Indirect search for CP-violation in the scalar sector by the precision test of Higgs couplings

Mitsunori KUBOTA

Osaka University

Debut talk

[arXiv: 1808.08770]

Collaborators: M. Aoki[1], K. Hashino[2,3], D. Kaneko[1], S. Kanemura[2]

1: Univ. of Kanazawa, 2: Osaka Univ., 3: Univ. of Toyama

Introduction

◆Discovered Higgs boson looks like the SM one.

◆CP-violating scalar sector is motivated by the baryon number asymmetry of the Universe.

◆Until now, there are no sign of non-SM particles.

We focus on the precision test of the discovered Higgs boson to explore the CP-violation in the scalar sector.

In this talk,...

Z_2 sym. : To avoid FCNC at tree level.
[S. L. Glashow and S. Weinberg, PRD15, 1958 (1977)]

◆We consider the 2HDM with softly broken Z_2.

$\mathrm{2HDM}$

- Simple extension of the SM.
- CP-violation can be introduced.

◆We analyze the Higgs coupling constants $(hVV, h\tau\tau, hbb, hcc)$ in the CP-conserving 2HDM and the CP-violating 2HDM.

◆We then compare these results.

2HDM with CPV

[T. D. Lee, PRD8, 1226 (1973)]

[J. F. Gunion and H. E Haber, PRD72, 095002 (2005)]

[I. F. Ginzburg and M. Krawczyk, PRD72, 115013 (2005)]

[G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, PR516, 1 (2012)]

[B. Grzadkowski, O. M. Ogreid and P. Osland, JHEP 11, 084 (2014)]

[D. Fontes, M. Mühlleitner, J. C. Romão, R. Santos, J. P. Silva and J. Wittbrodt, JHEP 02, 073 (2018)]

and so on.

Several talks are also relevant.

CPV parameter in this model

$\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$ under Z_2.

◆Potential of 2HDM (with softly broken Z_2 sym.)

$$V = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - \{\mu_3^2(\Phi_1^\dagger\Phi_2) + h.c.\}$$
$$+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right\}$$

◆Vacuum expectation value

$(j = 1, 2)$

$$\Phi_j = \begin{pmatrix} w_j^+ \\ \frac{1}{\sqrt{2}}(v_j + h_j + iz_j) \end{pmatrix} e^{i\theta_j}$$

$$v^2 \equiv v_1^2 + v_2^2 = (246GeV)^2$$

The redefinition of the phases can get θ_j to disappear.

Stationary condition

$$\left.\frac{\partial V}{\partial h_1}\right|_0 = 0, \quad \left.\frac{\partial V}{\partial h_2}\right|_0 = 0, \quad \left.\frac{\partial V}{\partial z_1}\right|_0 = 0$$

⇒

$$\mu_1^2 = \frac{v_2}{v_1}\mathrm{Re}(\mu_3^2) - \frac{1}{2}(\lambda_1 v_1^2 + \lambda_{345} v_2^2)$$
$$\mu_2^2 = \frac{v_1}{v_2}\mathrm{Re}(\mu_3^2) - \frac{1}{2}(\lambda_2 v_2^2 + \lambda_{345} v_1^2)$$
$$2\,\mathrm{Im}(\mu_3^2) = v_1 v_2\,\mathrm{Im}(\lambda_5)$$

$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \mathrm{Re}(\lambda_5)$$

◆Parameters in this model

$$v_1, v_2, \mathrm{Re}(\mu_3^2), \lambda_1, \lambda_2, \lambda_3, \lambda_4, \mathrm{Re}(\lambda_5), \mathrm{Im}(\lambda_5)$$

CP mixing between the neutral scalars

Higgs basis

[Davidson and Haber, PRD72, 035004 (2005)]

$$\begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix} = \begin{pmatrix}\cos\beta & \sin\beta\\ -\sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} \qquad \tan\beta = \frac{v_2}{v_1}$$

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1' + iG^0)\end{pmatrix}, \qquad \phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + ih_3')\end{pmatrix}$$

◆ Mass matrix: $\mathcal{M}^2_{ij} \equiv \partial^2 V / \partial h_i' \partial h_j' \big|_0 \;(i,j = 1\text{-}3)$

$m_{H_1} = 125$ GeV

$$\mathcal{M}^2 = \begin{pmatrix}\mathcal{M}^2_{11} & \mathcal{M}^2_{12} & \mathcal{M}^2_{13}\\ \mathcal{M}^2_{12} & \mathcal{M}^2_{22} & \mathcal{M}^2_{23}\\ \mathcal{M}^2_{13} & \mathcal{M}^2_{23} & \mathcal{M}^2_{33}\end{pmatrix}$$

$\mathcal{M}^2_{13}, \mathcal{M}^2_{23} \propto \mathrm{Im}(\lambda_5)$

$$R^T \mathcal{M}^2 R = \mathrm{diag}(m^2_{H_1}, m^2_{H_2}, m^2_{H_3})$$

$$\begin{pmatrix}h_1'\\ h_2'\\ h_3'\end{pmatrix} = \begin{pmatrix}R_{11} & R_{12} & R_{13}\\ R_{21} & R_{22} & R_{23}\\ R_{31} & R_{32} & R_{33}\end{pmatrix}\begin{pmatrix}H_1\\ H_2\\ H_3\end{pmatrix}$$

h_1', h_2' : CP even, h_3' : CP odd

$\mathrm{Im}(\lambda_5) \neq 0 \Rightarrow$ CP mixing

Higgs couplings

◆Types of 2HDM

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}_L (i\sigma_2 \Phi_u^*) u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + h.c.$$

Z_2 charge assignment in each Type

	Φ_1	Φ_2	Q_L	L_L	u_R	d_R	e_R
Type-I	$+$	$-$	$+$	$+$	$-$	$-$	$-$
Type-II	$+$	$-$	$+$	$+$	$-$	$+$	$+$
Type-X	$+$	$-$	$+$	$+$	$-$	$-$	$+$
Type-Y	$+$	$-$	$+$	$+$	$-$	$+$	$-$

[Barger, Hewett and Phillips, PRD41, 3421 (1990)]
[Aoki, Kanemura, Tsumura and Yagyu, PRD80, 015017 (2009)]

◆Higgs couplings

$$\mathcal{L}_{H_1 VV}^{2\mathrm{HDM}} = \underline{R_{11}} \left(g_{hWW}^{\mathrm{SM}} W_\mu^+ W^{-\mu} + \frac{1}{2} g_{hZZ}^{\mathrm{SM}} Z_\mu Z^\mu \right) H_1$$

$$\mathcal{L}_{H_1 ff}^{2\mathrm{HDM}} = -g_{hff}^{\mathrm{SM}} \bar{f} \underline{(c_f^s + i\gamma_5 c_f^p)} f H_1$$

H_1: 125 GeV Higgs
f : u, d and e
V : W and Z

$$c_f^s = R_{11} + R_{21}\xi_f$$
$$c_f^p = (-2I_f) R_{31} \xi_f$$

$I_u = 1/2,\ I_d = I_e = -1/2$

	ξ_u	ξ_d	ξ_e
Type-I	$+\cot\beta$	$+\cot\beta$	$+\cot\beta$
Type-II	$+\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$+\cot\beta$	$+\cot\beta$	$-\tan\beta$
Type-Y	$+\cot\beta$	$-\tan\beta$	$+\cot\beta$

Result

- $\kappa_V = \frac{g^{2HDM}_{H_1VV}}{g^{SM}_{hVV}} = R_{11}$
- $\frac{\Gamma_{2HDM}(H_1 \to f\bar{f})}{\Gamma_{SM}(h \to f\bar{f})} \simeq (c^s_f)^2 + (c^p_f)^2$

