no difference among all Types.

Results

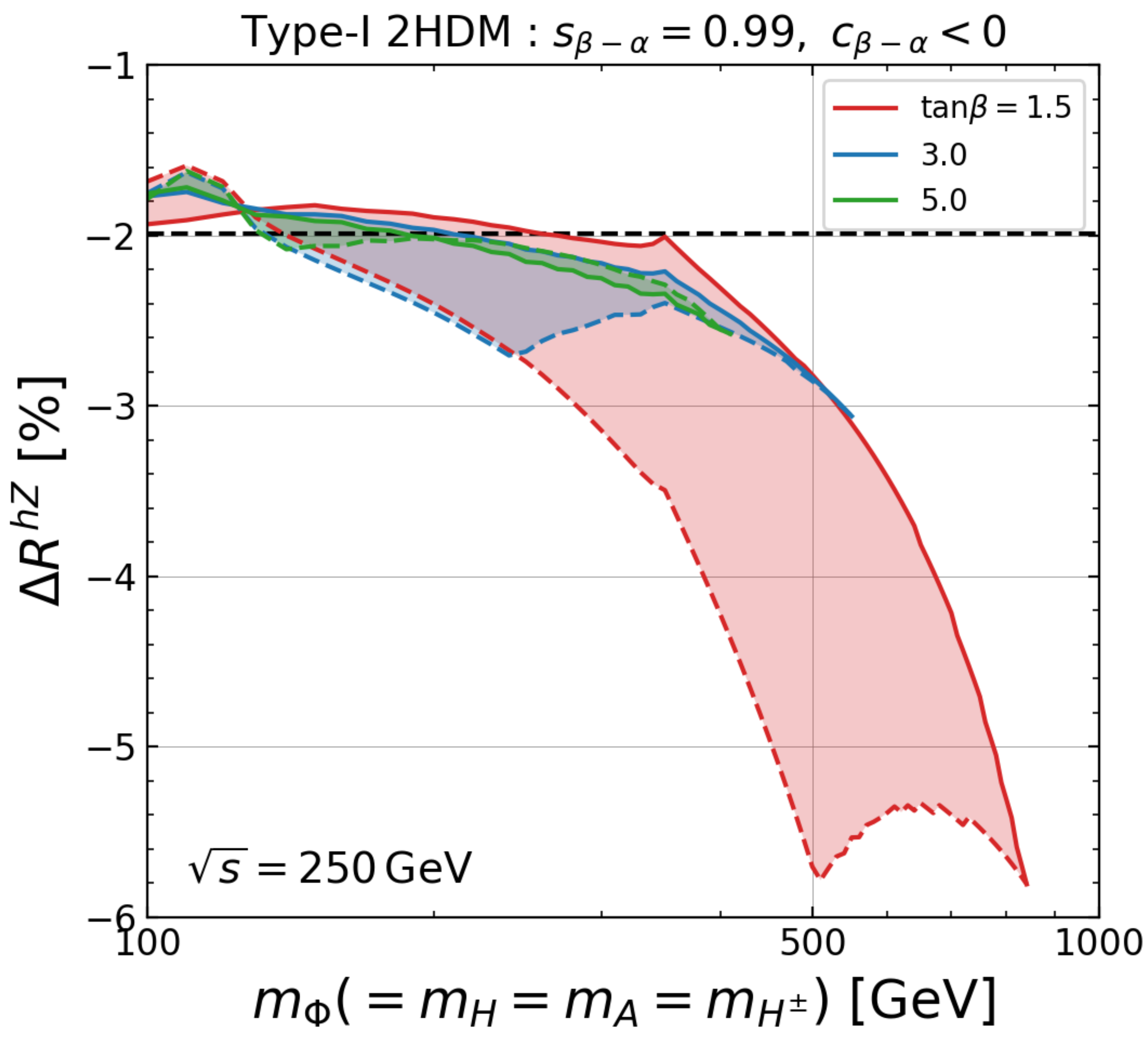
- A few percent deviations
- Decoupling

T. Appelquist, J. Carazzone PRD11 (1975)

- The hZZ vertex gives a dominant contribution

2HDM with $s_{\beta-\alpha} \neq 1$

$(P_e, P_{\bar{e}}) = (0,0), \quad \Delta R^{hZ} = \sigma_{\rm NP}/\sigma_{\rm SM} - 1$



M. Aiko, S. Kanemura, K. Mawatari, 2109.02884

LO

- 2% deviation

Constant

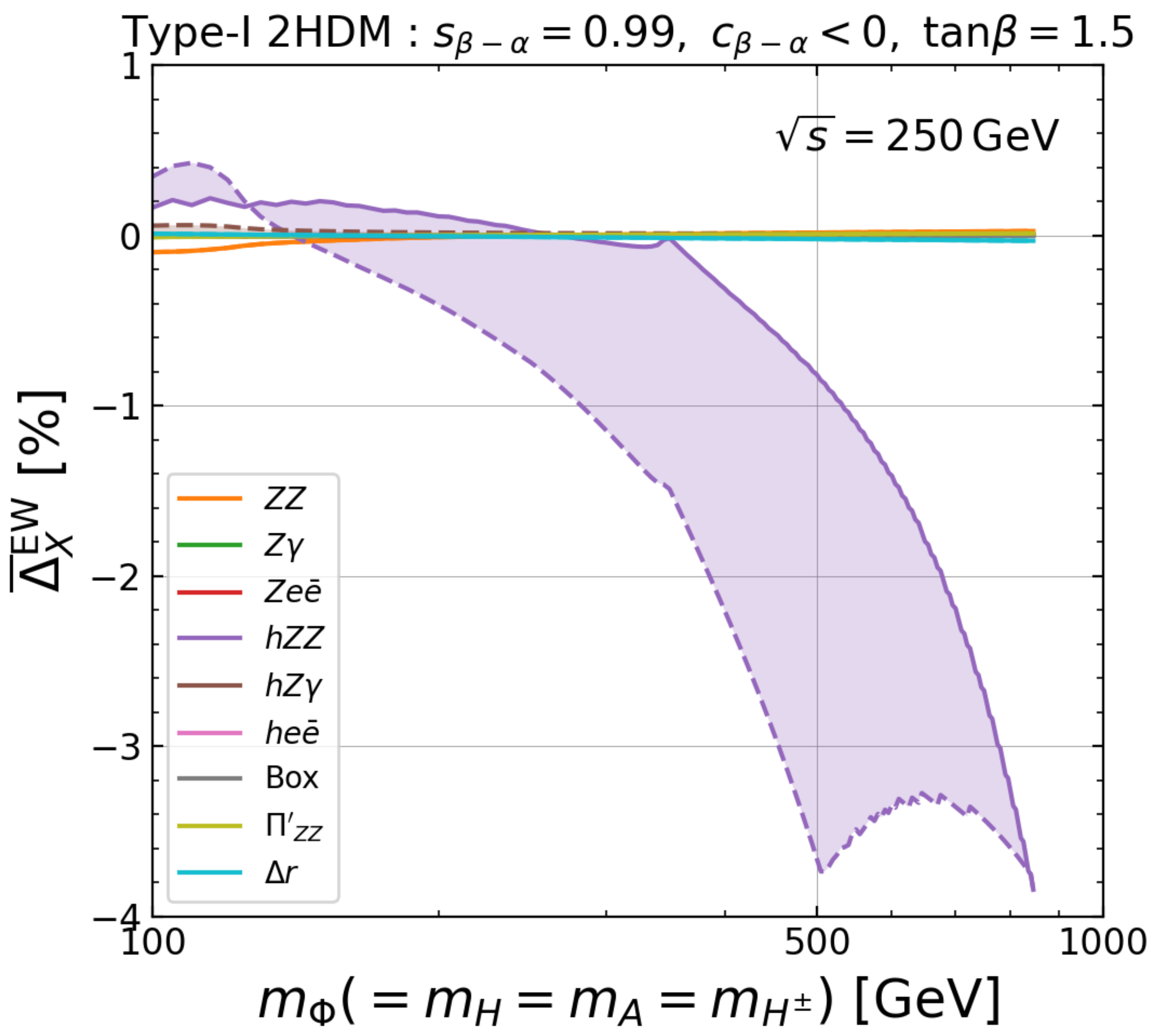
- Vacuum stability
- Perturbative unitarity
- S and T parameter

