BSM Higgs production $e^+e^- \to Z\phi$ at CEPC theory status

Based on EPJC81 11 (2021) [arXiv:2109.02884]

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CEPC Workshop 2022 (2022/10/24 Online)

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

- Direct searches of BSM Higgs bosons
- Indirect searches through precision measurements of SM-like Higgs boson

Extended Higgs models

Electroweak rho parameter

PDG2020

Representation of Higgs fields that relates to the EW symmetry breaking is constrained by $\rho \simeq 1$

$$\rho_{\rm tree} \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i v_i^2 \left[I_i(I_i+1) - Y_i^2 \right]}{2\sum_i v_i^2 Y_i^2}$$

Extended Higgs models with $\rho_{\rm tree} = 1$

- Higgs singlet model: doublet Φ + singlet S
- Two-Higgs doublet model (2HDM): two doublet Φ_1, Φ_2
- Higgs-septet model: doublet + septet ($I_i = 3,\ Y_i = 2$) — Hisano, Tsumura PRD87 (2013), Kanemura, Kikuchi, Yagyu PRD88 (2013)
- Georgi-Machacek model: doublet + real and complex triplet — Georgi and Machacek NPB262 (1985)

In this talk, we study 2HDM as a representative

Two-Higgs doublet model

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

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

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

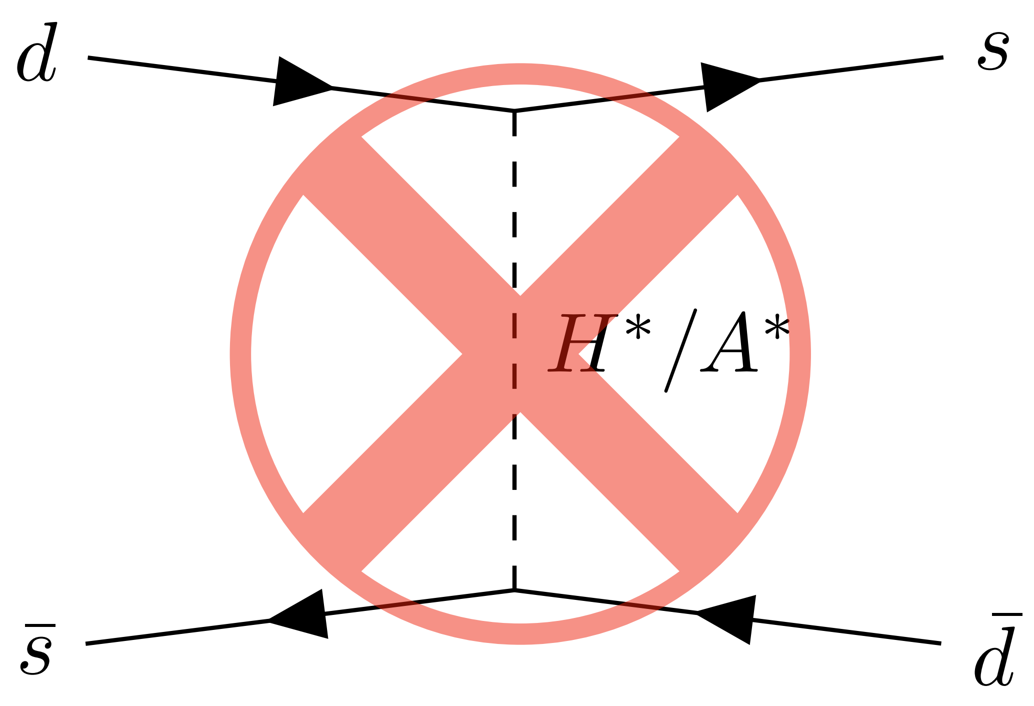
$$v^2 = v_1^2 + v_2^2,\ \tan\beta = v_2/v_1$$

Scalar particles

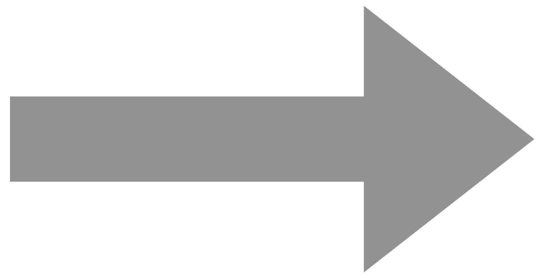
h, H (CP-even), A (CP-odd), $H^\pm$ (Singly charged)

Discrete symmetry

Softly broken Z_2 symmetry suppresses tree-level flavor changing neutral currents.



Glashow, Weinberg, PRD15 (1977)
Paschos, PRD15 (1966)



	Φ_1	Φ_2	Q	L	u_R	d_R	e_R
Type-I	+	-	+	+	-	-	-
Type-II	+	-	+	+	-	+	+
Type-X	+	-	+	+	-	-	+
Type-Y	+	-	+	+	-	+	-

Four types of the Yukawa interactions

Barger et al. PRD41 (1990), Aoki et al. PRD80 (2009)

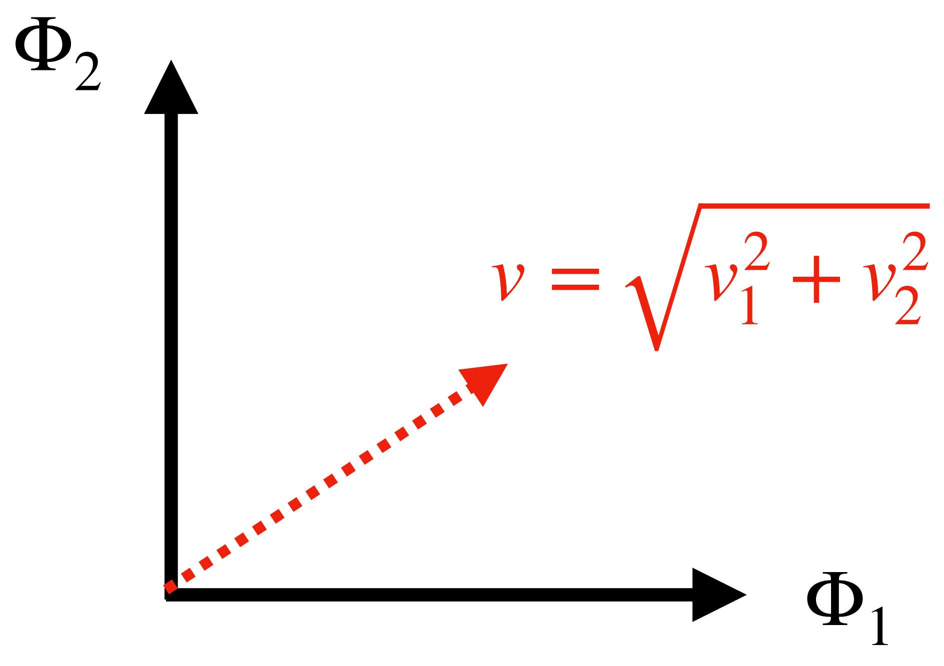
Higgs couplings in 2HDM

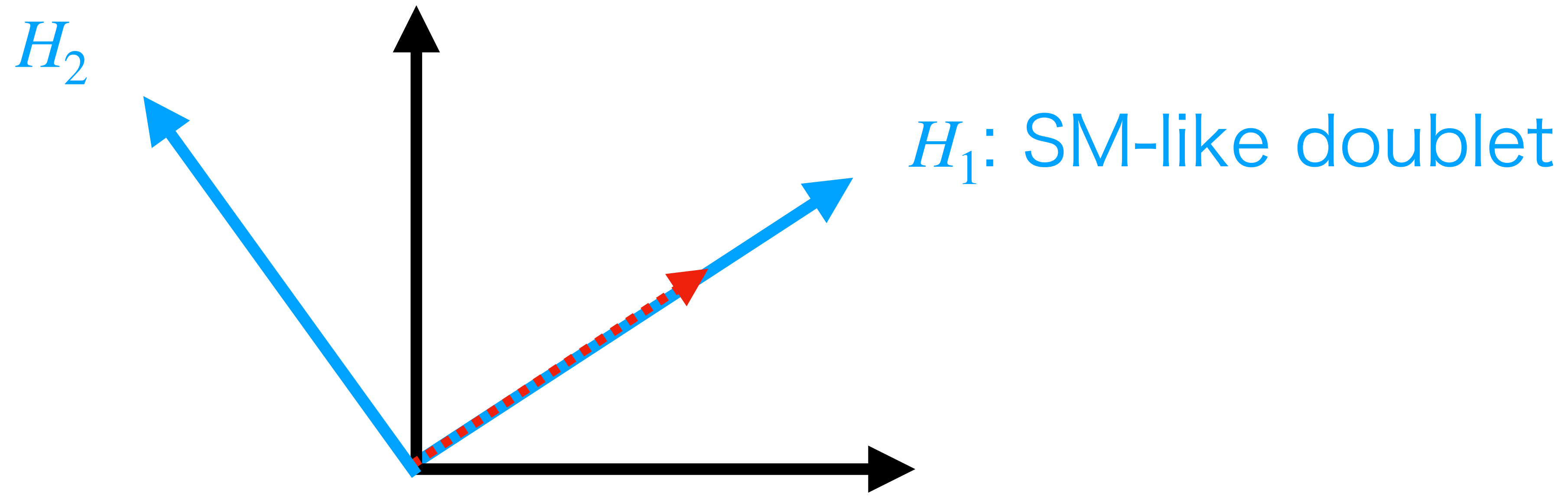
Higgs basis

Davidson, Haber, PRD72 (2005)

H_1 only obtains the vacuum expectation value.

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}, \quad \tan\beta = \frac{v_1}{v_2}$$





In the Higgs basis, the charged and CP-odd states are mass eigenstates, while the CP-even scalars are not mass eigenstates in general.

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + iA) \end{pmatrix}, \quad \mathcal{M}^2_{\rm even} = \begin{pmatrix} \mathcal{M}^2_{11} & \mathcal{M}^2_{12} \\ \mathcal{M}^2_{12} & \mathcal{M}^2_{22} \end{pmatrix}$$

Higgs couplings in 2HDM

Sum rule on the Higgs-gauge couplings

The two CP-even scalars are mixed.

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & s_{\beta-\alpha} \\ -s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}, \quad m_h \leq m_H$$

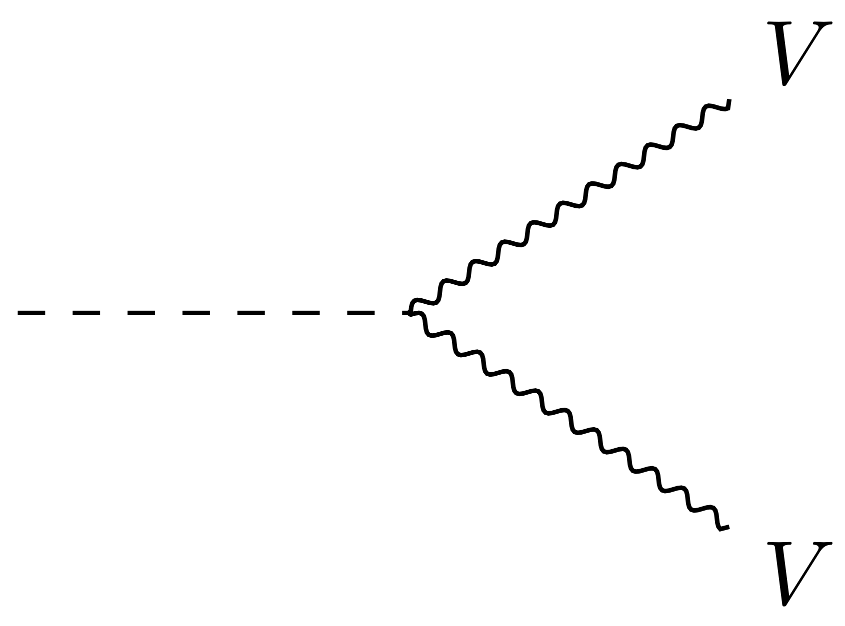
There are two distinct scenario

- Scenario-I : h is the SM-like Higgs boson
- Scenario-II : H is the SM-like Higgs boson