◆ Input parameters

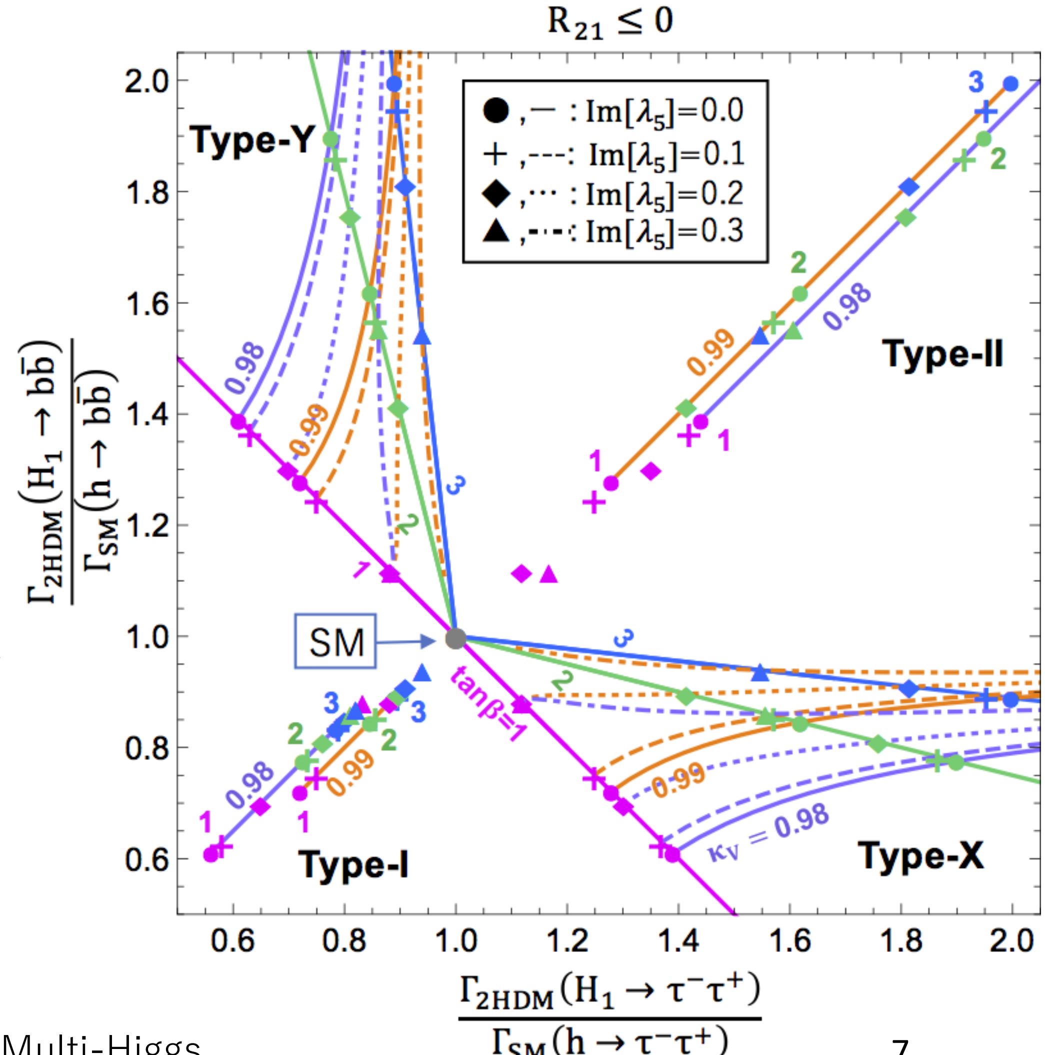
$$\begin{aligned} v &= 246 \text{ GeV}, \\ m_{H_1} &= 125 \text{ GeV}, \\ \tilde{m}_H &= 200 \text{ GeV}, \\ \tilde{m}_A &= 250 \text{ GeV} \end{aligned}$$

$\tilde{m}_H, \tilde{m}_A$ $(\mathrm{Im}(\lambda_5) \to 0)$
$\longrightarrow$ Mass eigenvalues

$\kappa_V, \tan\beta, \mathrm{Im}[\lambda_5]$
are variables.

They are independent of
$\mathrm{Re}(\mu_3^2), m_{H^\pm}$ at the tree level

CP-conserving case is plotted by
[Kanemura, Tsumura, Yagyu and Yokoya, PRD90, 075001 (2014)]



Result

- $\kappa_V = \dfrac{g^{\rm 2HDM}_{H_1VV}}{g^{\rm SM}_{hVV}} = R_{11}$
- $\dfrac{\Gamma_{\rm 2HDM}(H_1 \to f\bar{f})}{\Gamma_{\rm SM}(h \to f\bar{f})} \simeq (c_f^s)^2 + (c_f^p)^2$

Input parameters

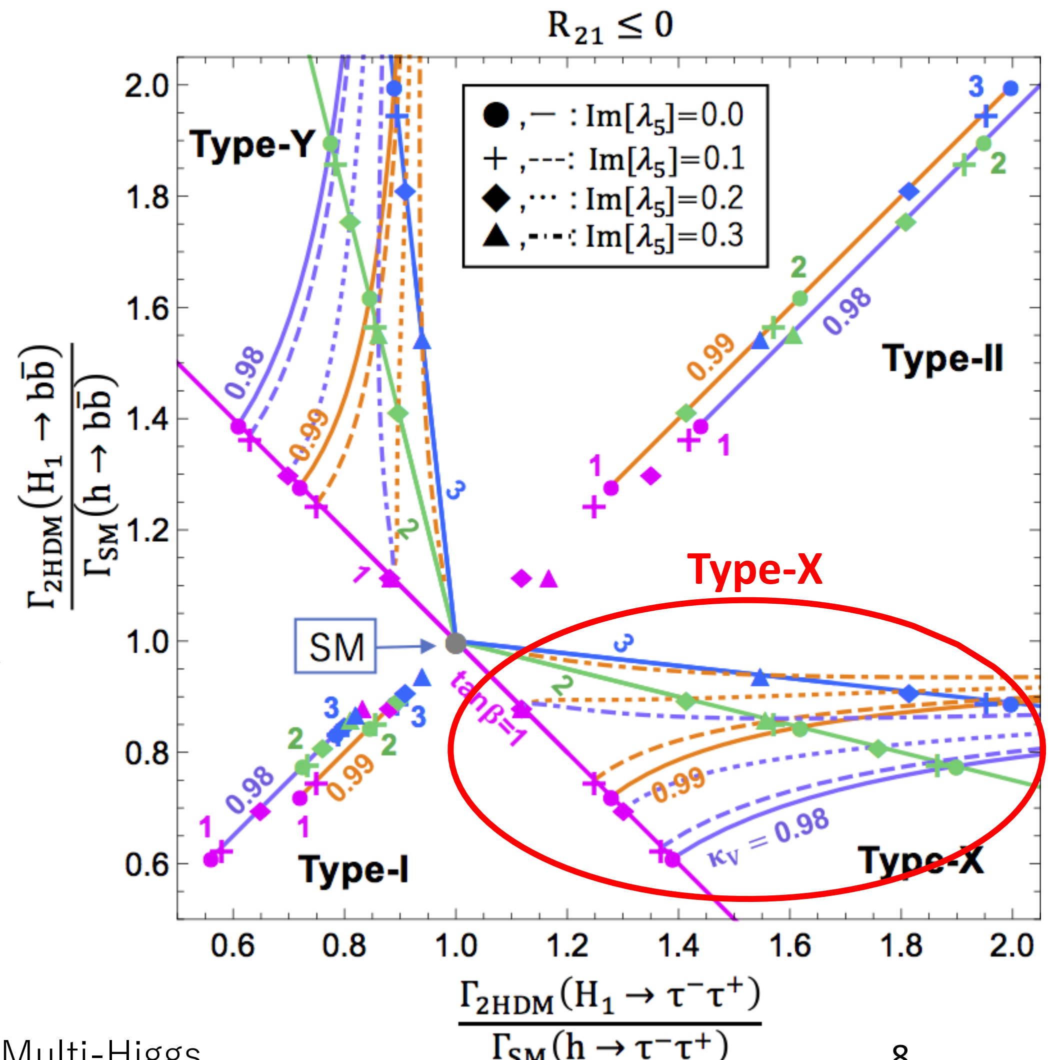
$$\begin{aligned} v &= 246\ \text{GeV}, \\ m_{H_1} &= 125\ \text{GeV}, \\ \tilde{m}_H &= 200\ \text{GeV}, \\ \tilde{m}_A &= 250\ \text{GeV} \end{aligned}$$

$\tilde{m}_H, \tilde{m}_A$ $(\text{Im}(\lambda_5) \to 0)$ $\longrightarrow$ Mass eigenvalues

$\kappa_V, \tan\beta, \text{Im}[\lambda_5]$ are variables.