Results

- Loop effects are comparable
- Non-decoupling
  - The larger effects the heavier masses.
- The hZZ vertex gives a dominant contribution

2HDM with $s_{\beta-\alpha} \neq 1$

$(P_e, P_{\bar{e}}) = (0, 0)$, $\overline{\Delta}_X^{\mathrm{EW}}$: Each NP effects



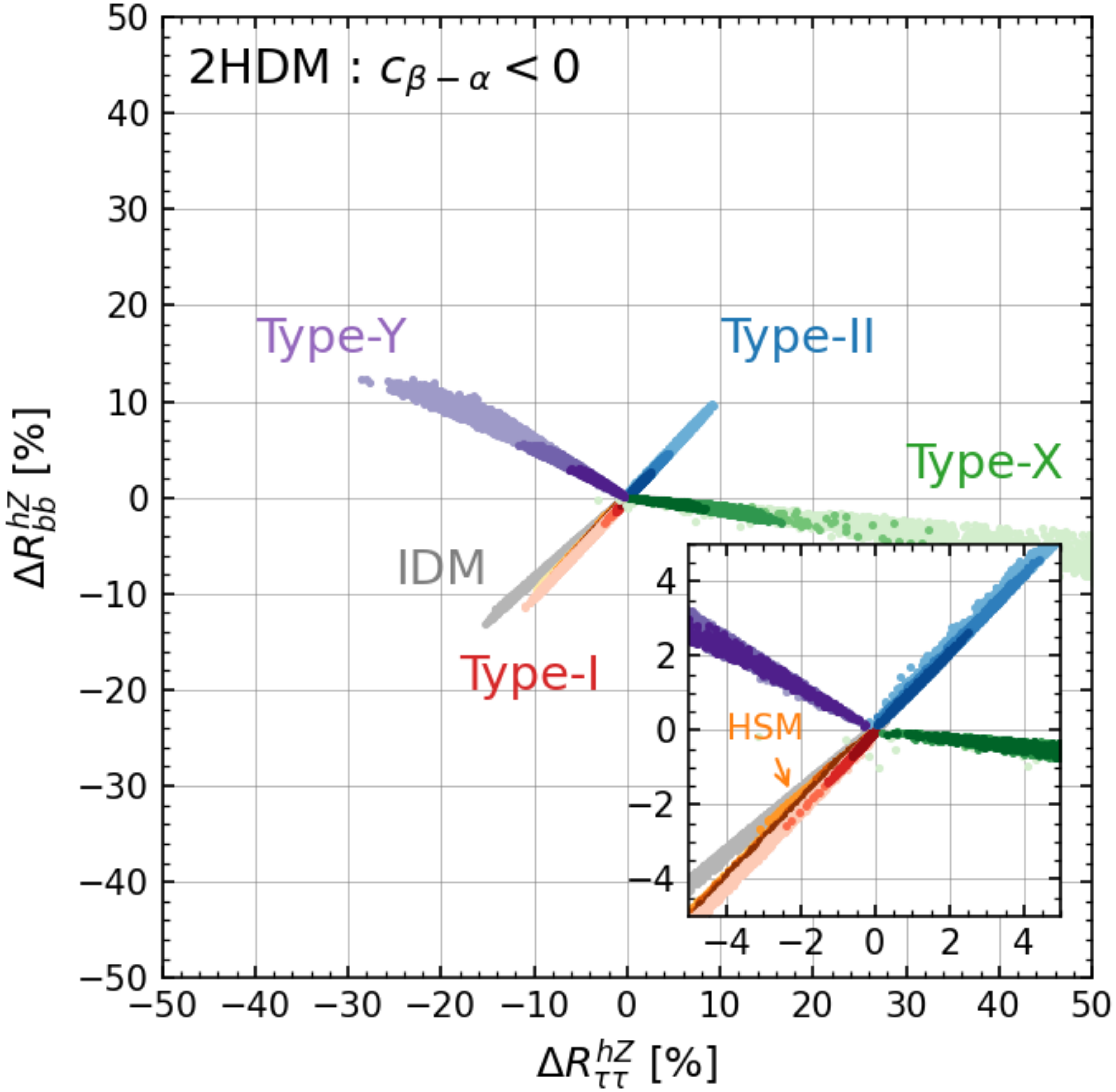
M. Aiko, S. Kanemura, K. Mawatari, 2109.02884

LO
- 2% deviation

Constant
- Vacuum stability
- Perturbative unitarity
- S and T parameter

Results
- Loop effects are comparable
- Non-decoupling
  - The larger effects the heavier masses.
- The hZZ vertex gives a dominant contribution

$(P_e, P_{\bar{e}}) = (-0.8, +0.3)$



M. Aiko, S. Kanemura, K. Mawatari, 2109.02884

Deviation in $\sigma \times \mathrm{BR}$

$$\Delta R^{hZ}_{XY} = \frac{\sigma_{\mathrm{NP}}(e^+e^- \to hZ)\mathrm{BR}_{\mathrm{NP}}(h \to XY)}{\sigma_{\mathrm{SM}}(e^+e^- \to hZ)\mathrm{BR}_{\mathrm{SM}}(h \to XY)} - 1$$

Results

- Each type of 2HDMs shows a different correlation.
- Type-I 2HDM, HSM and IDM show the almost same correlation.