J. Bernon et al. PRD93 (2016)

SM-like Higgs boson's couplings are modified from the SM values.

$$\begin{pmatrix} H \\ h \end{pmatrix}$$



$$= g_{hVV}^{\rm SM} \begin{pmatrix} c_{\beta-\alpha} \\ s_{\beta-\alpha} \end{pmatrix} g^{\mu\nu}, \quad \sum_i g_{h_iVV}^2 = (g_{hVV}^{\rm SM})^2 = \frac{m_V^2}{v^2}$$

Higgs couplings in 2HDM

Higgs signal measurement

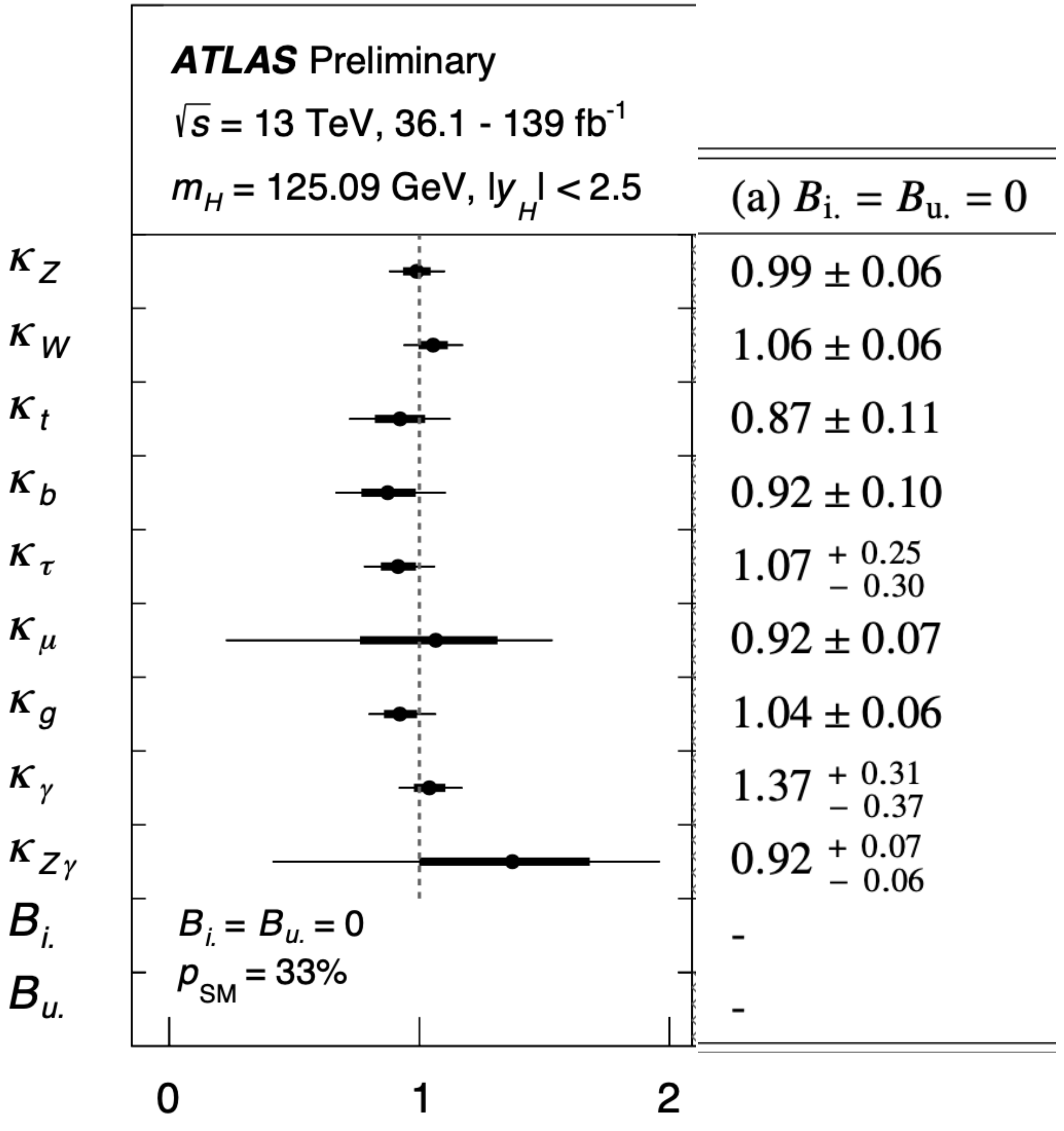
New physics effects are parametrized by scaling factors κ_i.

$$g_{h_i VV} = \kappa_V^{h_i} \frac{m_V}{v}, \quad g_{h_i ff} = \kappa_f^{h_i} \frac{m_f}{v}$$

At LO in the 2HDM,

$$\kappa_V^h = s_{\beta-\alpha}, \quad \kappa_f^h = s_{\beta-\alpha} - \zeta_f c_{\beta-\alpha}$$
$$\kappa_V^H = c_{\beta-\alpha}, \quad \kappa_f^H = c_{\beta-\alpha} + \zeta_f s_{\beta-\alpha}$$

Higgs signal measurements favor Higgs alignment scenario with $s_{\beta-\alpha} = 1$ or $c_{\beta-\alpha} = 1$



ATLAS-CONF-2021-053

Higgs alignment in Scenario-I

Higgs alignment

$$\tan 2(\beta-\alpha) = \frac{-2\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2-\mathcal{M}_{22}^2} \simeq 0, \quad \mathcal{M}_{\rm even}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

Alignment w/ decoupling

$$\mathcal{M}_{11}^2 = f(\lambda_i)v^2, \quad \mathcal{M}_{12}^2 = g(\lambda_i)v^2, \quad \mathcal{M}_{22}^2 = M^2 + h(\lambda_i)v^2, \quad M^2 = m_{12}^2/(s_\beta c_\beta)$$

The size of the numerator is constrained by perturbative unitarity. Lee, Quigg, Thacker PRD16 (1977)

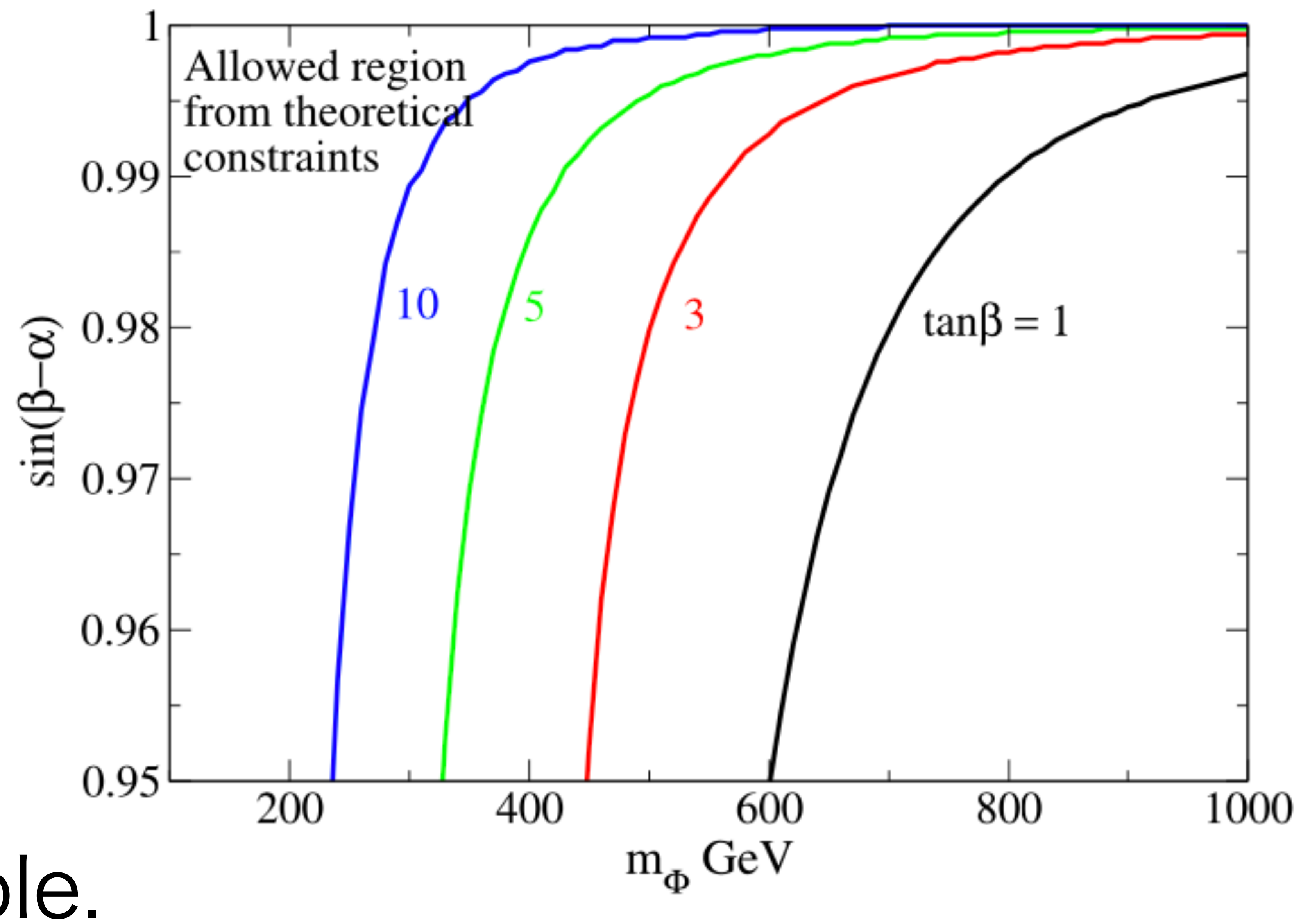
When $M^2 \to \infty$, $\tan 2(\beta-\alpha) \to 0$. Gunion, Haber PRD67 (2003)

Additional Higgs bosons decouple from EW scale

$$m_\Phi^2 = M^2 + f_\Phi(\lambda_i)v^2 \to \infty$$

Appelquist, Carazzone PRD11 (1975)

If $\tan 2(\beta-\alpha) \neq 0$, additional Higgs bosons cannot decouple.



Kanemura, Kikuchi, Yagyu NPB896 (2015)

Higgs alignment in Scenario-I

Higgs alignment

$$\tan 2(\beta-\alpha) = \frac{-2\mathcal{M}^2_{12}}{\mathcal{M}^2_{11}-\mathcal{M}^2_{22}} \simeq 0, \quad \mathcal{M}^2_{\rm even} = \begin{pmatrix} \mathcal{M}^2_{11} & \mathcal{M}^2_{12} \\ \mathcal{M}^2_{12} & \mathcal{M}^2_{22} \end{pmatrix}$$

Alignment w/o decoupling

$$\mathcal{M}^2_{11} = f(\lambda_i)v^2, \quad \mathcal{M}^2_{12} = g(\lambda_i)v^2, \quad \mathcal{M}^2_{22} = M^2 + h(\lambda_i)v^2, \quad M^2 = m^2_{12}/(s_\beta c_\beta)$$

$g(\lambda_i)$ can be zero so that $\tan 2(\beta-\alpha) \to 0$

$$g(\lambda_i) = -\frac{1}{2}\left(\lambda_1 c^2_\beta - \lambda_2 s^2_\beta - \lambda_{345} c_{2\beta}\right) s_{2\beta} \to 0, \quad \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

The additional Higgs bosons remain on the EW scale, $m^2_\Phi = M^2 + f_\Phi(\lambda_i)v^2$

Alignment w/o decoupling is a favorable scenario for BSM problems.

e.g. Electroweak baryogenesis, Muon g-2, CDF anomaly on m_W

Higgs alignment in Scenario-II

Higgs alignment

$$\tan 2(\beta-\alpha) = \frac{-2\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2} \simeq 0, \quad \mathcal{M}_{\rm even}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