They are independent of $\text{Re}(\mu_3^2), m_{H^\pm}$ at the tree level

CP-conserving case is plotted by [Kanemura, Tsumura, Yagyu and Yokoya, PRD90, 075001 (2014)]

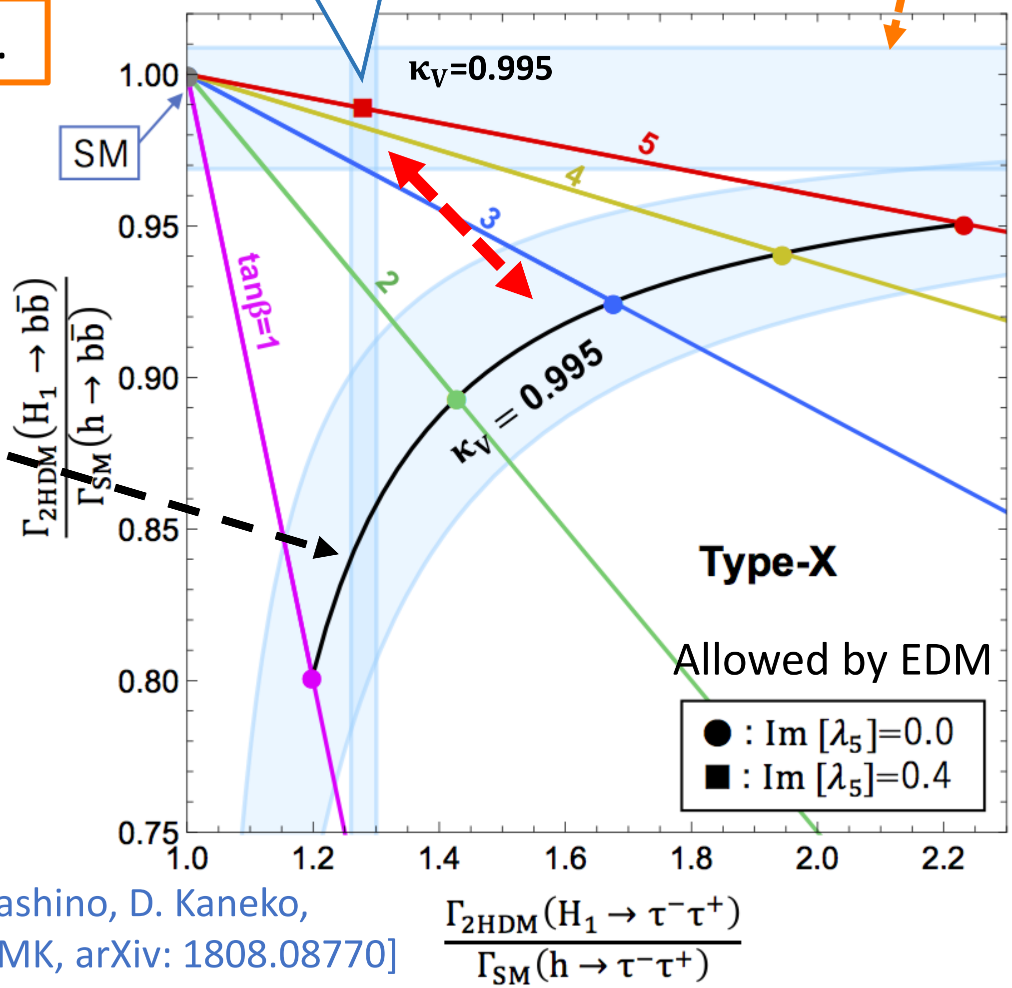


Result

ILC250 ($2ab^{-1}$) [K. Fujii, et al., arXiv: 1710.07621] κ_Z: 0.38% κ_b: 1.8% κ_τ: 1.9%

$8ab^{-1}$: κ_V: 0.2% $\kappa_{b,\tau}$: 1 %

For instance, if κ_V measures 0.995, …



- In the CP-conserving 2HDM, the ratio of decay rate for the fermion should be on the black curve.

$\mathrm{Im}[\lambda_5] = 0$

The deviation from the black curve is indirect effect of CP-violation.

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

Summary

◆In this talk, we analyze the CP-violating effect on the Higgs coupling constants in the 2HDM from the viewpoint of indirect search.

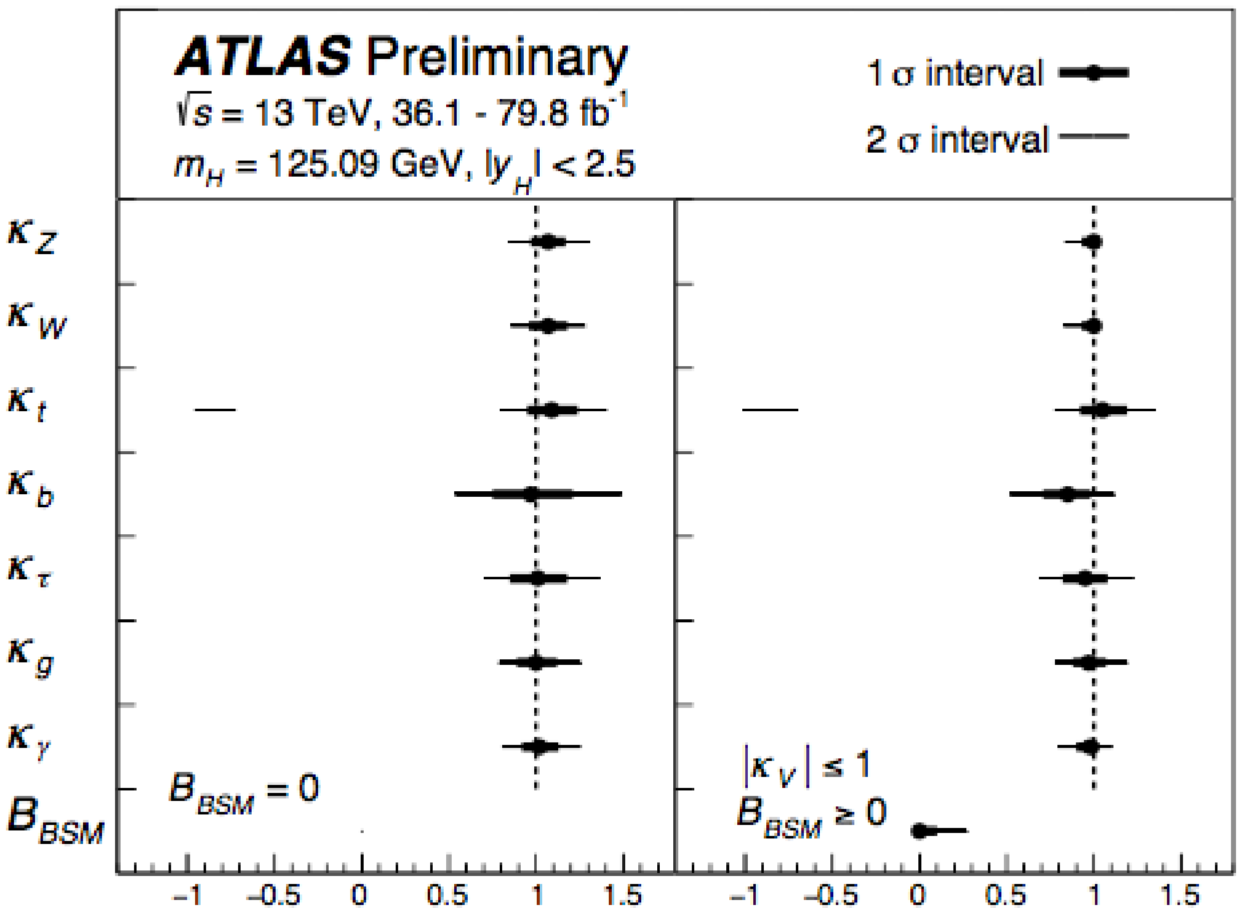
◆The prediction of the Higgs couplings in the CP-violating 2HDM can be certainly deviated from the CP-conserving one.

◆By measuring the Higgs couplings very precisely we are able to extract the information of the CP-violation in the scalar sector.

Back up

Current data

[ATLAS-CONF-2018-031]