Experimental accuracy

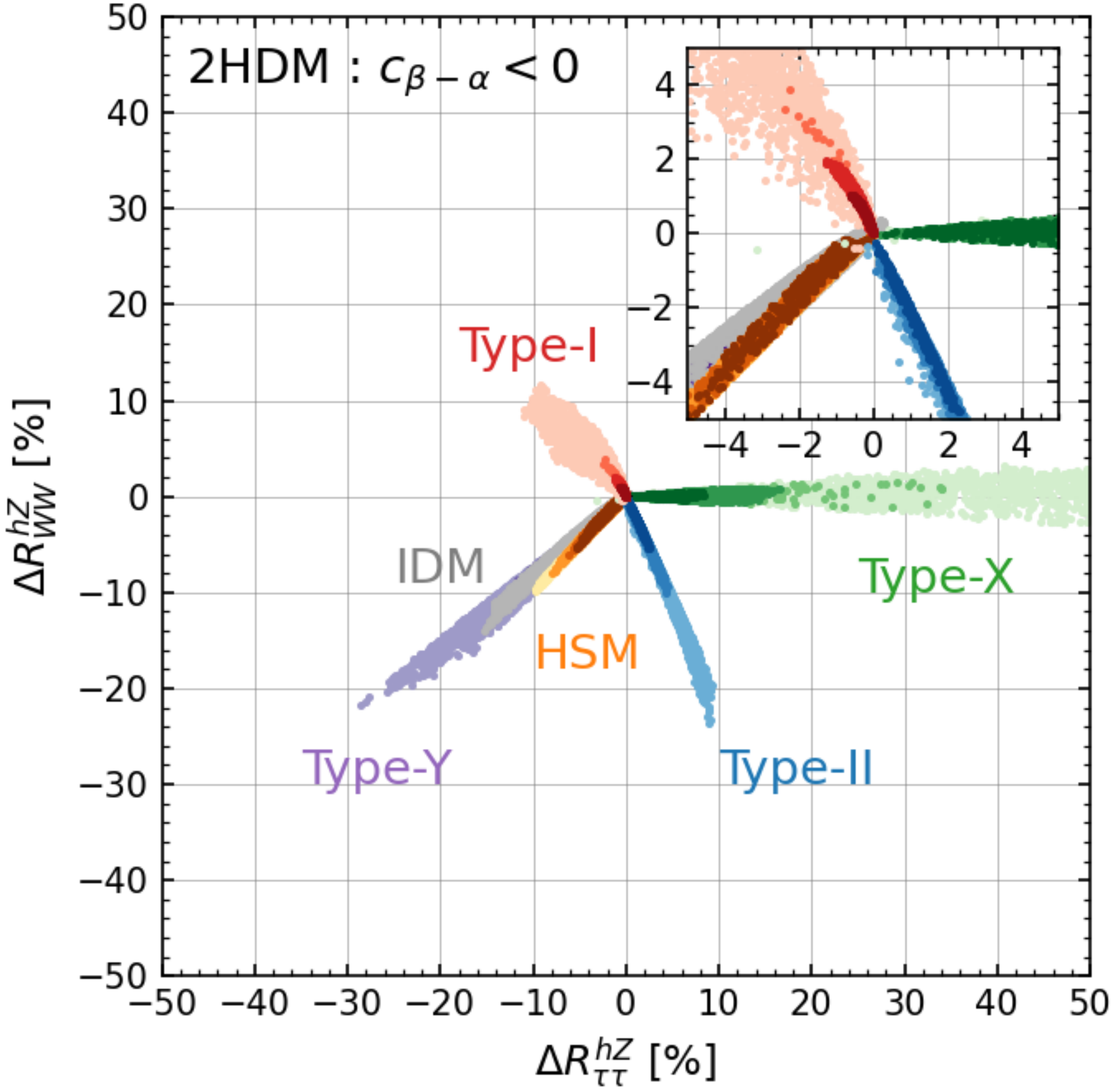
T. Barklow et al. PRD97 (2018)

$\Delta R^{hZ}_{bb} = 1.3~\%$, $\Delta R^{hZ}_{\tau\tau} = 3.2~\%$ at $1~\sigma$

Sizable deviations to detect at the ILC250.

Correlation : $\Delta R^{hZ}_{\tau\tau}$ vs. ΔR^{hZ}_{WW}

$(P_e, P_{\bar{e}}) = (-0.8, +0.3)$



M. Aiko, S. Kanemura, K. Mawatari, 2109.02884

Results

Type-I 2HDM shows a different correlation from the HSM and the IDM.

Experimental accuracy

$\Delta R^{hZ}_{WW} = 4.6\ \%$ at $1\ \sigma$ — T. Barklow et al. PRD97 (2018)

If $m_\Phi \leq 800$ GeV, deviations can be detected at the ILC.