Alignment w/o decoupling

$$\mathcal{M}_{11}^2 = f(\lambda_i)v^2, \quad \mathcal{M}_{12}^2 = g(\lambda_i)v^2, \quad \mathcal{M}_{22}^2 = M^2 + h(\lambda_i)v^2, \quad M^2 = m_{12}^2/(s_\beta c_\beta)$$

$g(\lambda_i)$ can be zero so that $\tan 2(\beta-\alpha) \to 0$

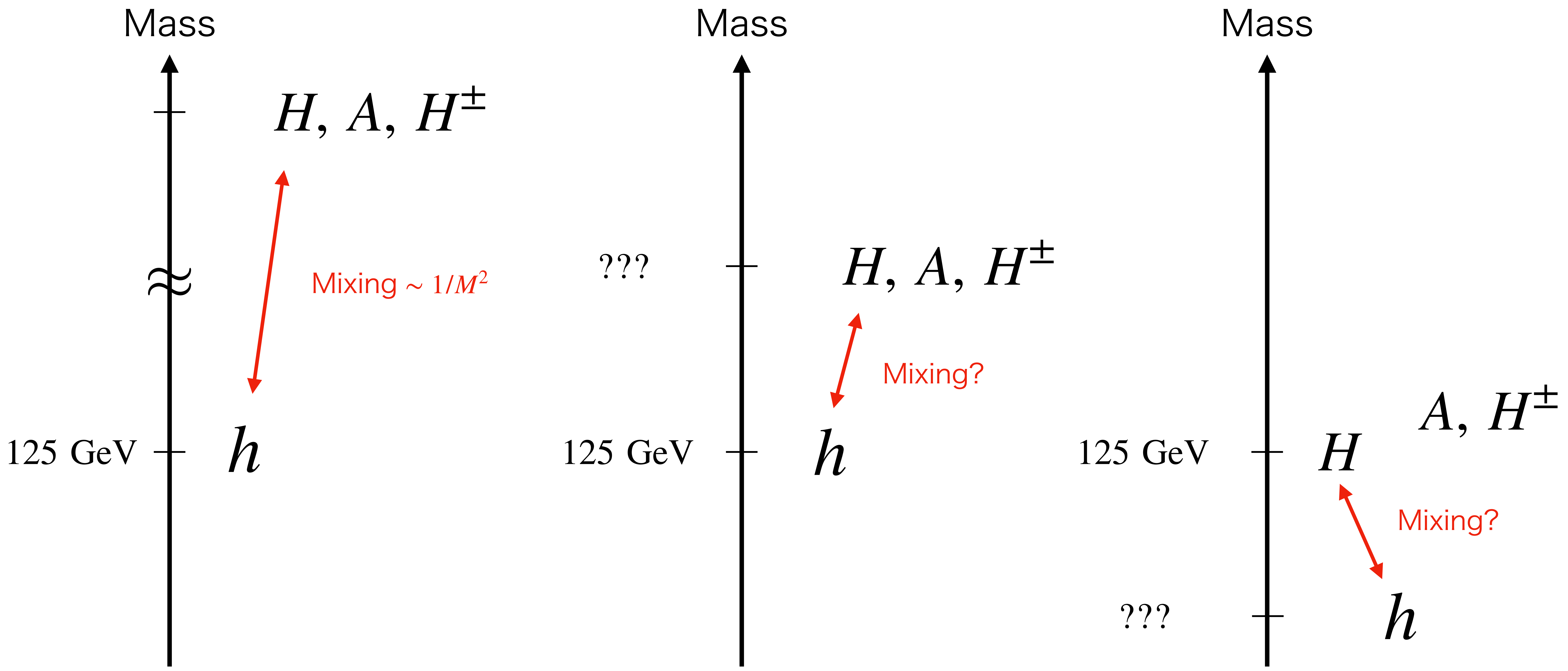
$$g(\lambda_i) = -\frac{1}{2}\left(\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}\right) s_{2\beta} \to 0, \quad \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

Since $m_h \leq m_H$, we cannot take decoupling limit.

$$m_h^2 = M^2 + f_h(\lambda_i)v^2 \quad \text{with} \quad c_{\beta-\alpha} = 1$$

The additional Higgs bosons remain at the EW scale, $m_\Phi^2 = M^2 + f_\Phi(\lambda_i)v^2$

Scenarios in 2HDM



If deviations in the Higgs couplings are measured, the mass scale of the additional Higgs bosons can be deduced.

Higgs strahlung process

Higgs strahlung process is the main target at future lepton colliders (CEPC, ILC, FCC-ee)

- $\sigma(e^+e^- \to hZ)$ takes a maximal value at $\sqrt{s} = 240 - 250$ GeV.
- $\sigma(e^+e^- \to hZ)$ can be measured by using the recoil mass technique. J. Yan et al. PRD94 (2016)

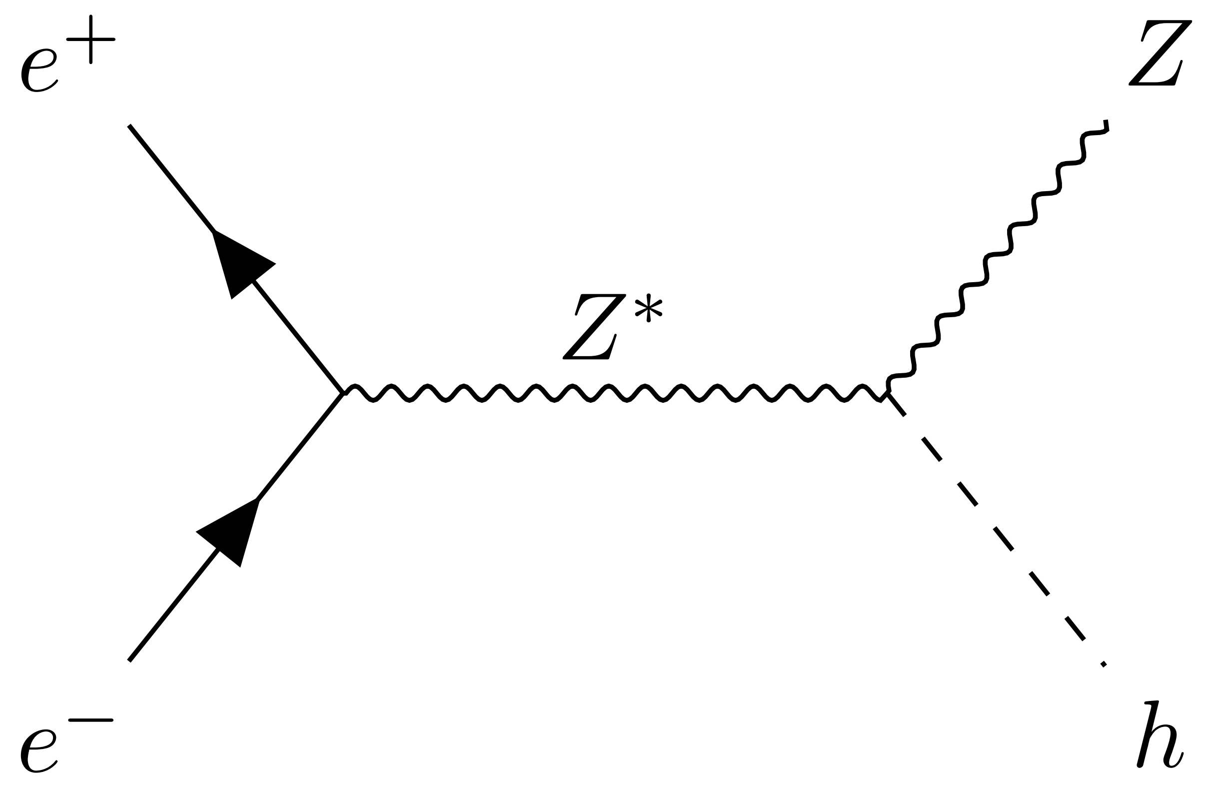
  Z boson energy : $E_Z = (s + m_Z^2 - m_h^2)/(2\sqrt{s})$

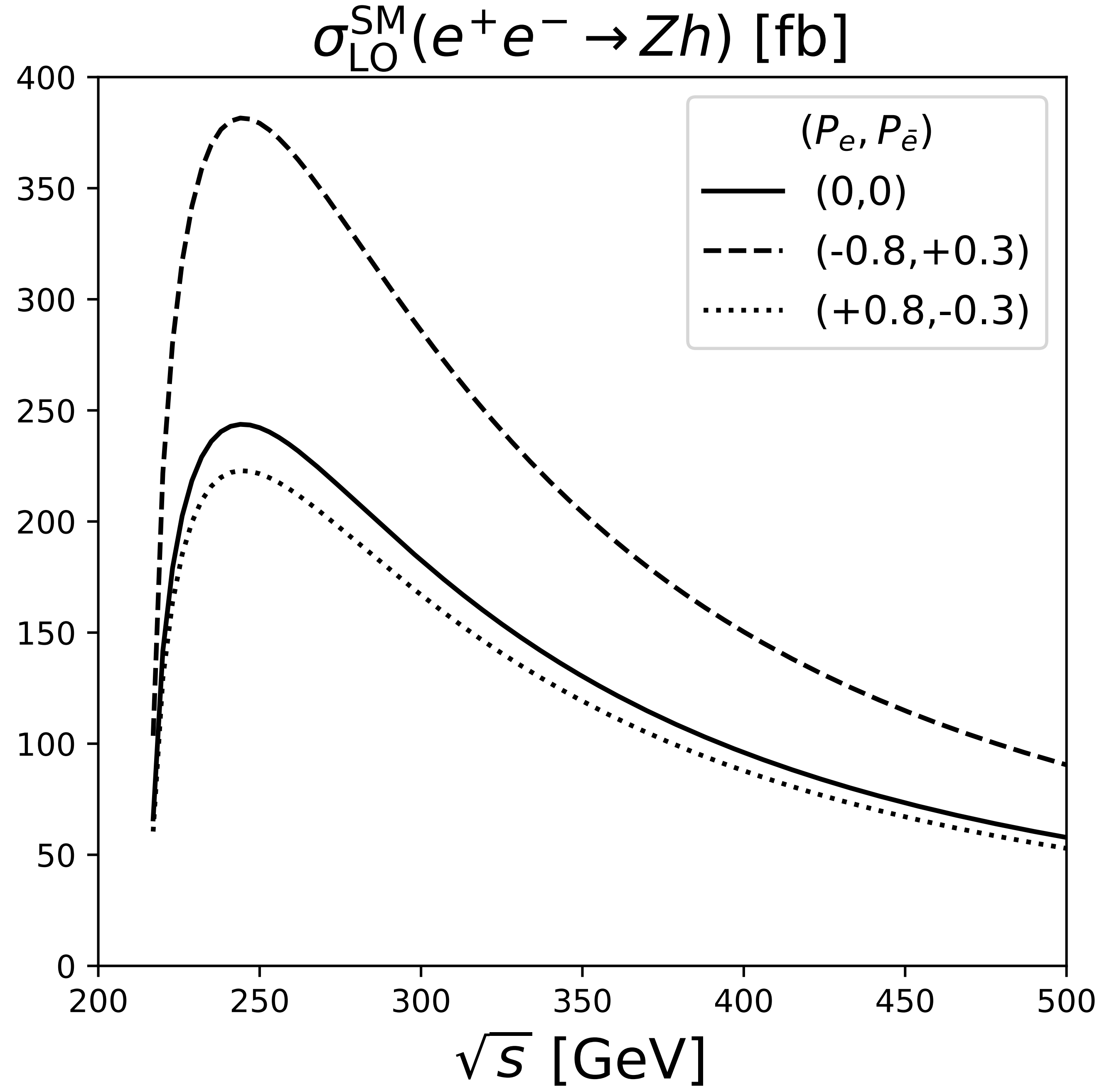
We can directly access the g_{hZZ} coupling

$\sigma(e^+e^- \to HZ)$ is suppressed by $c_{\beta-\alpha}^2$ due to the sum rule.

$$g_{HVV} = \frac{m_V}{v} c_{\beta-\alpha} \simeq 0$$

*) In Scenario-II, $h \leftrightarrow H$ and $c_{\beta-\alpha} \leftrightarrow s_{\beta-\alpha}$