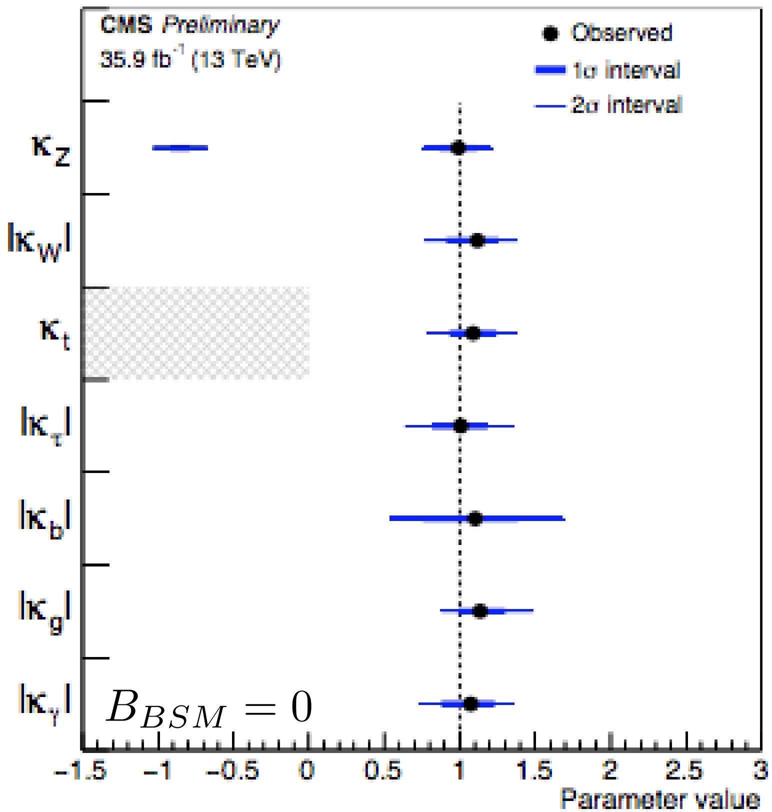
Current data

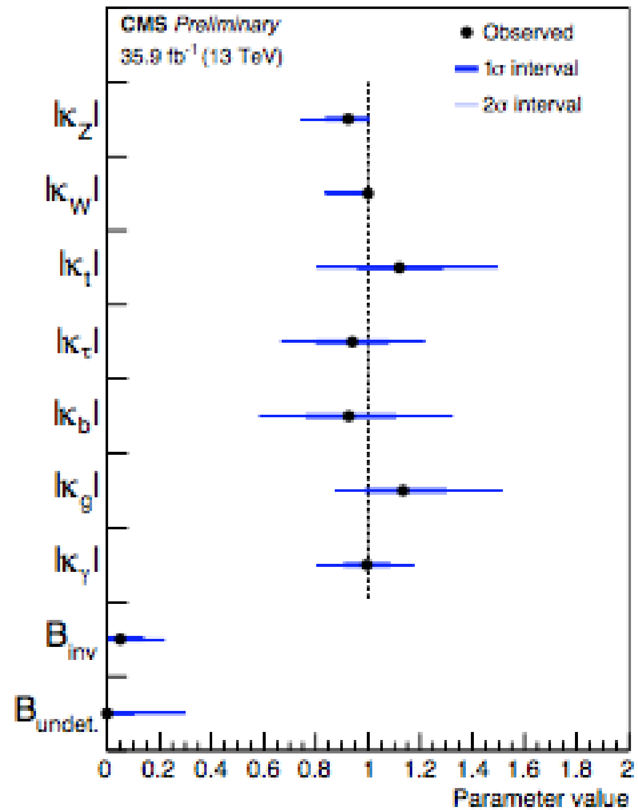
[ATLAS-CONF-2018-031]

Parameter	(a) no BSM	(b) with BSM
κ_Z	1.07 ± 0.10	restricted to $\kappa_Z \leq 1$
κ_W	1.07 ± 0.11	restricted to $\kappa_W \leq 1$
κ_b	$0.97^{+0.24}_{-0.22}$	$0.85^{+0.13}_{-0.14}$
κ_t	$1.09^{+0.15}_{-0.14}$	$1.05^{+0.14}_{-0.13}$
κ_τ	$1.02^{+0.17}_{-0.16}$	0.95 ± 0.13
κ_γ	$1.02^{+0.09}_{-0.12}$	$0.98^{+0.05}_{-0.08}$
κ_g	$1.00^{+0.12}_{-0.11}$	$0.97^{+0.10}_{-0.09}$
B_{BSM}	-	< 0.26 at 95% CL

Current data

[CMS-PAS-HIG-17-031]





Current data

[CMS-PAS-HIG-17-031]

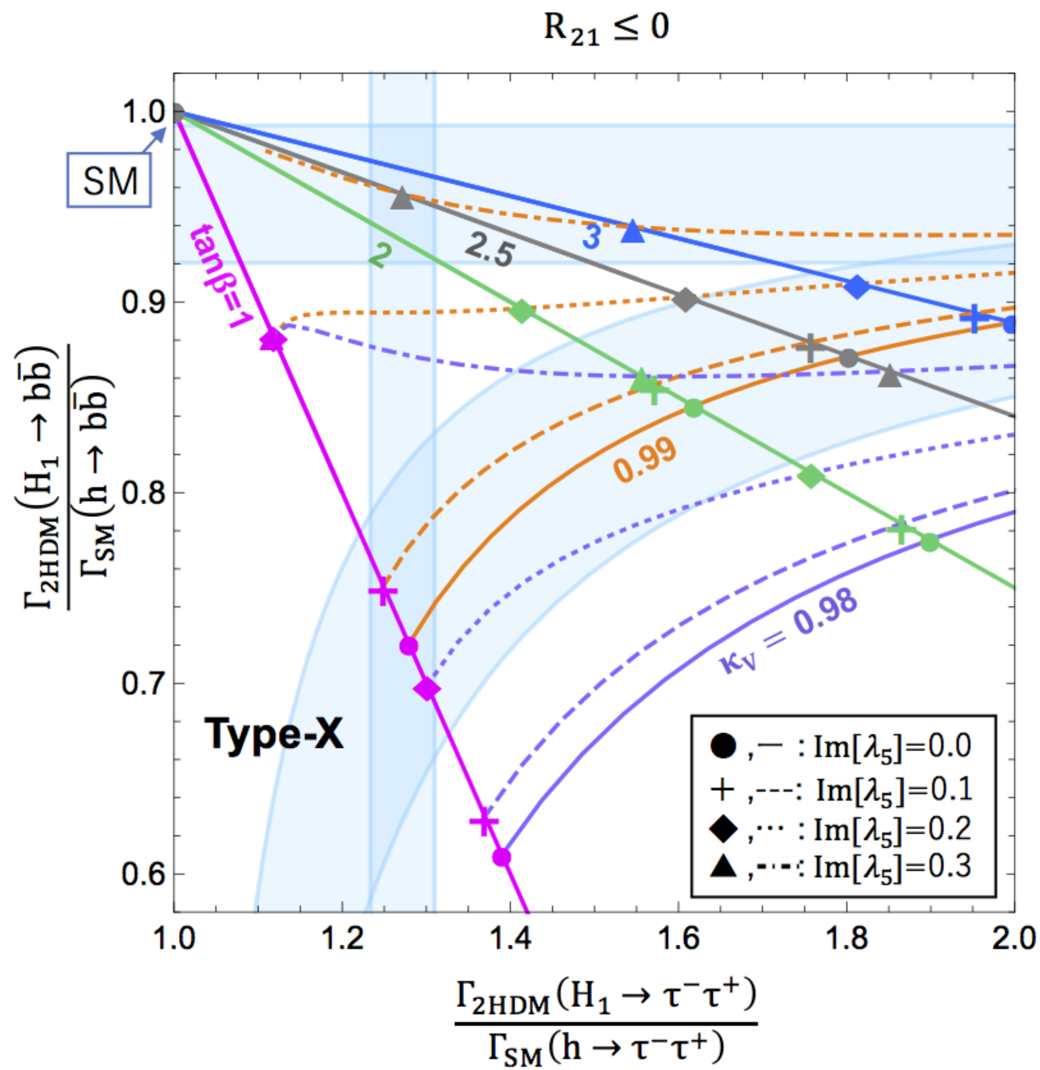
$BR_{inv.} = 0$				$BR_{inv.} > 0, \kappa_V < 1$			
		Uncertainty				Uncertainty	
Parameter	Best fit	Stat.	Syst.	Parameter	Best fit	Stat.	Syst.
κ_Z	$0.99\ ^{+0.11}_{-0.11}\ \left(^{+0.11}_{-0.11}\right)$	$^{+0.09}_{-0.09}\ \left(^{+0.09}_{-0.09}\right)$	$^{+0.06}_{-0.06}\ \left(^{+0.06}_{-0.06}\right)$	κ_Z	$0.89\ ^{+0.09}_{-0.08}\ \left(^{+0.00}_{-0.11}\right)$	$^{+0.07}_{-0.07}\ \left(^{+0.00}_{-0.09}\right)$	$^{+0.05}_{-0.04}\ \left(^{+0.00}_{-0.06}\right)$
κ_W	$1.12\ ^{+0.13}_{-0.19}\ \left(^{+0.12}_{-0.12}\right)$	$^{+0.10}_{-0.18}\ \left(^{+0.09}_{-0.09}\right)$	$^{+0.08}_{-0.07}\ \left(^{+0.07}_{-0.07}\right)$	κ_W	$1.00\ ^{+0.00}_{-0.05}\ \left(^{+0.00}_{-0.12}\right)$	$^{+0.00}_{-0.04}\ \left(^{+0.00}_{-0.09}\right)$	$^{+0.00}_{-0.02}\ \left(^{+0.00}_{-0.07}\right)$
κ_t	$1.09\ ^{+0.14}_{-0.14}\ \left(^{+0.14}_{-0.15}\right)$	$^{+0.08}_{-0.08}\ \left(^{+0.08}_{-0.09}\right)$	$^{+0.12}_{-0.12}\ \left(^{+0.12}_{-0.12}\right)$	κ_t	$1.12\ ^{+0.17}_{-0.16}\ \left(^{+0.18}_{-0.15}\right)$	$^{+0.09}_{-0.09}\ \left(^{+0.13}_{-0.09}\right)$	$^{+0.14}_{-0.13}\ \left(^{+0.12}_{-0.12}\right)$
κ_τ	$1.01\ ^{+0.17}_{-0.18}\ \left(^{+0.16}_{-0.15}\right)$	$^{+0.11}_{-0.15}\ \left(^{+0.11}_{-0.11}\right)$	$^{+0.12}_{-0.09}\ \left(^{+0.11}_{-0.11}\right)$	κ_τ	$0.91\ ^{+0.13}_{-0.13}\ \left(^{+0.14}_{-0.15}\right)$	$^{+0.08}_{-0.08}\ \left(^{+0.09}_{-0.11}\right)$	$^{+0.11}_{-0.10}\ \left(^{+0.11}_{-0.11}\right)$
κ_b	$1.10\ ^{+0.27}_{-0.33}\ \left(^{+0.25}_{-0.23}\right)$	$^{+0.19}_{-0.30}\ \left(^{+0.19}_{-0.17}\right)$	$^{+0.19}_{-0.14}\ \left(^{+0.17}_{-0.15}\right)$	κ_b	$0.91\ ^{+0.19}_{-0.16}\ \left(^{+0.18}_{-0.23}\right)$	$^{+0.12}_{-0.11}\ \left(^{+0.13}_{-0.17}\right)$	$^{+0.14}_{-0.11}\ \left(^{+0.13}_{-0.15}\right)$
κ_g	$1.14\ ^{+0.15}_{-0.13}\ \left(^{+0.14}_{-0.12}\right)$	$^{+0.10}_{-0.09}\ \left(^{+0.10}_{-0.09}\right)$	$^{+0.11}_{-0.09}\ \left(^{+0.10}_{-0.09}\right)$	κ_g	$1.17\ ^{+0.18}_{-0.14}\ \left(^{+0.17}_{-0.12}\right)$	$^{+0.11}_{-0.10}\ \left(^{+0.13}_{-0.09}\right)$	$^{+0.14}_{-0.11}\ \left(^{+0.10}_{-0.09}\right)$
κ_γ	$1.07\ ^{+0.15}_{-0.18}\ \left(^{+0.12}_{-0.12}\right)$	$^{+0.10}_{-0.17}\ \left(^{+0.10}_{-0.10}\right)$	$^{+0.11}_{-0.07}\ \left(^{+0.07}_{-0.07}\right)$	κ_γ	$0.96\ ^{+0.09}_{-0.08}\ \left(^{+0.08}_{-0.12}\right)$	$^{+0.06}_{-0.06}\ \left(^{+0.07}_{-0.09}\right)$	$^{+0.07}_{-0.05}\ \left(^{+0.05}_{-0.07}\right)$
				$BR_{inv.}$	$0.04\ ^{+0.09}_{+0.00}\ \left(^{+0.08}_{+0.00}\right)$	$^{+0.03}_{-0.03}\ \left(^{+0.04}_{-0.00}\right)$	$^{+0.08}_{-0.00}\ \left(^{+0.07}_{-0.00}\right)$
				$BR_{undet.}$	$0.00\ ^{+0.09}_{+0.00}\ \left(^{+0.20}_{+0.00}\right)$	$^{+0.08}_{-0.00}\ \left(^{+0.17}_{-0.00}\right)$	$^{+0.03}_{-0.00}\ \left(^{+0.11}_{-0.00}\right)$