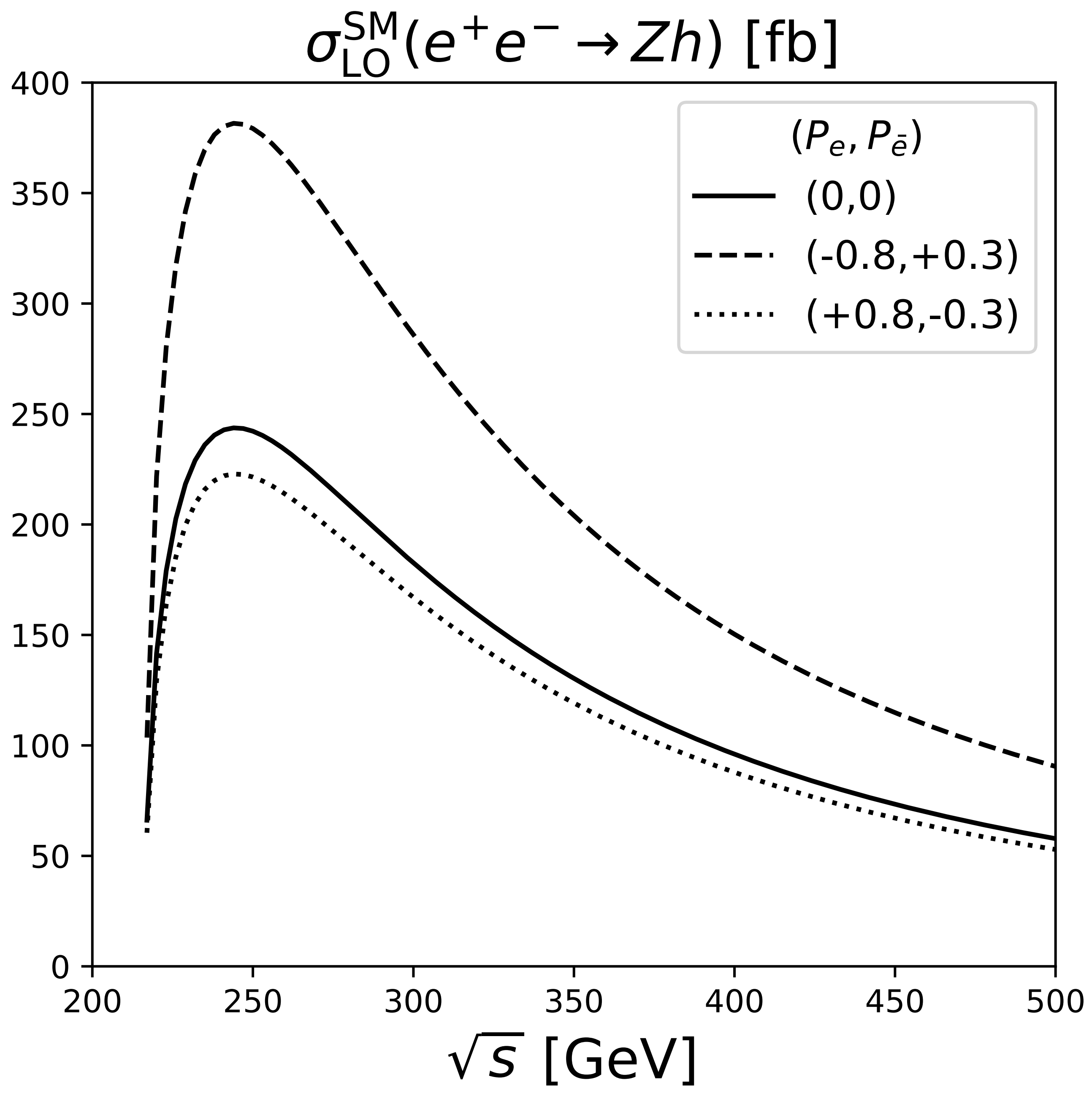
Further discrimination

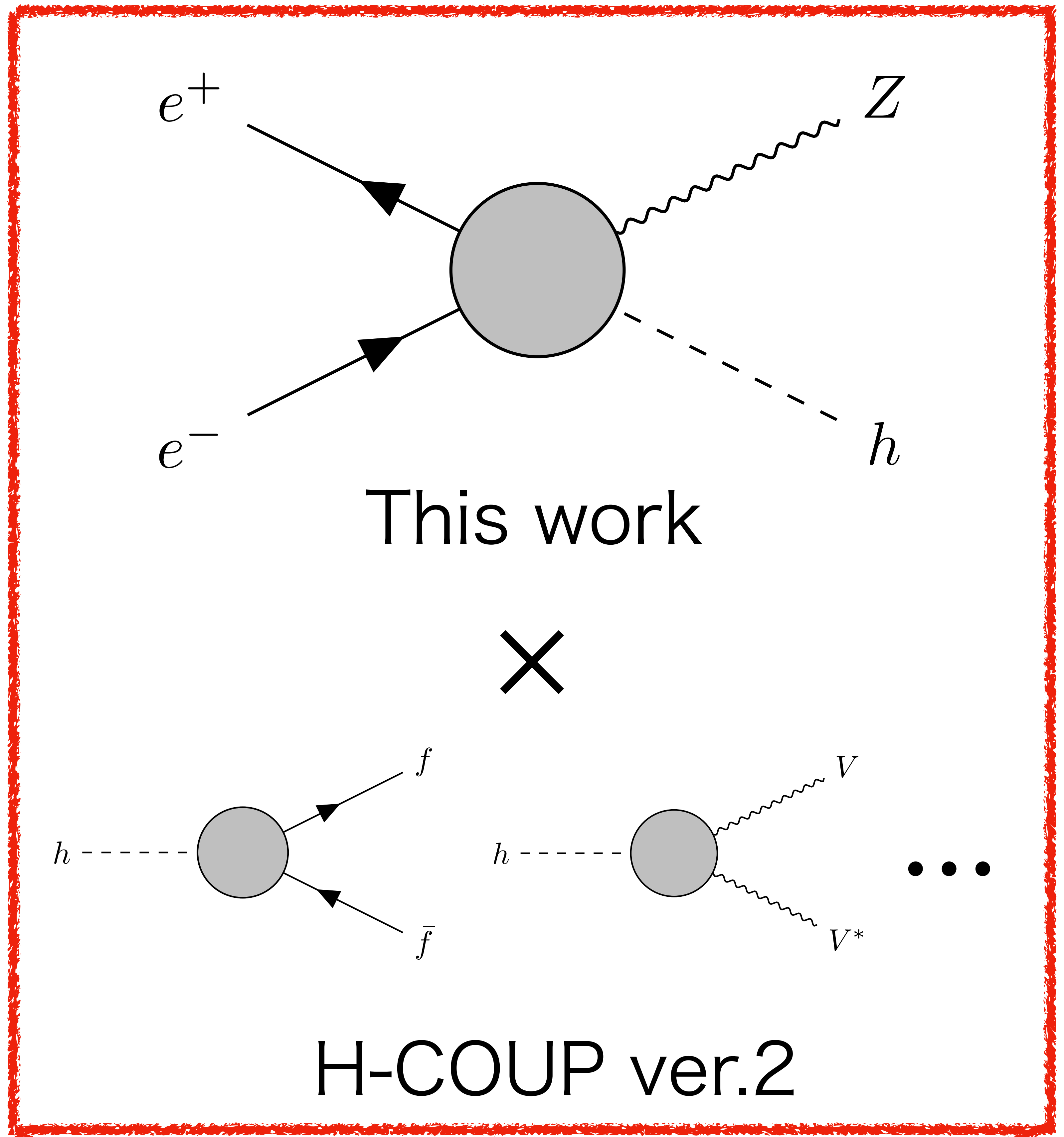
$h \to \gamma\gamma$ might be useful. But it is challenging only at the ILC. $(\Delta R^{hZ}_{\gamma\gamma} = 34\ \%$ at $1\sigma)$

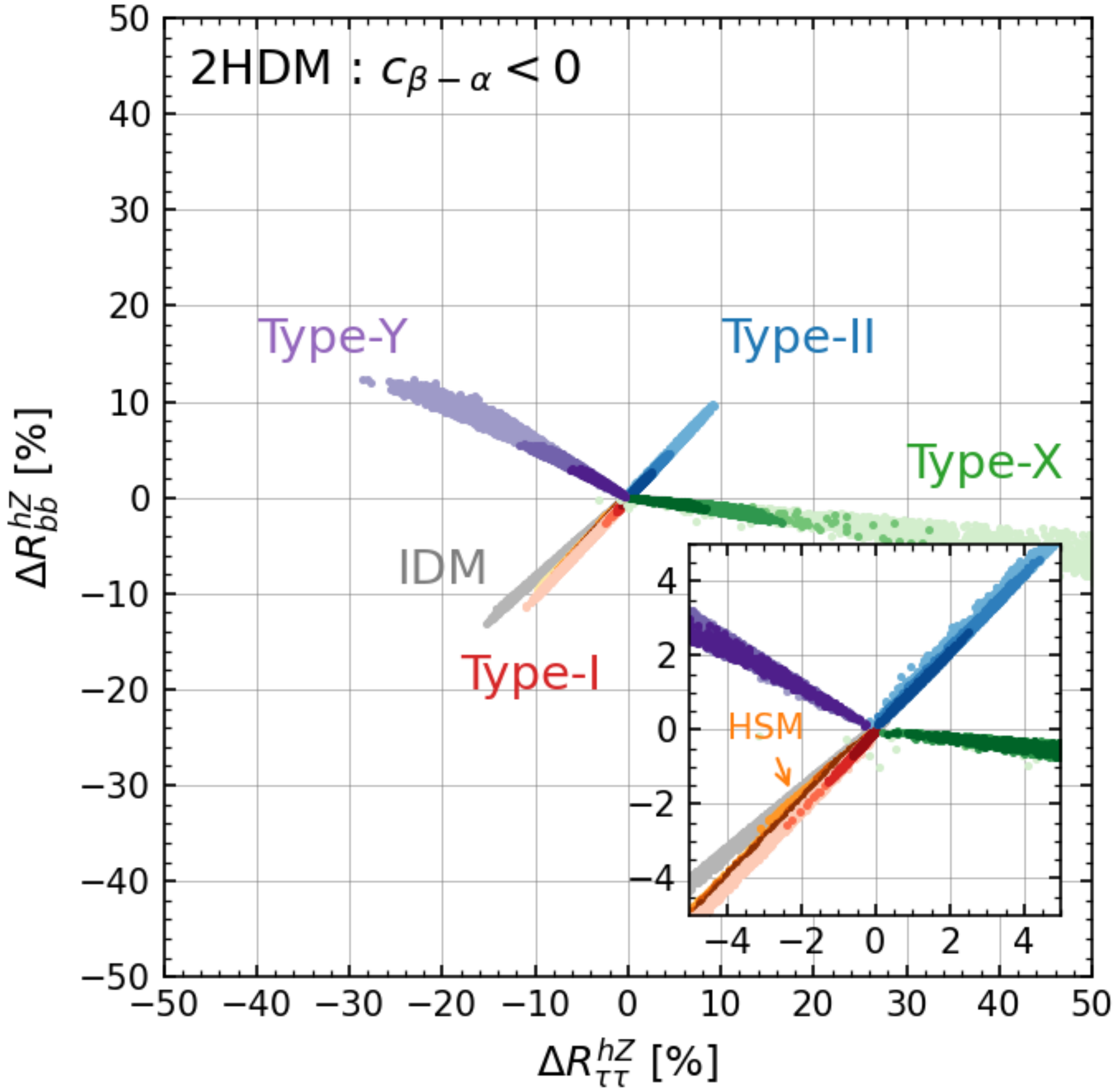
→ Combined study with the HL-LHC

This work

We analyze the cross-section for $e^+e^- \to hZ$ at the full next-to-leading order in various extended Higgs models.







Precision measurement at the ILC250

H-COUP ver.3

Discrimination of the extended Higgs models

Back up

$e^+e^- \to hZ$ process (LO)

ILC, CEPC, FCC-ee : $\sqrt{s} = 240 - 250$ GeV

$\to \sigma(e^+e^- \to hZ)$ takes a maximal value.