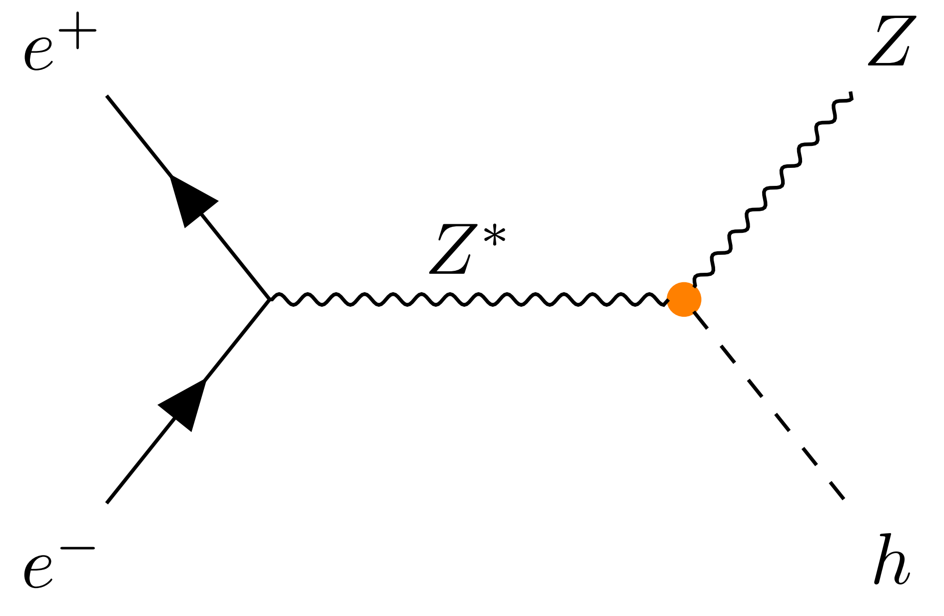


Higher-order calculation

LO

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

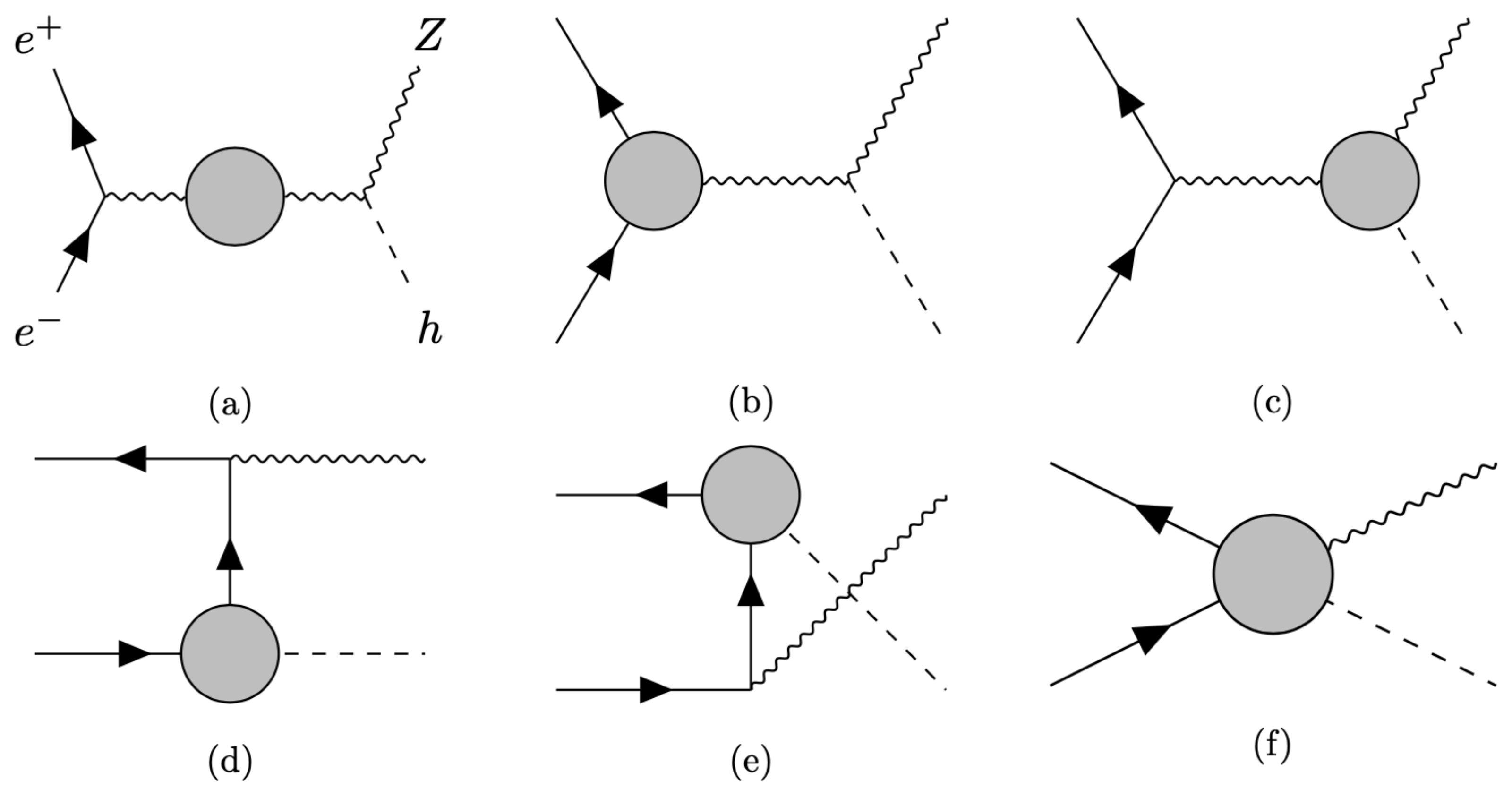
- LHC data indicate a SM-like scenario $s_{\beta-\alpha} \approx 1$.



NLO

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

Each size of correction is comparable.



Experimental accuracy

$\Delta\sigma(e^+e^- \to hZ) = 0.26\,\%$ at CEPC 240 GeV, 20 ab^{-1} Snowmass: 2205.08553 (2022)

Higher-order calculations are essentially important.