Result [M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

◆ ILC prospect

	ILC250	+ILC500
	κ fit	κ fit
$g(hbb)$	1.8	0.60
$g(hcc)$	2.4	1.2
$g(hgg)$	2.2	0.97
$g(hWW)$	1.8	0.40
$g(h\tau\tau)$	1.9	0.80
$g(hZZ)$	0.38	0.30
$g(h\gamma\gamma)$	1.1	1.0
$g(h\mu\mu)$	5.6	5.1
$g(h\gamma Z)$	16	16

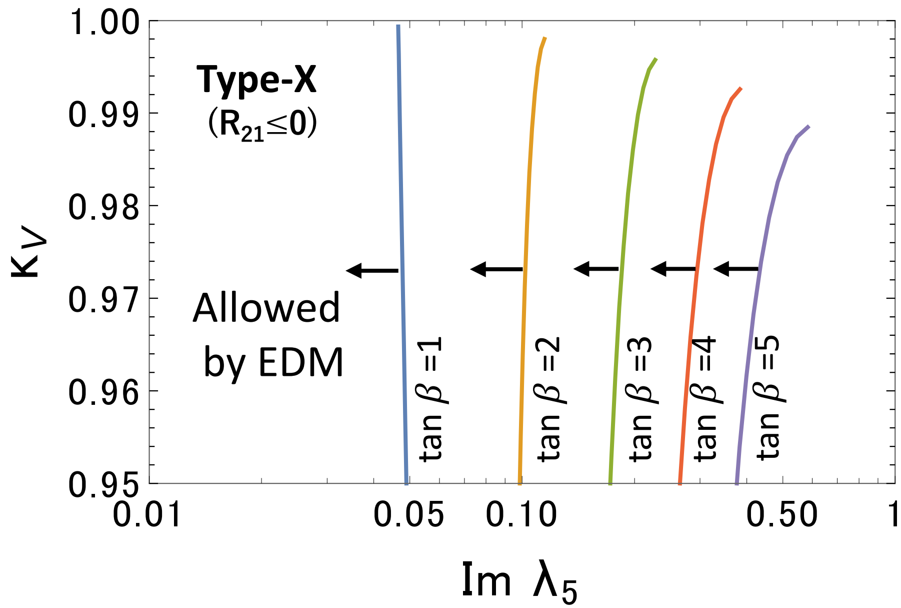
Sensitivity: [K. Fujii, et al., arXiv: 1710.07621]



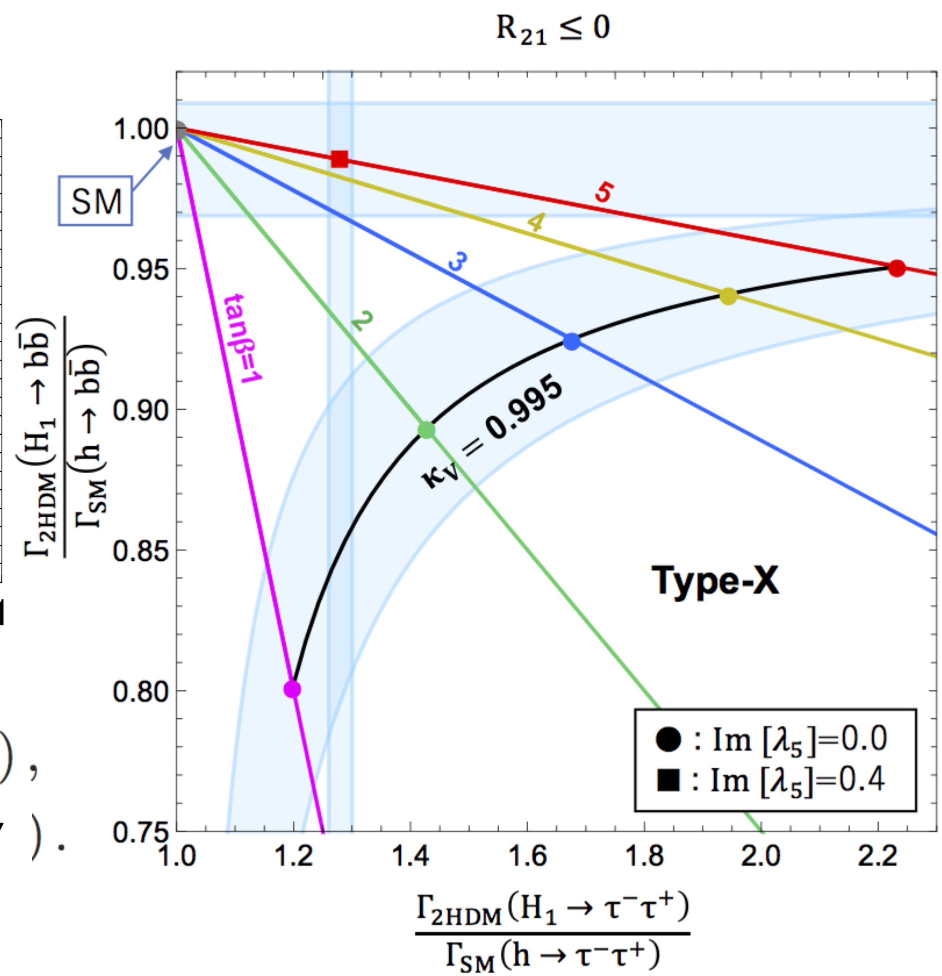
Result [M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