Z boson energy : $E_Z = (s + m_Z^2 - m_h^2)/(2\sqrt{s})$

$\to \sigma(e^+e^- \to hZ)$ can be measured by using the recoil mass technique J. Yan et al. PRD94 (2016)

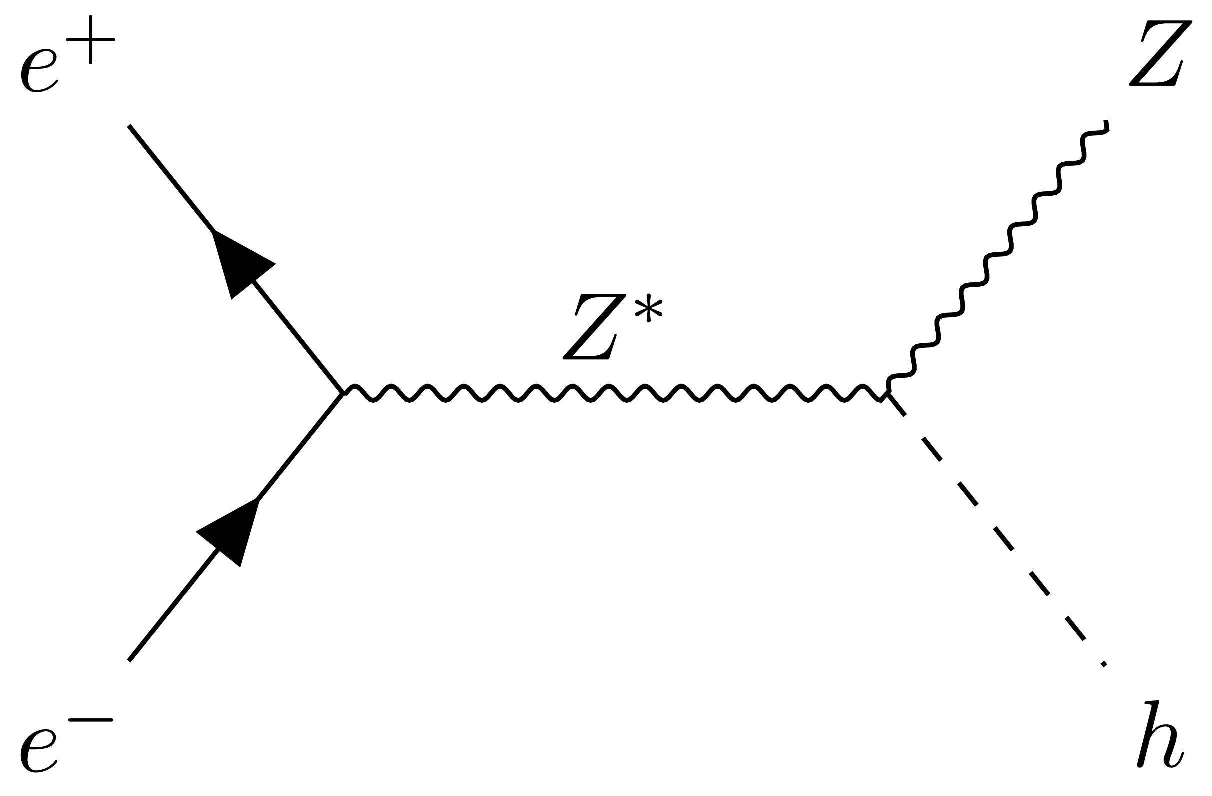
Helicity :

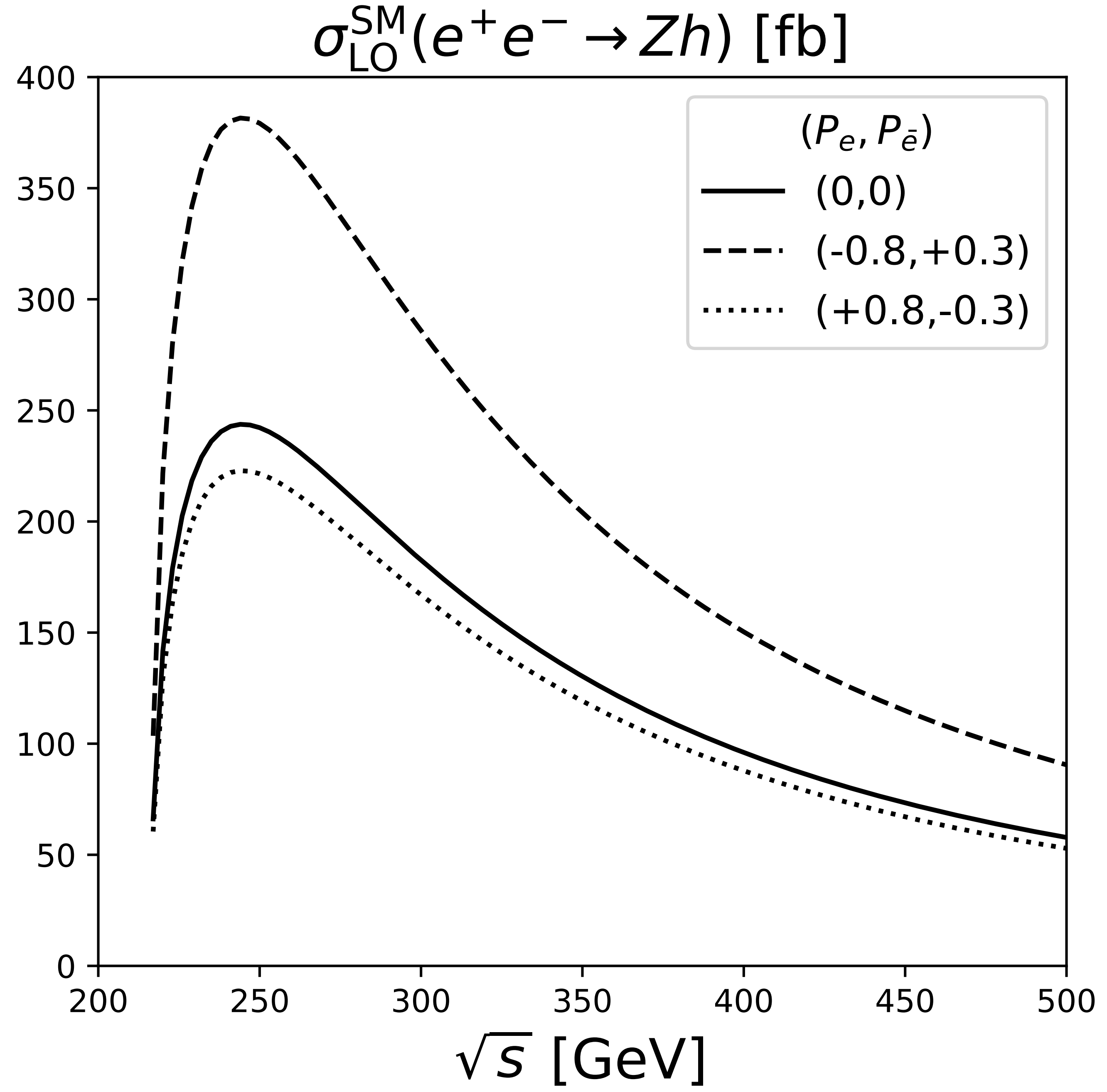
In-state $(\sigma_e, \sigma_{\bar{e}})$: $(-,+), (+,-)$, ~~$(-,-)$~~, ~~$(+,+)$~~ $m_e/v \to 0$