Higher-order calculation

From-factor decomposition

A. Denner et al. ZPC56 (1992)
Aiko, Kanemura, Mawatari, EPJC81 (2021)

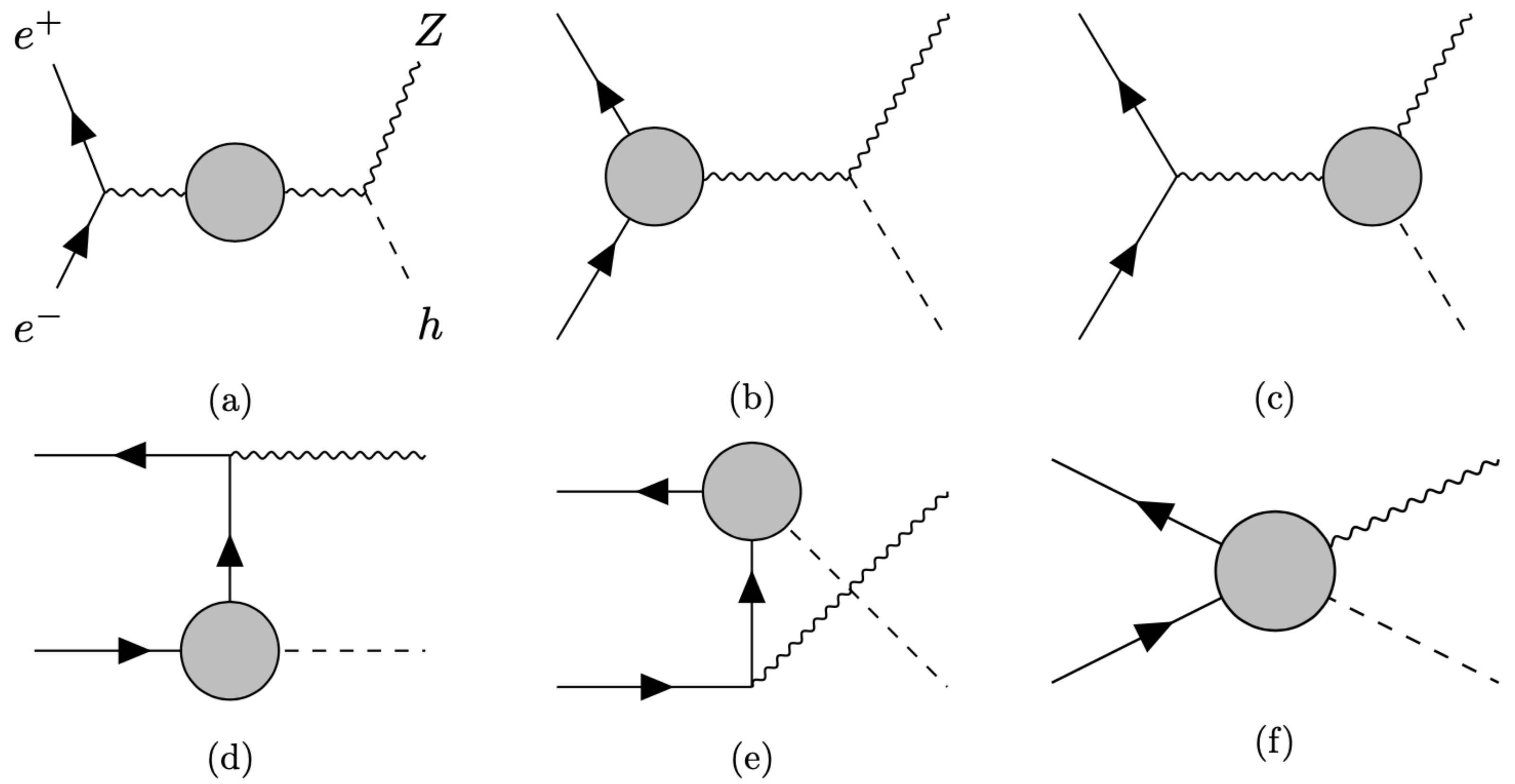
Helicity amplitude can be decomposed as

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

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

Renormalized quantities

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

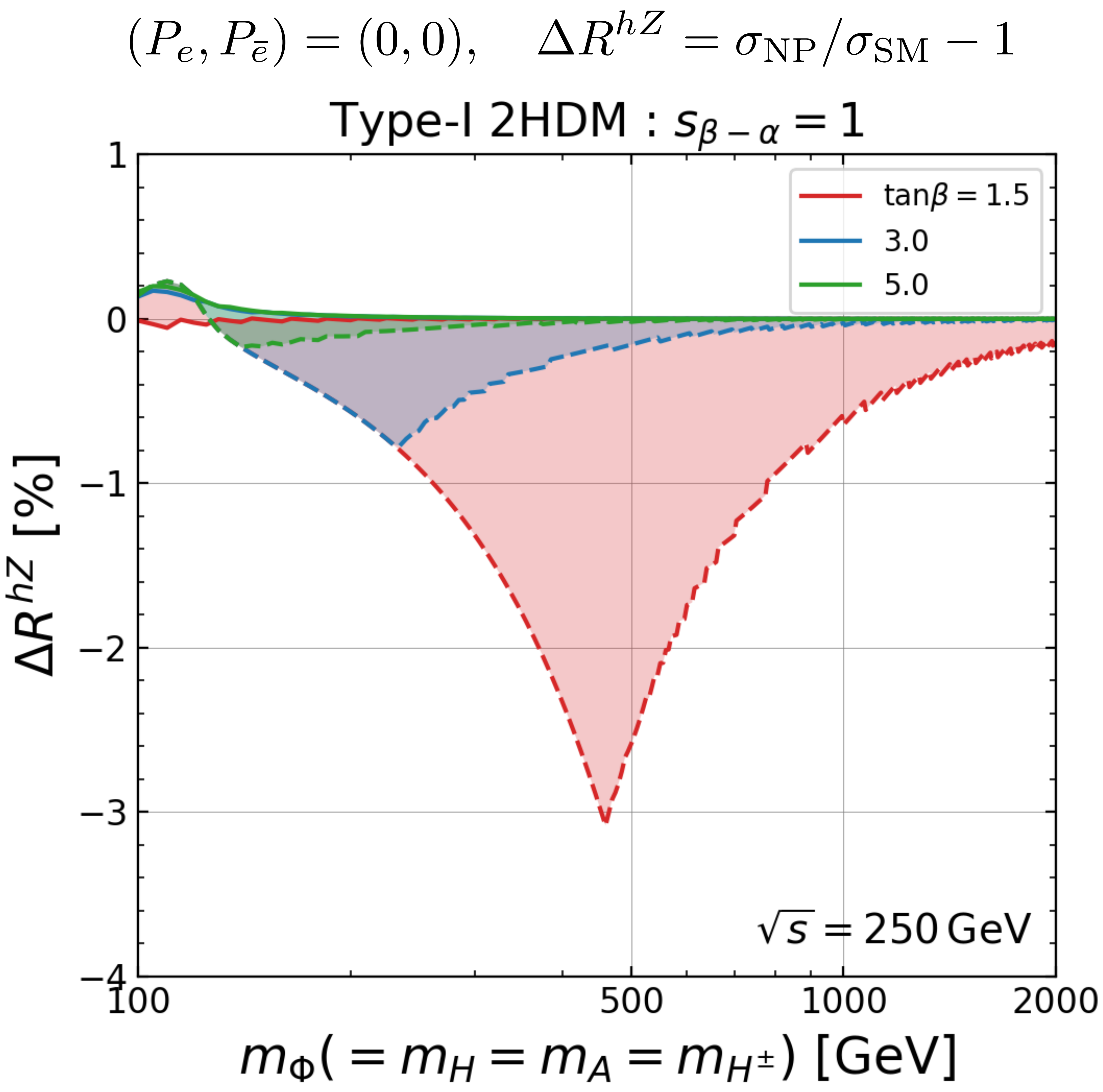


UV divergence: improved on-shell scheme Kanemura, Kikuchi, Sakurai, Yagyu, PRD96 (2017)

Gauge dependencies are removed by utilizing the pinch technique

IR divergence: regularized by finite photon mass, and photon mass dependence is removed by adding a real photon emission. Kniehl ZPC55 (1992); Denner et al. ZPC56 (1992)

Scenario-I with $s_{\beta-\alpha} = 1$



Aiko, Kanemura, Mawatari, EPJC81 (2021)

LO
- No deviation

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

We find almost no difference among all Types.

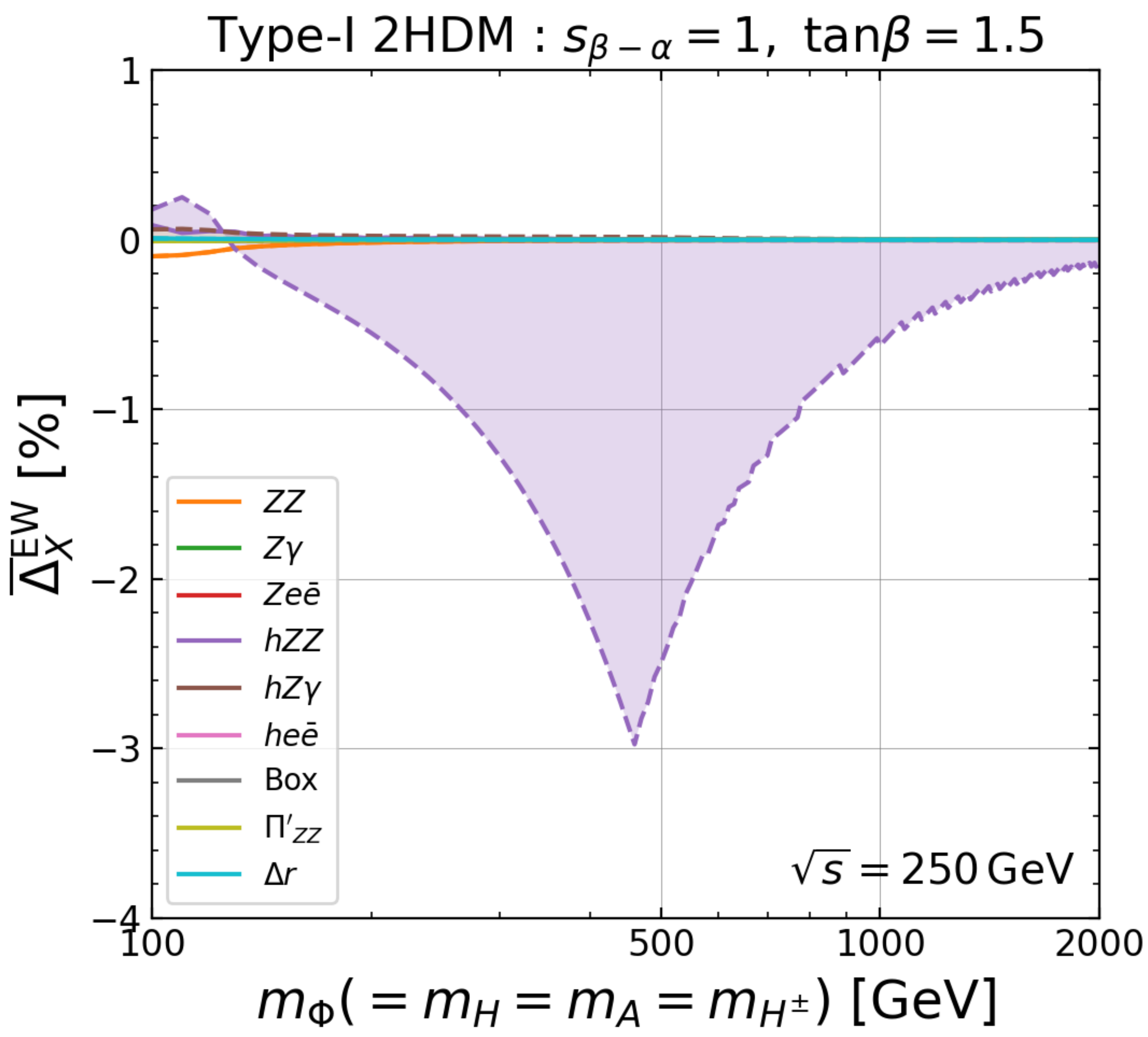
Results
- A few percent deviations
- Decoupling

T. Appelquist, J. Carazzone PRD11 (1975)

- The hZZ vertex gives a dominant contribution

Scenario-I with $s_{\beta-\alpha} = 1$

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



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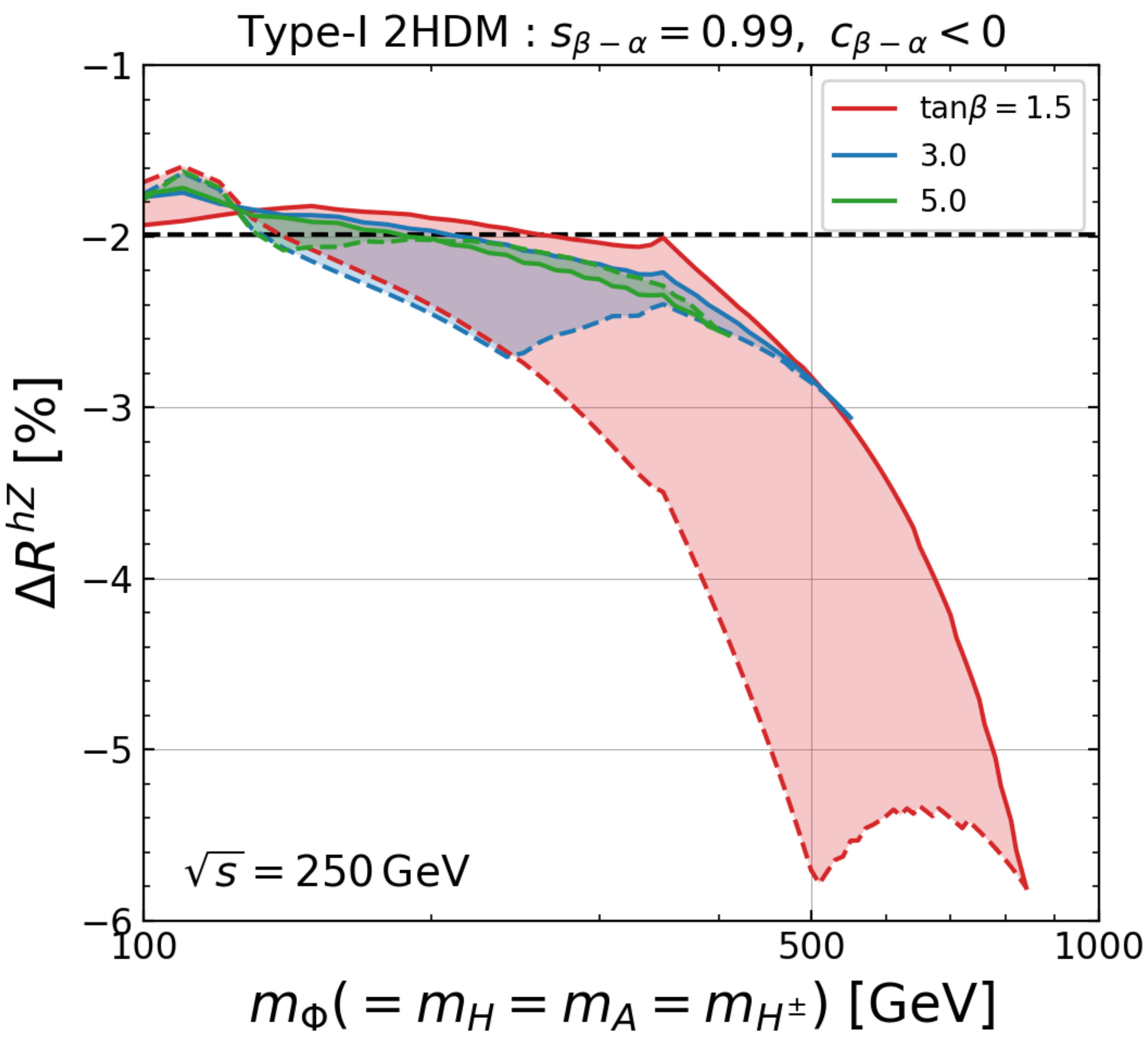
Scenario-I with $s_{\beta-\alpha} \neq 1$

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



Aiko, Kanemura, Mawatari, EPJC81 (2021)