Sensitivity: κ_V: 0.2% κ_f: 1 %

◆ EDM constraint
（Type-X (R_{21}≤0) ）



$$|C_u^P| \lesssim 7\times10^{-3}\ (\mathrm{I}),\qquad 2\times10^{-2}\ (\mathrm{II}),$$
$$3\times10^{-2}\ (\mathrm{X}),\qquad 6\times10^{-3}\ (\mathrm{Y}).$$



[Cheung, Lee, Senaha and Tseng, JHEP 06, 149 (2014)]
[Keus, King, Moretti and Yagyu, JHEP 04, 048 (2016)]

2HDM with softly broken Z_2

$$\hat{\phi}_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1' + iG^0) \end{pmatrix}, \quad \hat{\phi}_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + ih_3') \end{pmatrix}$$

$$\begin{pmatrix} h_1' \\ h_2' \\ h_3' \end{pmatrix} = R \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

mass eigenstates

- CP conserving case ($\mathrm{Im}(\lambda_5) = 0$), for the mixing states (h_1', h_2', h_3') ,

$$\mathcal{M}^2_{CPC} = \begin{pmatrix} m_h^2 s^2_{\beta-\alpha} + m_H^2 c^2_{\beta-\alpha} & \frac{1}{2}(m_h^2 - m_H^2) s_{2(\beta-\alpha)} & 0 \\ \frac{1}{2}(m_h^2 - m_H^2) s_{2(\beta-\alpha)} & m_h^2 c^2_{\beta-\alpha} + m_H^2 s^2_{\beta-\alpha} & 0 \\ 0 & 0 & m_A^2 \end{pmatrix}$$

- CP violating case ($\mathrm{Im}(\lambda_5) \neq 0$),

$$\mathcal{M}^2 = \begin{pmatrix} \tilde{m}_h^2 s^2_{\beta-\tilde{\alpha}} + \tilde{m}_H^2 c^2_{\beta-\tilde{\alpha}} & \frac{1}{2}(\tilde{m}_h^2 - \tilde{m}_H^2) s_{2(\beta-\tilde{\alpha})} & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) s_{2\beta} \\ \frac{1}{2}(\tilde{m}_h^2 - \tilde{m}_H^2) s_{2(\beta-\tilde{\alpha})} & \tilde{m}_h^2 c^2_{\beta-\tilde{\alpha}} + \tilde{m}_H^2 s^2_{\beta-\tilde{\alpha}} & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) c_{2\beta} \\ -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) s_{2\beta} & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) c_{2\beta} & \tilde{m}_A^2 \end{pmatrix}$$

[Kanemura and Yagyu, Phys.Lett. B751 (2015) 289-296]
[Keus, King, Moretti and Yagyu, JHEP 04, 048 (2016)]

- Parameters in this model

$$v(= 246\ \mathrm{GeV}), m_{H_1}(= 125\ \mathrm{GeV}), M, m_{H^\pm}, \tilde{m}_H, \tilde{m}_A, \kappa_V, \tan\beta, \mathrm{Im}(\lambda_5)$$

2HDM with softly broken $\boldsymbol{Z_2}$

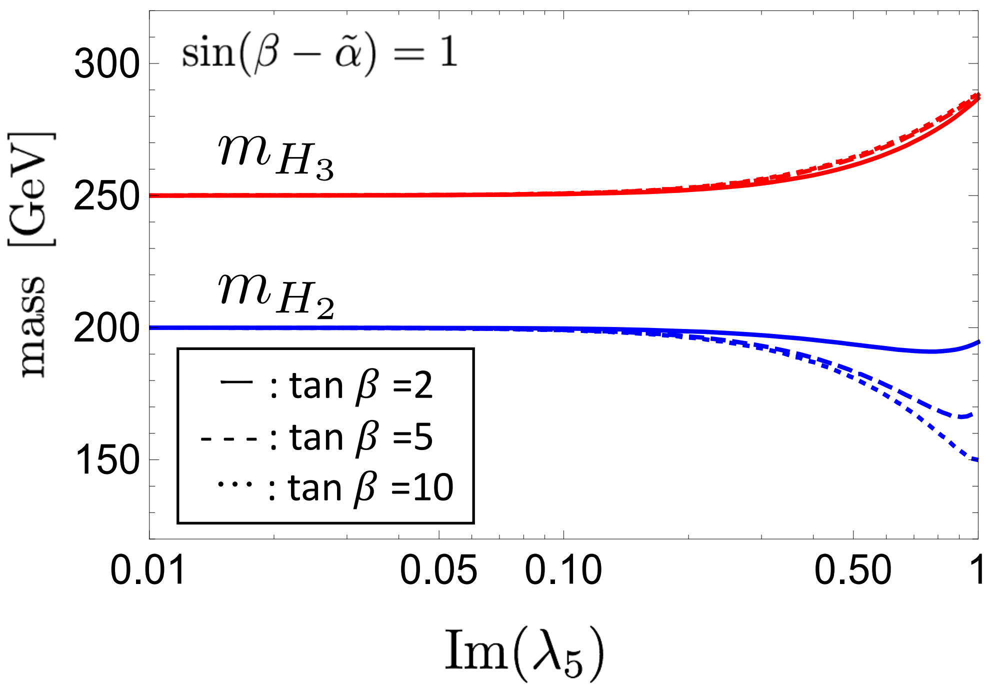
$$\begin{cases} \mathcal{M}^2 = \tilde{\mathcal{M}}^2 + \Delta\mathcal{M}^2 \\ R = \tilde{R} + \Delta R \end{cases}$$

$$\Delta\mathcal{M}^2, \Delta R, \to 0 \ (\mathrm{Im}(\lambda_5) \to 0)$$

$$\begin{aligned} \mathrm{diag}(m_{H_1}^2, m_{H_2}^2, m_{H_3}^2) &= R^T \mathcal{M}^2 R \\ &= \tilde{R}^T \tilde{\mathcal{M}}^2 \tilde{R} + \Delta(R^T \mathcal{M}^2 R) \\ &= \mathrm{diag}(\tilde{m}_h^2, \tilde{m}_H^2, \tilde{m}_A^2) + \mathrm{diag}(\Delta m_h^2, \Delta m_H^2, \Delta m_A^2) \end{aligned}$$

2HDM with softly broken Z_2

◆ Mass dimensional parameters $\tilde{m}_H, \tilde{m}_A$



$$\begin{aligned} v &= 246\ \mathrm{GeV}, \\ m_h &= 125\ \mathrm{GeV}, \\ \tilde{m}_H &= 200\ \mathrm{GeV}, \\ \tilde{m}_A &= 250\ \mathrm{GeV} \end{aligned}$$

When $\mathrm{Im}(\lambda_5)$ is small,

$$\tilde{m}_H \approx m_{H_2},\ \ \tilde{m}_A \approx m_{H_3}$$

Mass eigenvalue

$\tilde{m}_H, \tilde{m}_A\ (\mathrm{Im}(\lambda_5) \to 0)$
$\longrightarrow$ Mass eigenvalues

2HDM with softly broken $\boldsymbol{Z_2}$

◆ Ratio of decay rate

$$\frac{\Gamma_{2\mathrm{HDM}}(h \to f\bar{f})}{\Gamma_{\mathrm{SM}}(h \to f\bar{f})} \simeq (c_f^s)^2 + (c_f^p)^2$$

$$= (R_{11}^2 + R_{21}^2 \xi_f^2 + 2R_{11}R_{21}\xi_f) + (R_{31}^2 \xi_f^2)$$

$$= \kappa_V^2 + (1-\kappa_V^2)\xi_f^2 + 2\kappa_V R_{21}\xi_f$$

$$\to \kappa_V^2 + (1-\kappa_V^2)\xi_f^2 \qquad (R_{21} \to 0)$$

$$\kappa_V \equiv R_{11}$$

$$R_{11}^2 + R_{21}^2 + R_{31}^2 = 1$$

	ξ_u	ξ_d	ξ_e
Type-I	$+\cot\beta$	$+\cot\beta$	$+\cot\beta$
Type-II	$+\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$+\cot\beta$	$+\cot\beta$	$-\tan\beta$
Type-Y	$+\cot\beta$	$-\tan\beta$	$+\cot\beta$