Out-state : $\lambda = (+,-,0)$

Six helicity amplitude : $\mathcal{M}_{\sigma\lambda}(s,t) \quad (\sigma = \sigma_e = -\sigma_{\bar{e}})$

At the ILC : $(P_e, P_{\bar{e}}) = (\mp 0.8, \pm 0.3)$





Previous works

SM

NLO EW : J. Fleischer, F. Jegerlehner, NPB216 (1983); B. Kniehl ZPC55 (1992); A. Denner et al. ZPC56 (1992); G. Belanger et al, PR430 (2006)

Mixed EW-QCD : Y. Gong et al. PRD95 (2017), Q. Sun et al. PRD96 (2017)

NNLO EW : Z. Li et al. hep-ph 2012.12513

MSSM

NLO EW : P. Chankowski et al. NPB423 (1994); V. Driesen, W. Hollik, ZPC68 (1995); V. Driesen et al. ZPC71 (1996) S. Heinemeyer et al. EPJ C19 (2001)

2HDM

NLO EW : D. Lopez-Val et al. PRD81 (2010); W. Xie et al. PRD103 (2021)

IDM

NLO EW : H. Abouabid et al. JHEP 05 (2021)

This work {
- Extension of model space (HSM)
- Same scheme in the H-COUP
- Helicity-dependent cross section

Higher-order calculation

From-factor decomposition

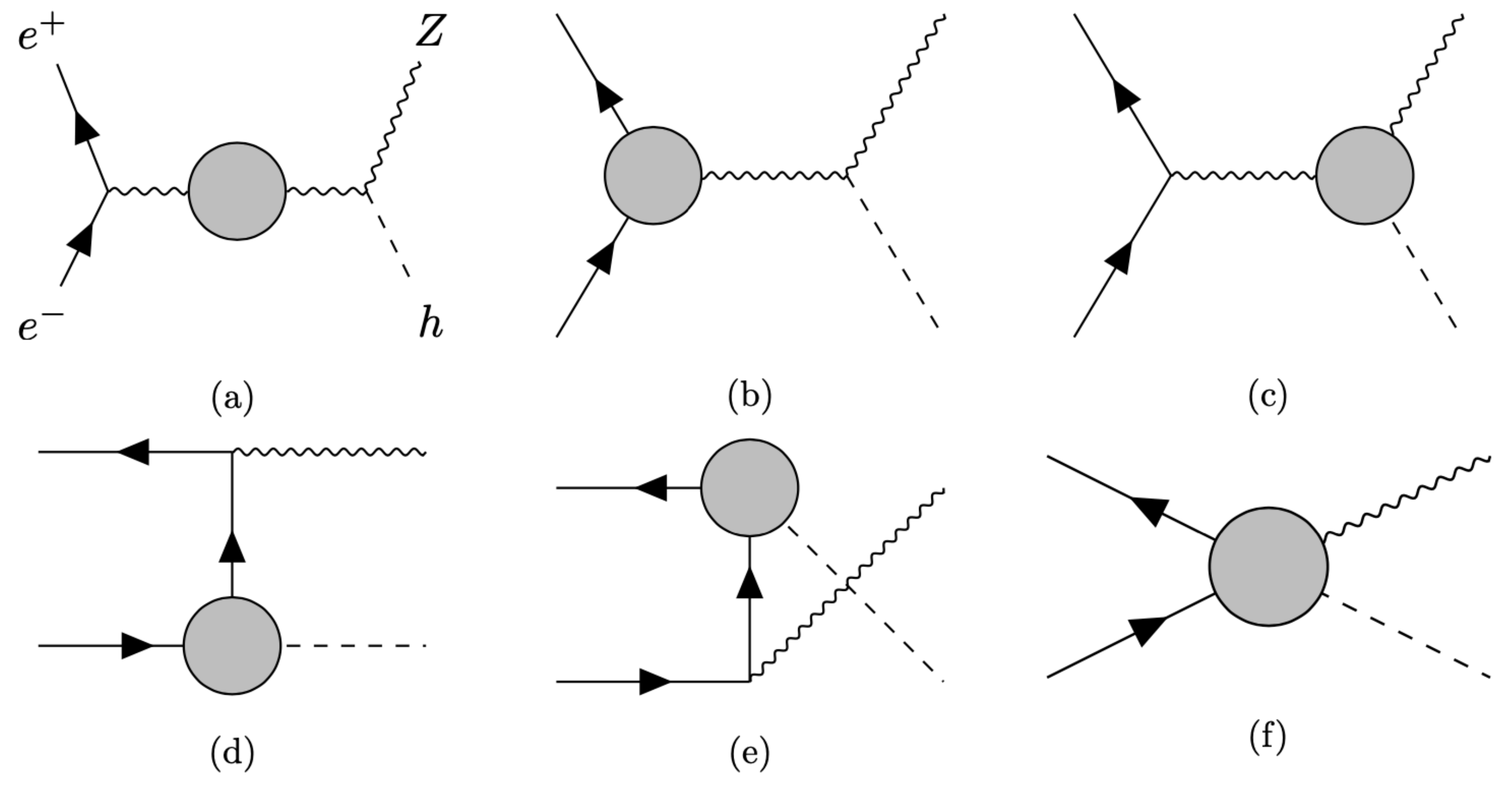
Helicity amplitude can be decomposed as

$$\mathcal{M}_{\sigma\lambda}(s,t) = \sum_{i=1}^{3} F_{i,\sigma}(s,t)\mathcal{M}_{i,\sigma\lambda}(s,t), \quad \mathcal{M}_{i,\sigma\lambda} = j_{\sigma,\mu}(p_e, p_{\bar{e}})T_i^{\mu\nu}(s,t)\varepsilon_\nu^*(k_Z,\lambda)$$

$$T_1^{\mu\nu} = g^{\mu\nu}$$
$$T_2^{\mu\nu} = k_Z^\mu (p_e + p_{\bar{e}})^\nu$$
$$T_3^{\mu\nu} = k_Z^\mu (p_e - p_{\bar{e}})^\nu$$

Renormalized quantities

$$F_{i,\sigma}^{(1)} = F_{i,\sigma}^{ZZ} + F_{i,\sigma}^{Z\gamma} + F_{i,\sigma}^{Ze\bar{e}} + F_{i,\sigma}^{hZZ} + F_{i,\sigma}^{hZ\gamma} + F_{i,\sigma}^{he\bar{e}} + F_{i,\sigma}^{\mathrm{Box}} + F_{i,\sigma}^{\Pi'_{ZZ}} + F_{i,\sigma}^{\Delta r}$$