LO

- 2% deviation

Constraints

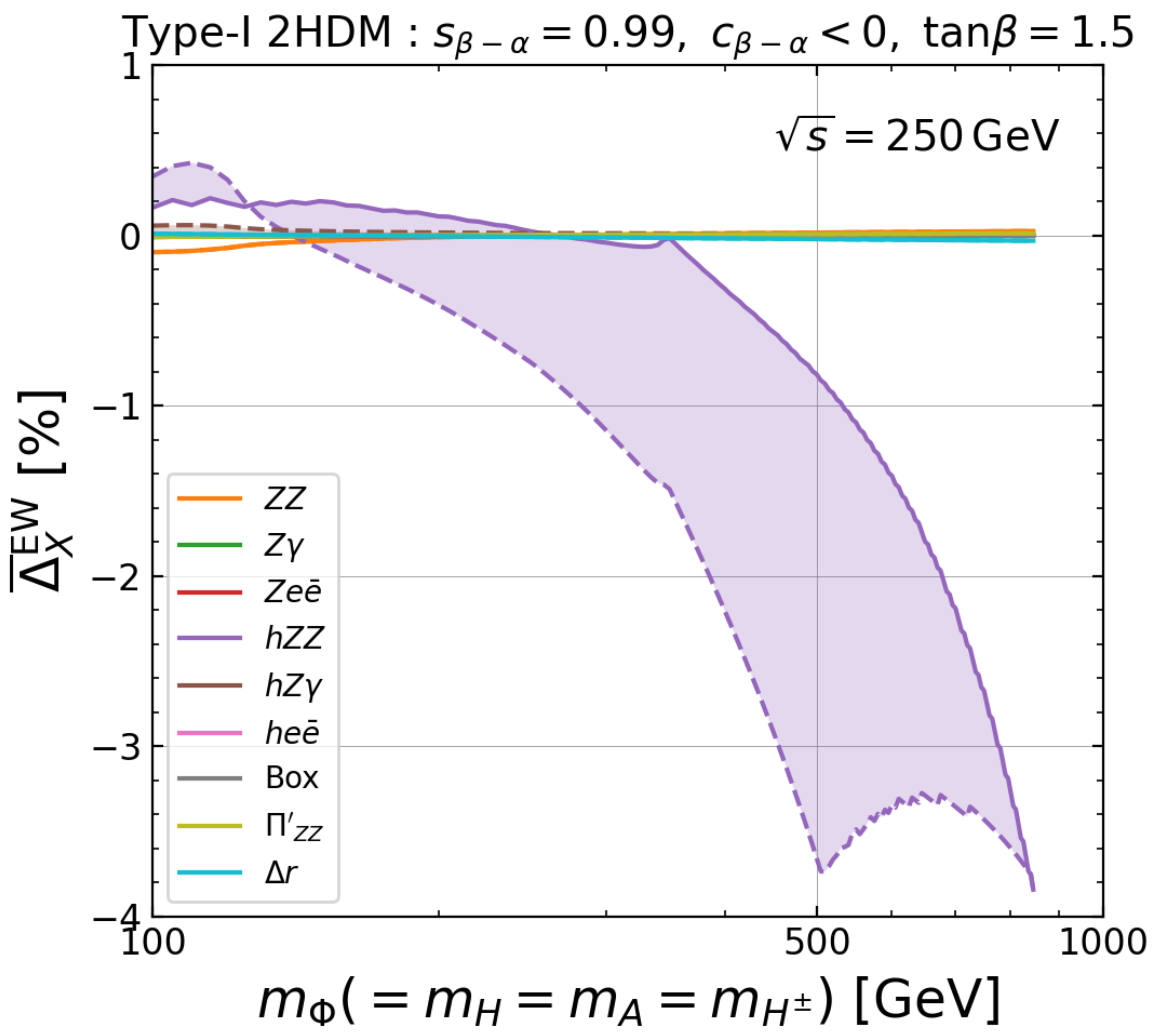
- Vacuum stability
- Perturbative unitarity
- S and T parameter

Results

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

Scenario-I with $s_{\beta-\alpha} \neq 1$

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



Aiko, Kanemura, Mawatari, EPJC81 (2021)

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- 2% deviation

Constraints

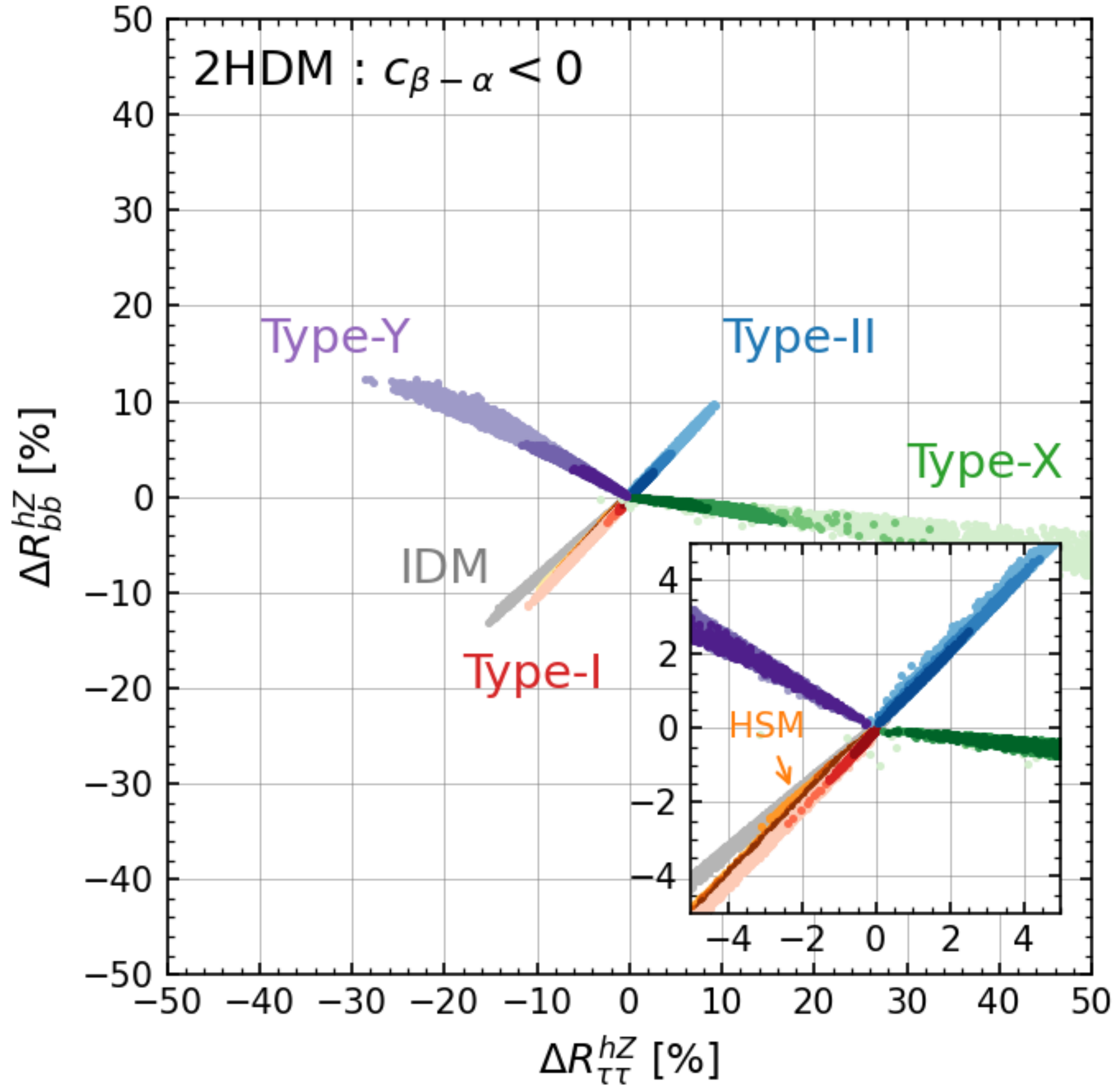
- Vacuum stability
- Perturbative unitarity
- S and T parameter

Results

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

Correlation in Scenario-I : $\Delta R^{hZ}_{\tau\tau}$ vs. ΔR^{hZ}_{bb}

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



Aiko, Kanemura, Mawatari, EPJC81 (2021)

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

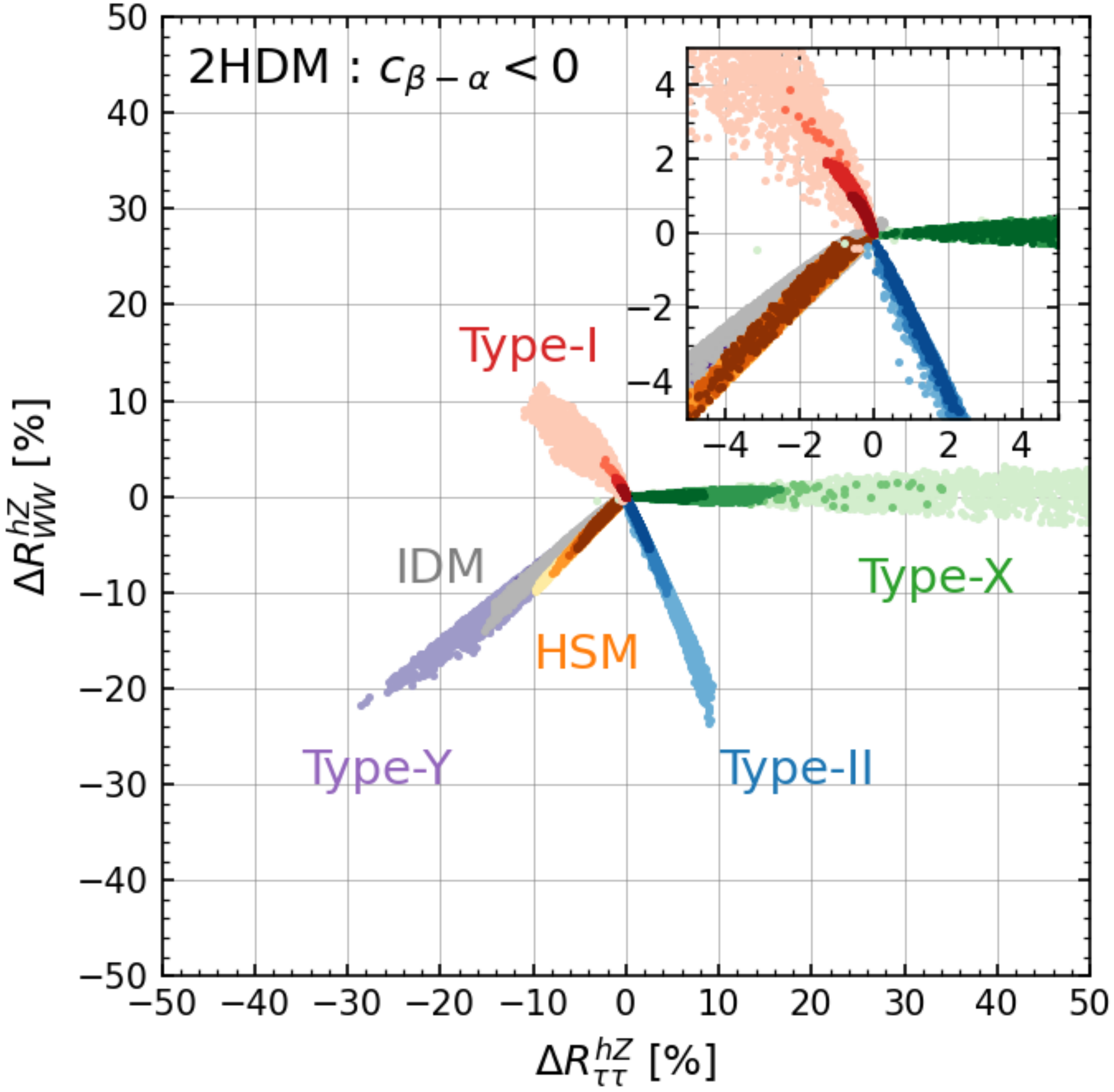
2205.08553

$\Delta R^{hZ}_{bb} = 0.28\ \%$, $\Delta R^{hZ}_{\tau\tau} = 0.84\ \%$ at $2\ \sigma$

Sizable deviations to detect at the CEPC.

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

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



Aiko, Kanemura, Mawatari, EPJC81 (2021)

Results

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

Experimental accuracy

2205.08553

$\Delta R^{hZ}_{WW} = 1.06$ % at $2\,\sigma$

If $m_\Phi \lesssim 1$ TeV, deviations can be detected at the CEPC.