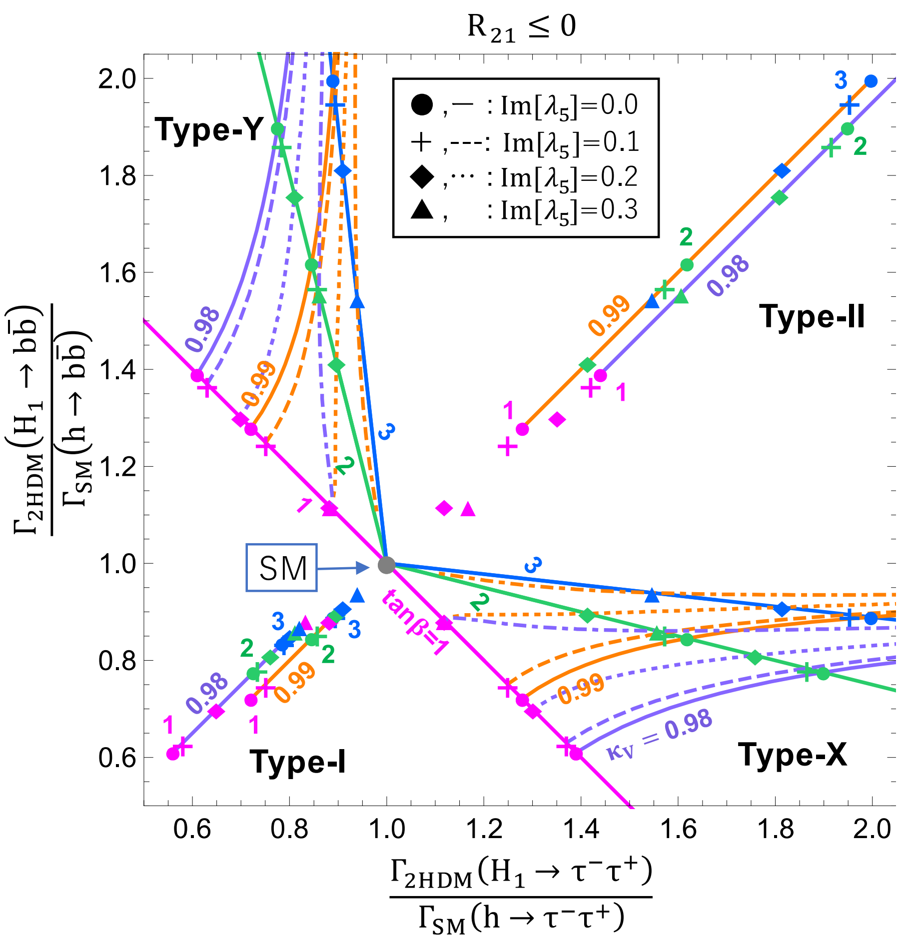
$\mathrm{Im}(\lambda_5)$ increase

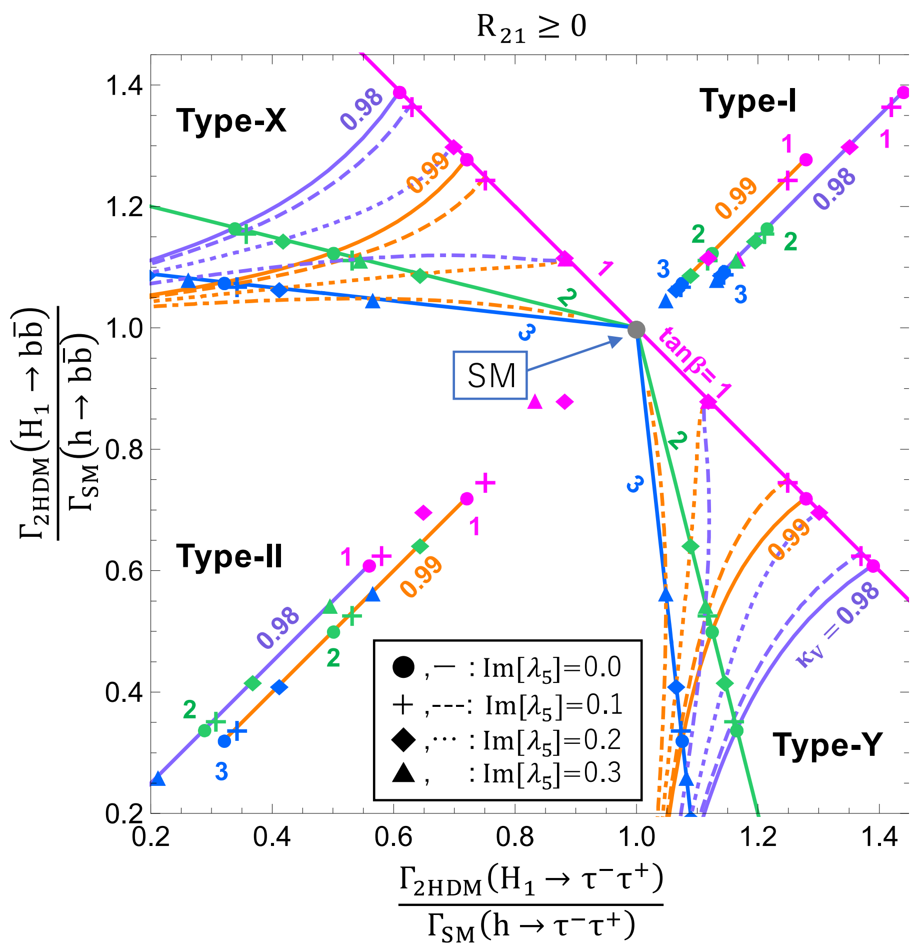
$\to |R_{31}|$ increase

$\to |R_{21}|$ decrease

Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

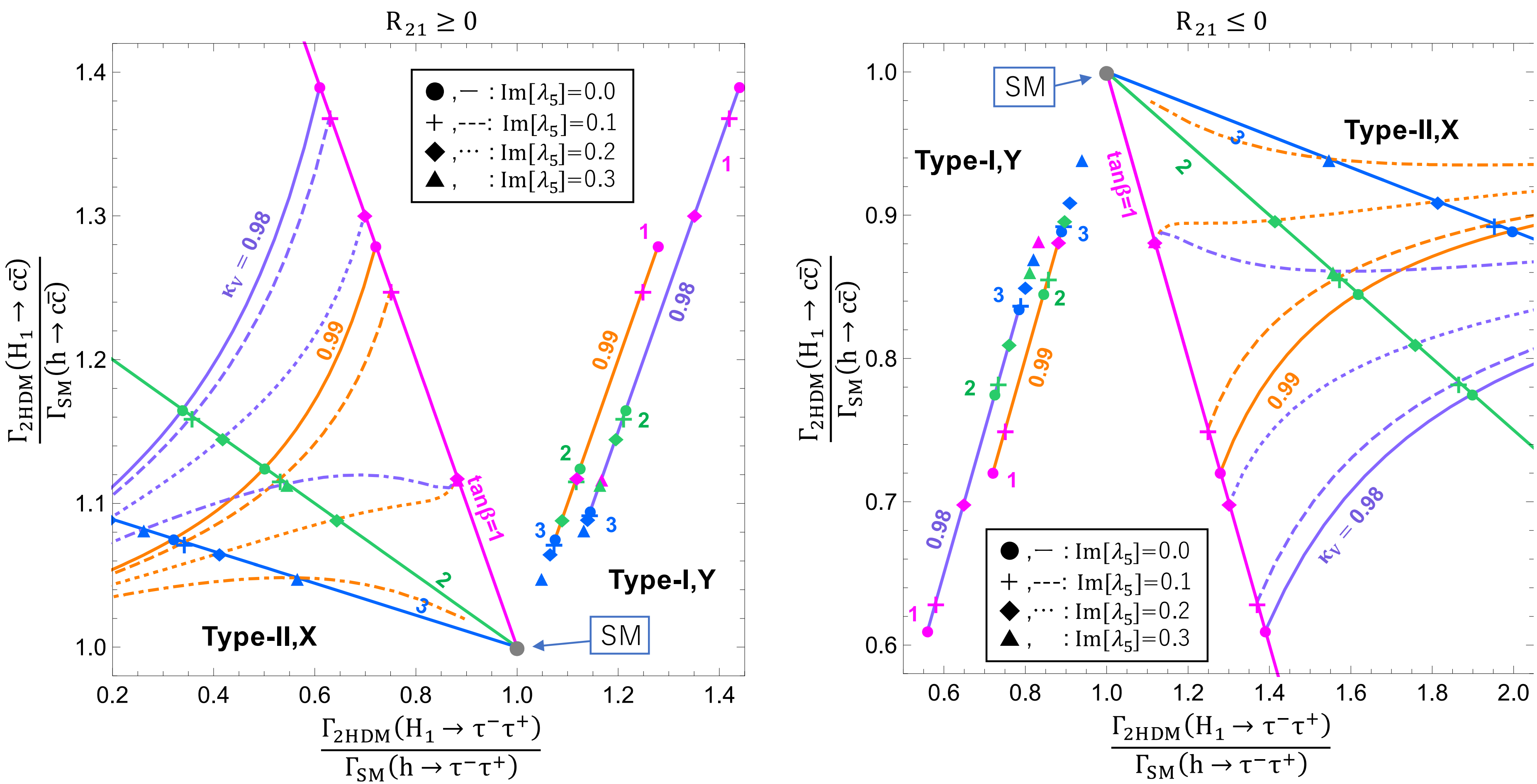




hbb-$h\tau\tau$

Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]