UV divergence: improved on-shell scheme

Gauge dependencies are removed by utilizing the pinch technique

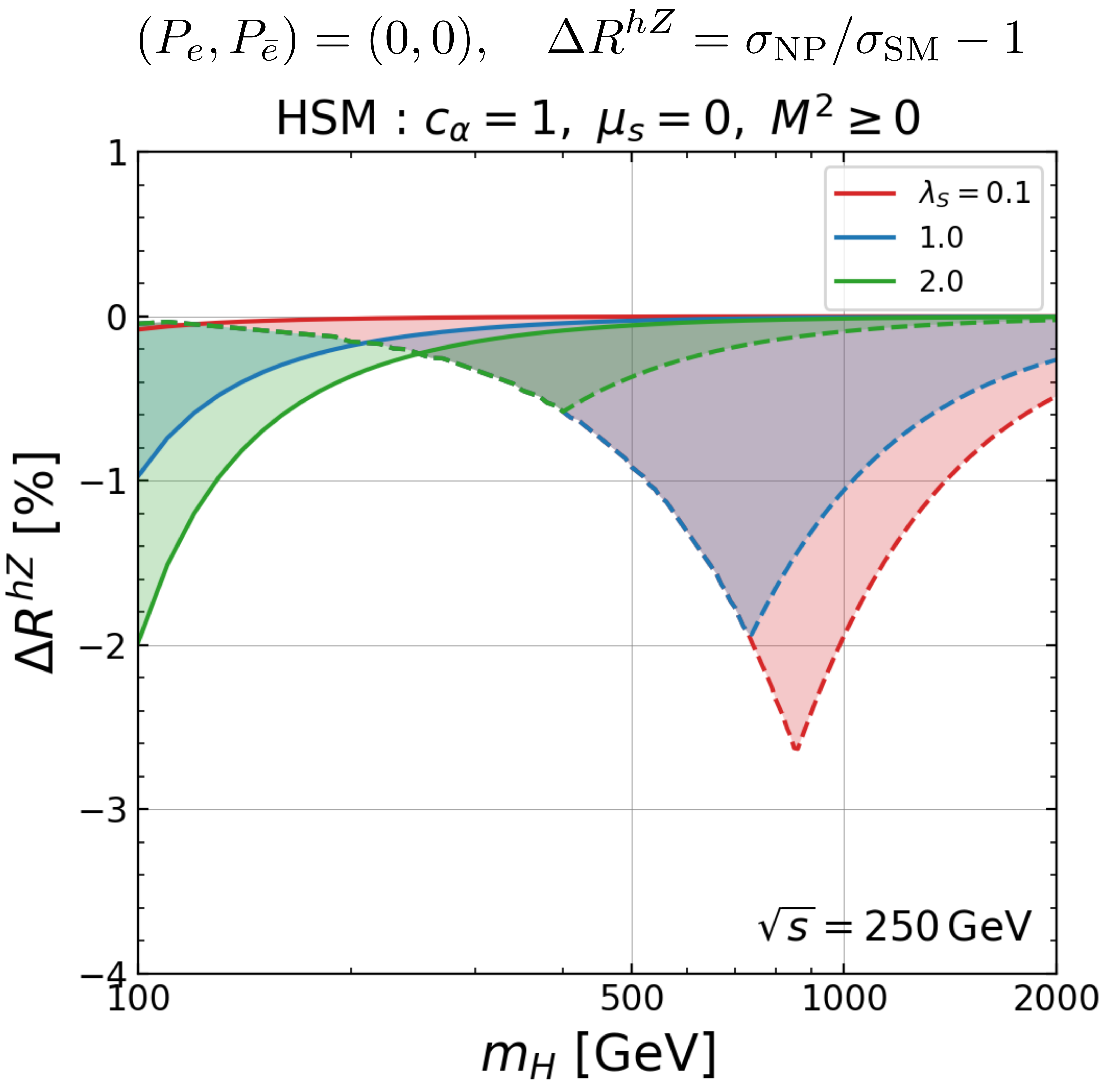
S. Kanemura, M. Kikuchi, K. Sakurai, K. Yagyu, PRD96 (2017)

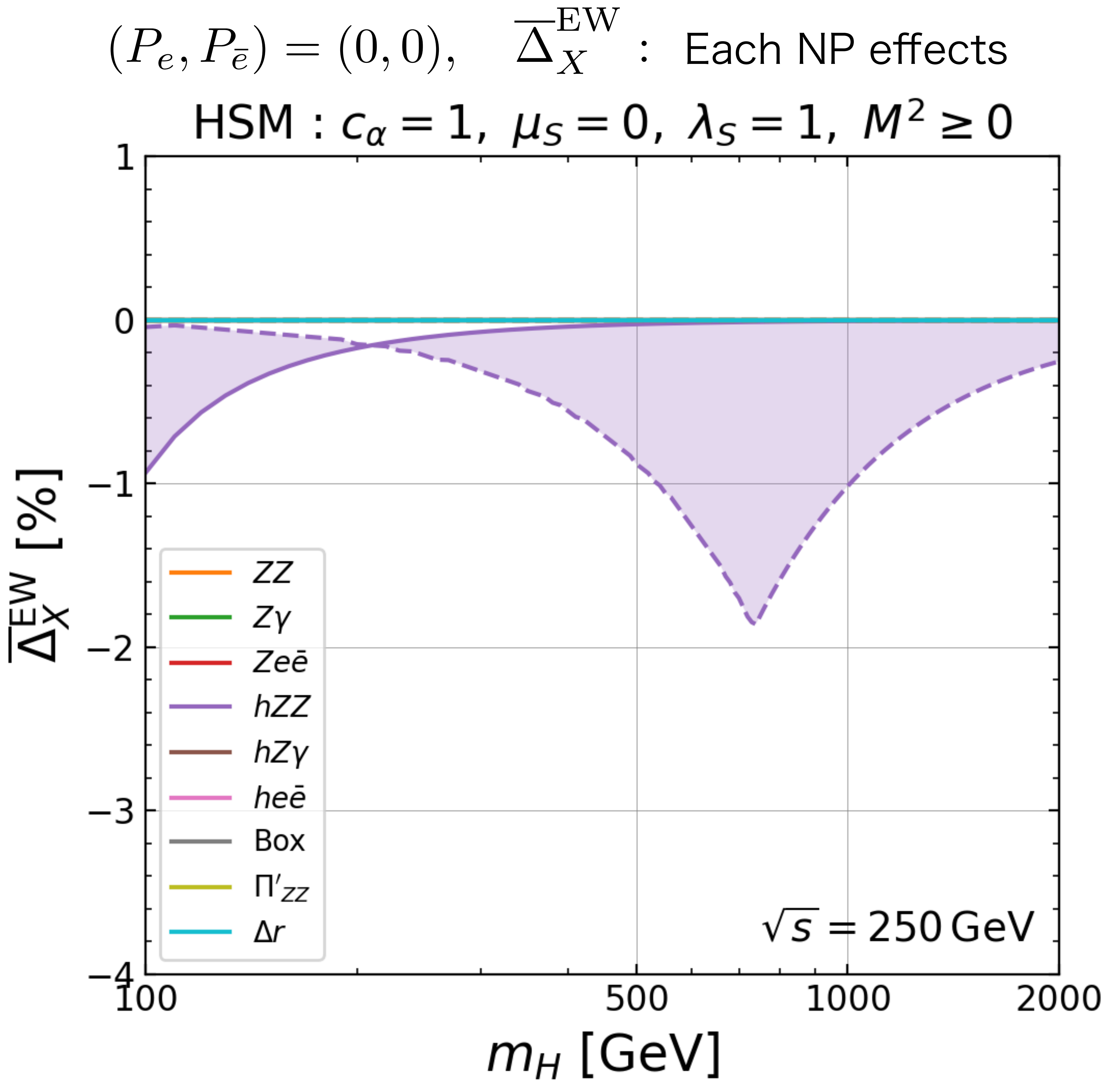
IR divergence: regularized by finite photon mass, and photon mass dependence is removed by adding a real photon emission.