Further discrimination

$h \to \gamma\gamma$ might be useful. ($\Delta R^{hZ}_{\gamma\gamma} = 6.04$ % at $2\,\sigma$)

→ Combined study with the HL-LHC

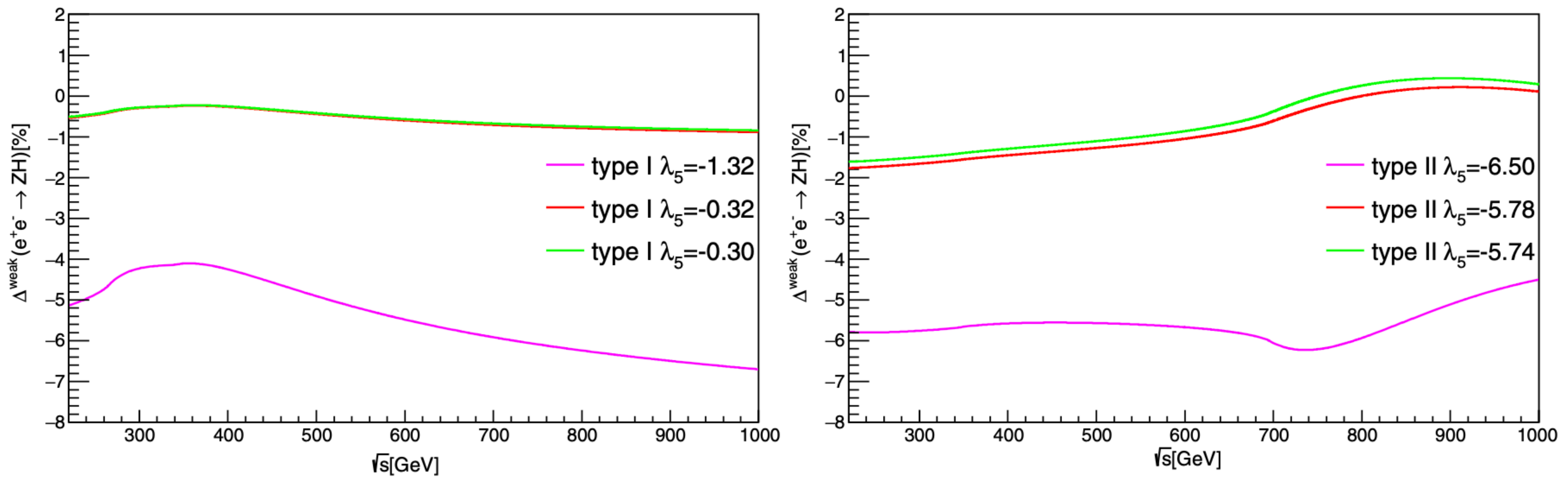
Benchmark scenarios

Xie, Benbrik, Habjia, Taj, Gong, Yan, PRD103 (2021)

BPs	$s_{\beta-\alpha}$	$\tan\beta$	m_h [GeV]	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]
BP1-H	-0.06	2.83	95	125	169	170
BP2-H	-0.03	2.16	95	125	600	600

$$\lambda_5 = \frac{M^2 - m_A^2}{v^2}$$

$$\Delta^{\rm weak}(e^+e^- \to ZH) = \sigma_{\rm NP}/\sigma_{\rm SM} - 1$$



(a) BP1-H (b) BP2-H

Sizable deviations to detect at CEPC even with $c_{\beta-\alpha} \simeq 1$

Conclusions

- $e^+e^- \to Z\phi$ is a target process at future lepton colliders (CEPC, ILC, FCC-ee).
- The size of the deviation tells us a scale of new physics.
- The pattern of the deviation tells us the structure of Yukawa interactions.
- Theoretical calculations with NLO EW corrections are available in various models.

2HDM：Lopez-Val et al. PRD81 (2010); Xie et al. PRD103 (2021)
IDM：Abouabid et al. JHEP 05 (2021)
MSSM：Chankowski et al. NPB423 (1994); Driesen, Hollik, ZPC68 (1995);
Driesen et al. ZPC71 (1996); Heinemeyer et al. EPJ C19 (2001)
cMSSM： Heinemeyer et al. EPJ C76 (2016)

Our work {
- Extension of model space (HSM)
- Same renormalization scheme → Model discrimination
- Helicity-dependent cross section

Conclusion and discussions

Conclusions

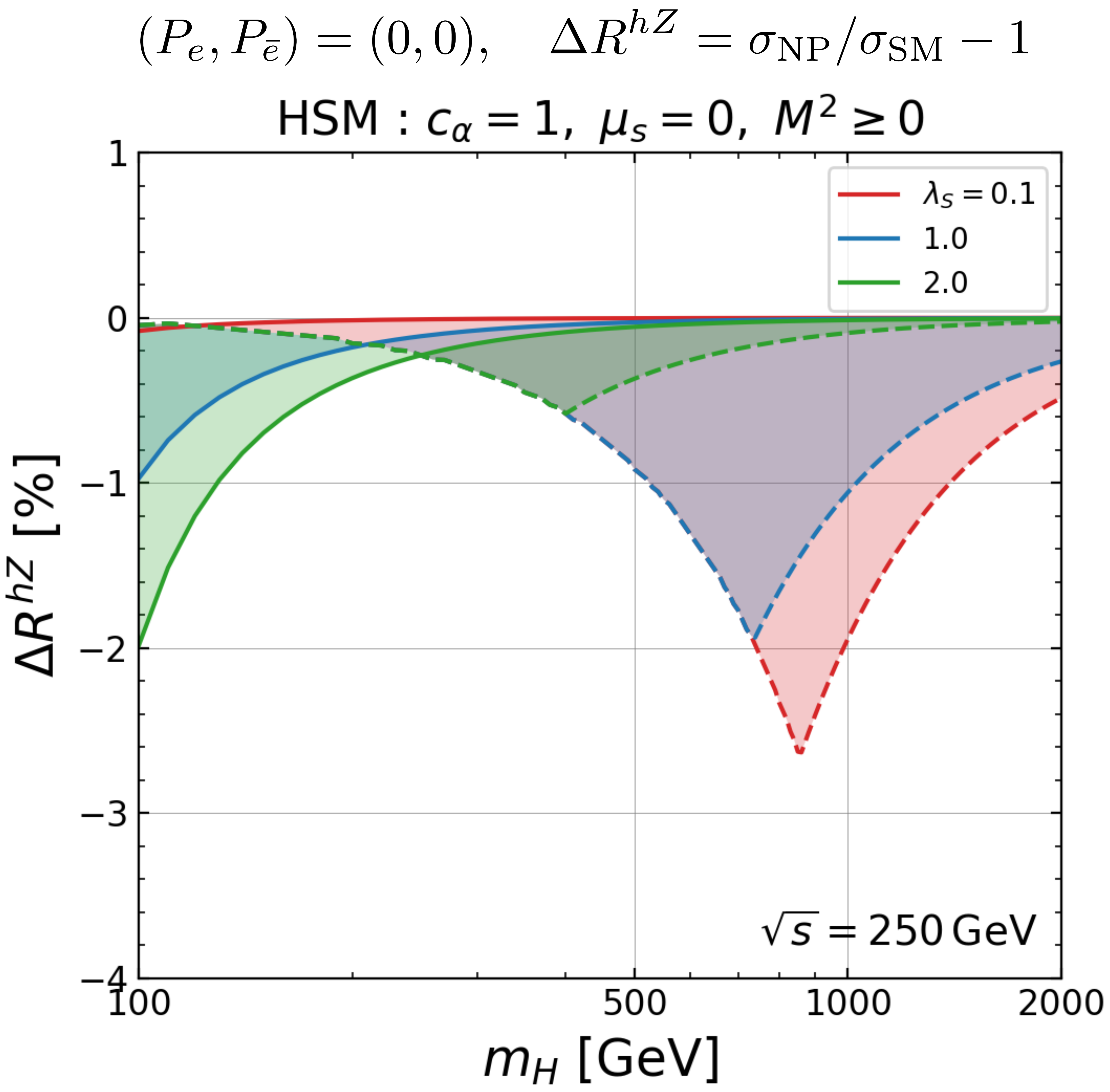
- $e^+e^- \to hZ$ is a target process at future lepton colliders (CEPC, ILC, FCC-ee).
- The size of the deviation tells us a scale of new physics.
- The pattern of the deviation tells us the structure of Yukawa interactions.
- Theoretical calculations with NLO EW corrections are available in various models.

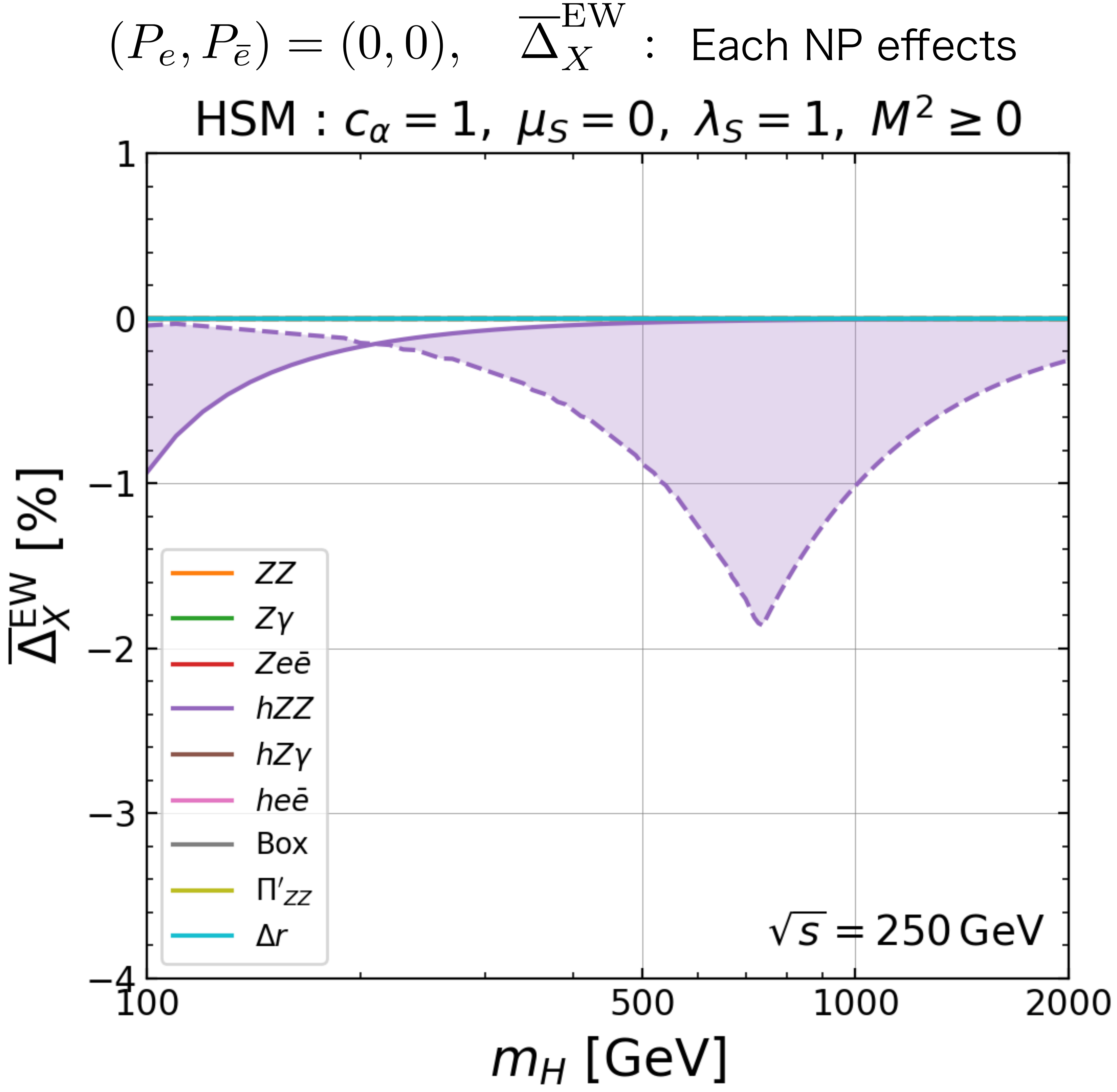
Discussion

- Can we investigate almost gaugephobic Higgs boson via $e^+e^- \to ZH$?
- Validity of the narrow width approximation for Z boson. Chen et al. Chinese Phys. C43 (2019)
- NNLO EW corrections are smaller than the estimated experimental error?

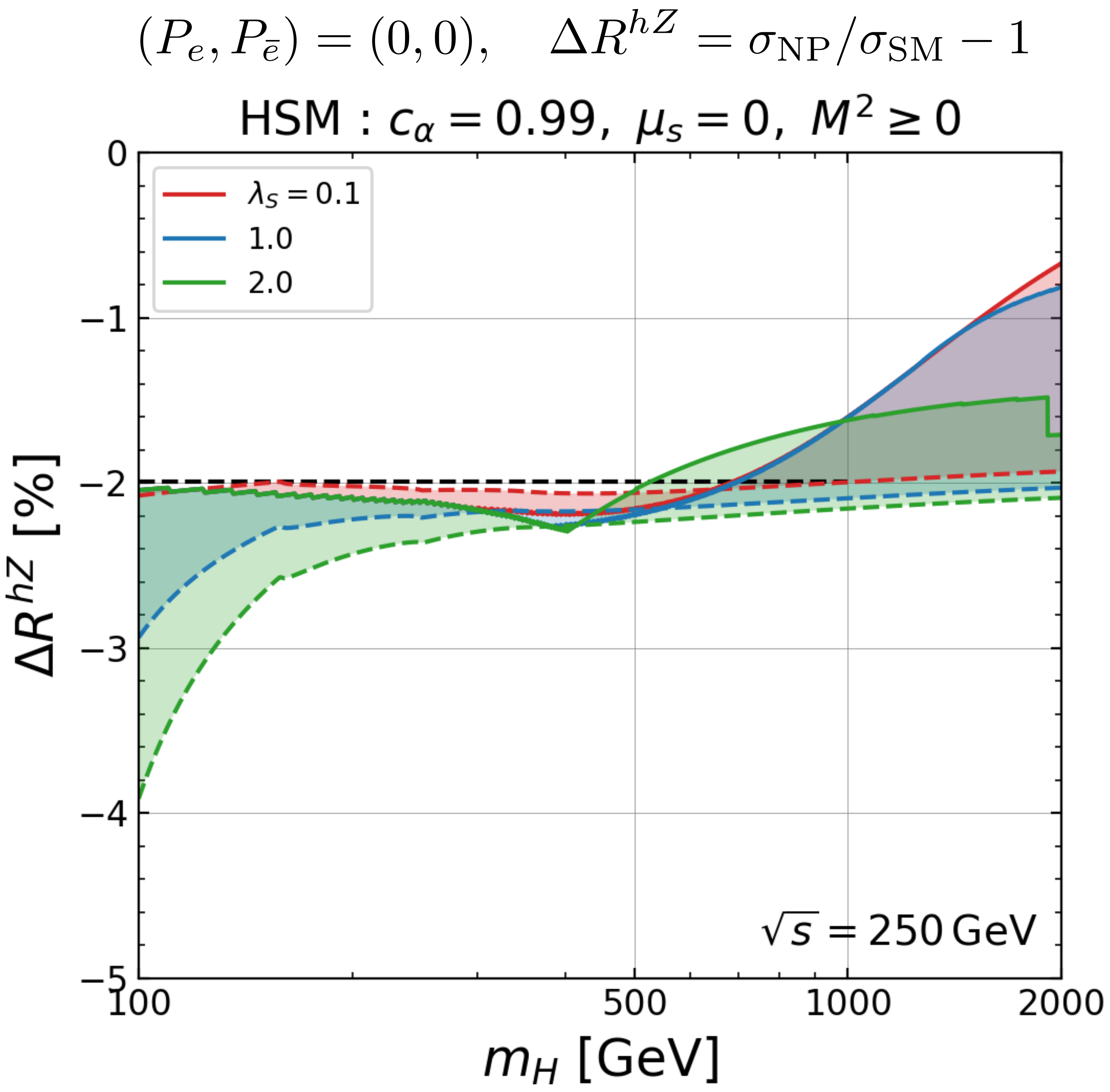
Back up

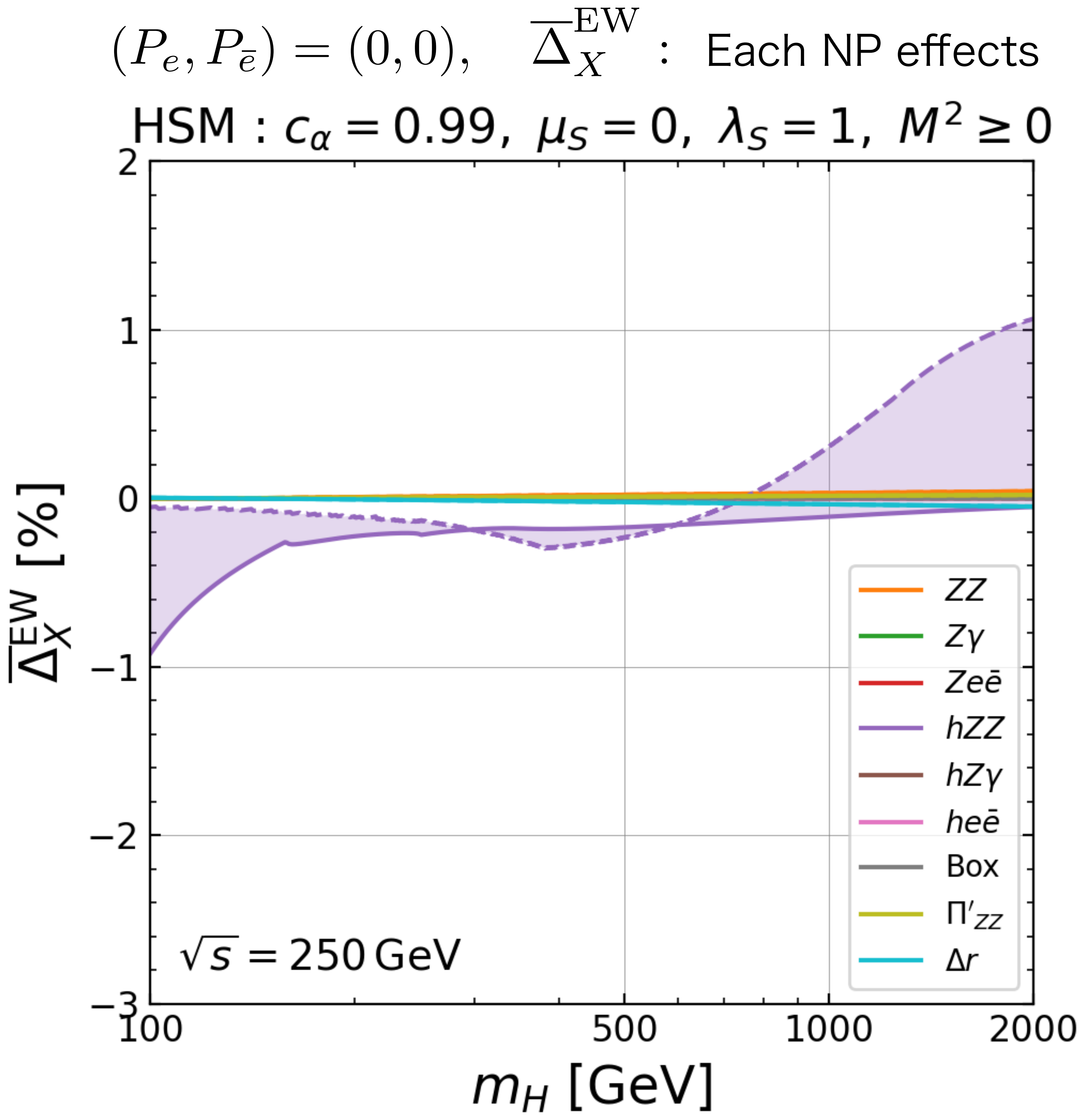
HSM with $c_\alpha = 1$



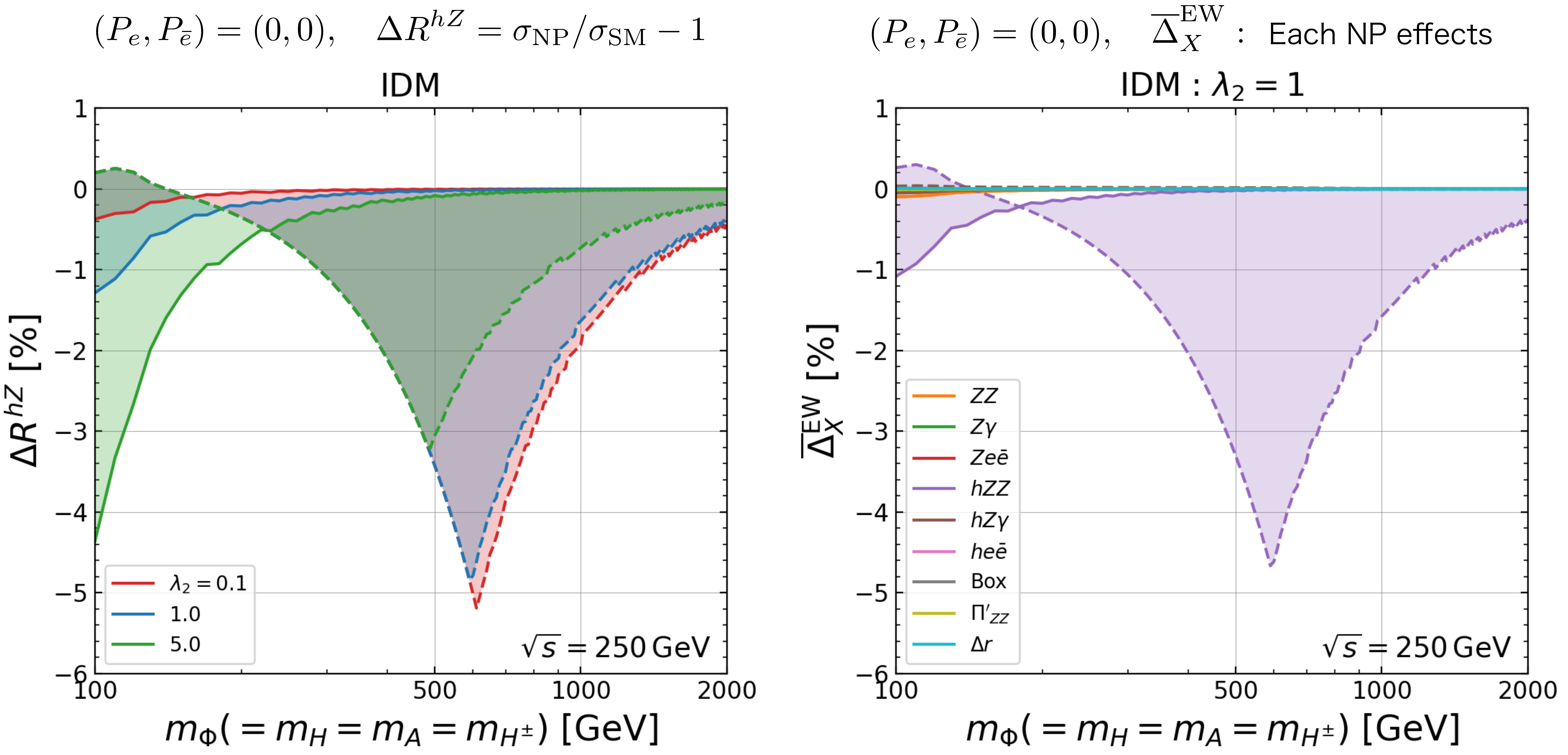


HSM with $c_\alpha \neq 1$





IDM



$(P_e, P_{\bar{e}}) = (0,0), \quad \Delta R^{hZ} = \sigma_{\rm NP}/\sigma_{\rm SM} - 1$
IDM
ΔR^{hZ} [%]
$\lambda_2 = 0.1$
1.0
5.0
$\sqrt{s} = 250$ GeV
$m_\Phi(= m_H = m_A = m_{H^\pm})$ [GeV]
$(P_e, P_{\bar{e}}) = (0,0), \quad \overline{\Delta}_X^{\rm EW}$: Each NP effects
IDM : $\lambda_2 = 1$
$\overline{\Delta}_X^{\rm EW}$ [%]
ZZ
$Z\gamma$
$Ze\bar{e}$
hZZ
$hZ\gamma$
$he\bar{e}$
Box
Π'_{ZZ}
Δr
$\sqrt{s} = 250$ GeV
$m_\Phi(= m_H = m_A = m_{H^\pm})$ [GeV]