B. Kniehl ZPC55 (1992); A. Denner et al. ZPC56 (1992)

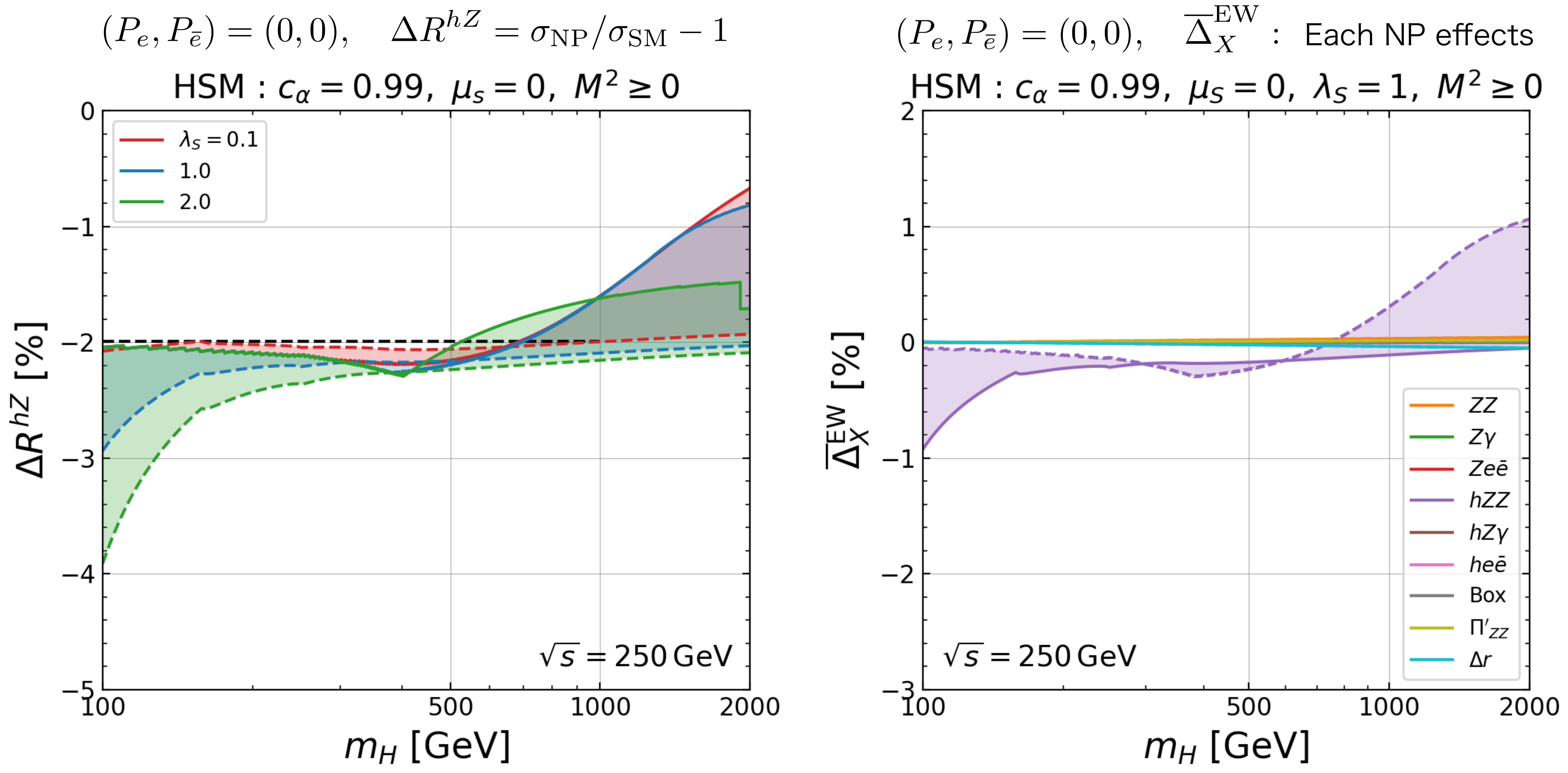
We have performed the systematic calculation based on the scheme in H-COUP.

HSM with $c_\alpha = 1$



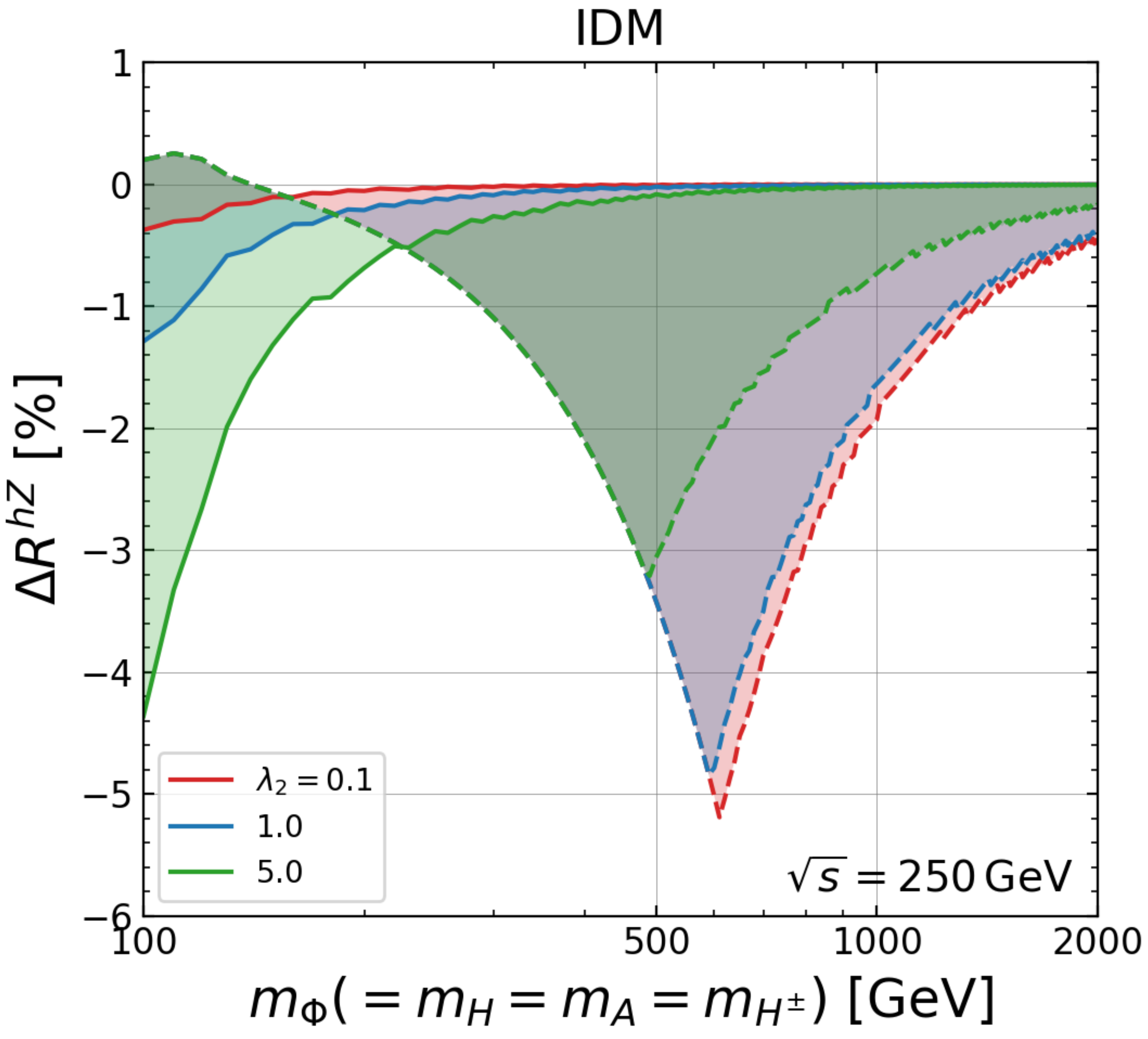


HSM with $c_\alpha \neq 1$



IDM

$(P_e, P_{\bar{e}}) = (0,0), \quad \Delta R^{hZ} = \sigma_{\rm NP}/\sigma_{\rm SM} - 1$



$(P_e, P_{\bar{e}}) = (0,0), \quad \overline{\Delta}_X^{\rm EW}$: Each NP effects