hcc-hττ

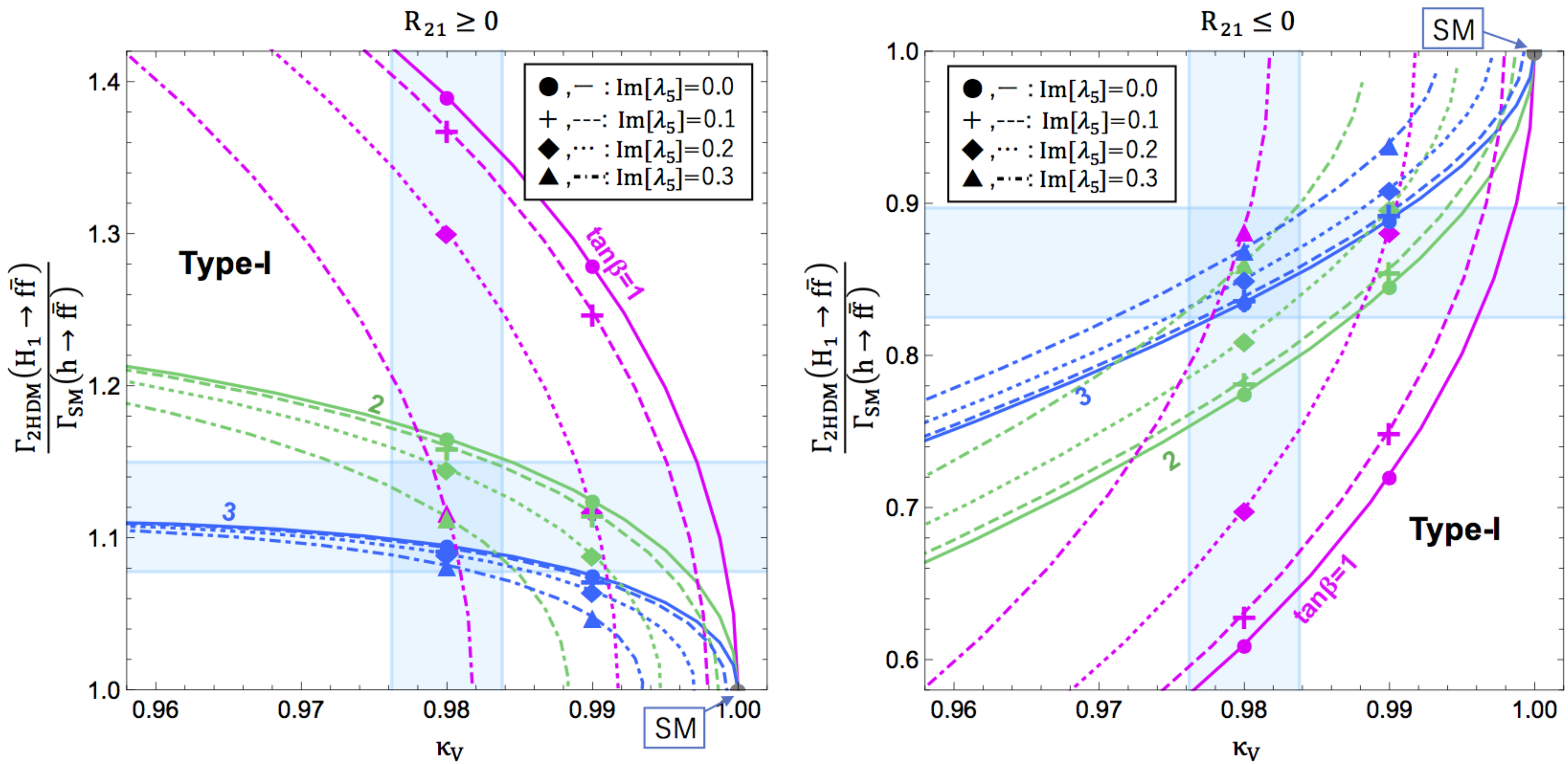
Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

Sensitivity: [K. Fujii, et al., arXiv: 1710.07621]

ILC250 ($2ab^{-1}$)

κ_Z: 0.38%
κ_b: 1.8%
κ_τ: 1.9%

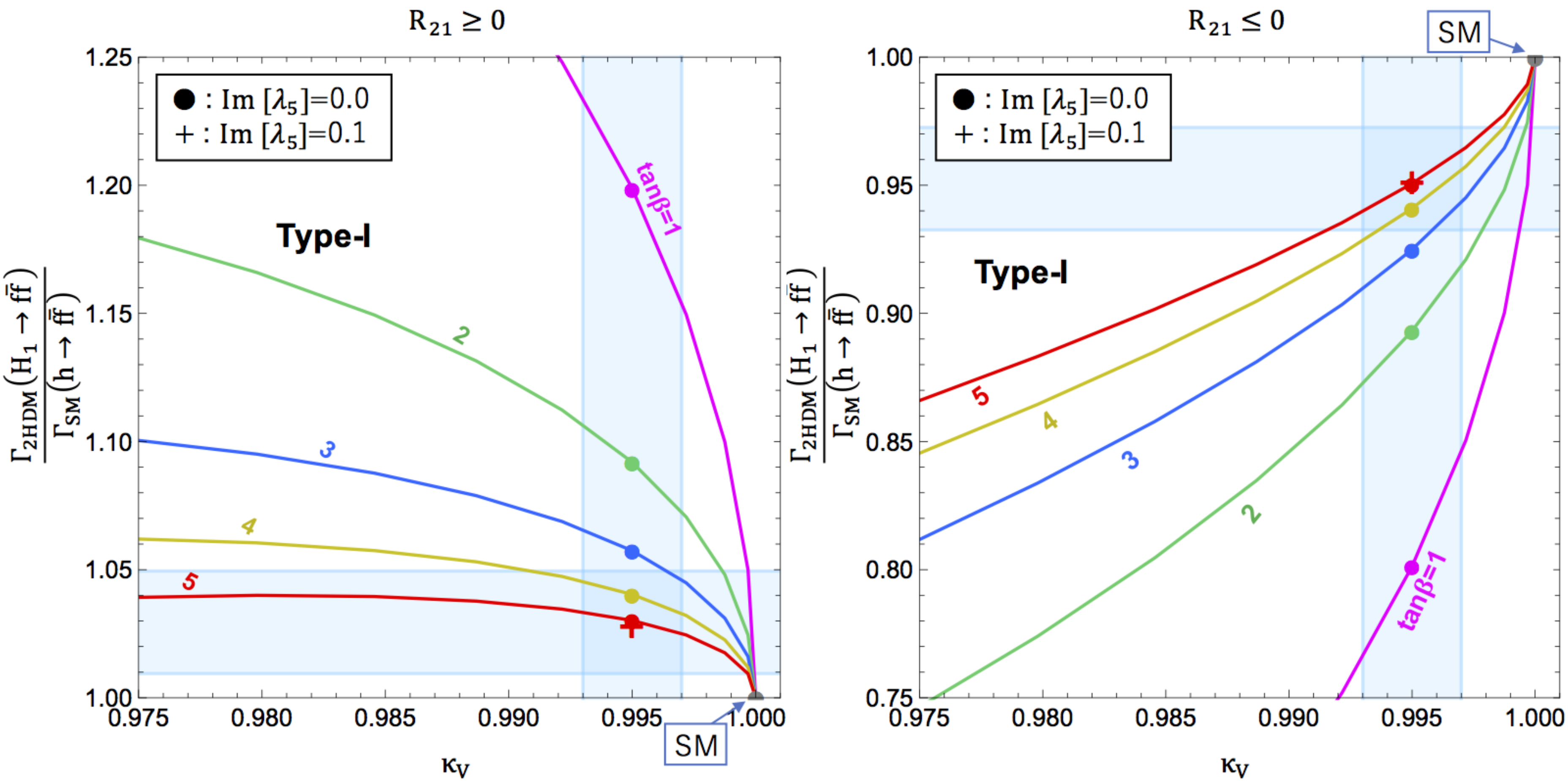


Type-I

Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

κ_V: 0.2%
$\kappa_{b,\tau}$: 1 %



Type-I

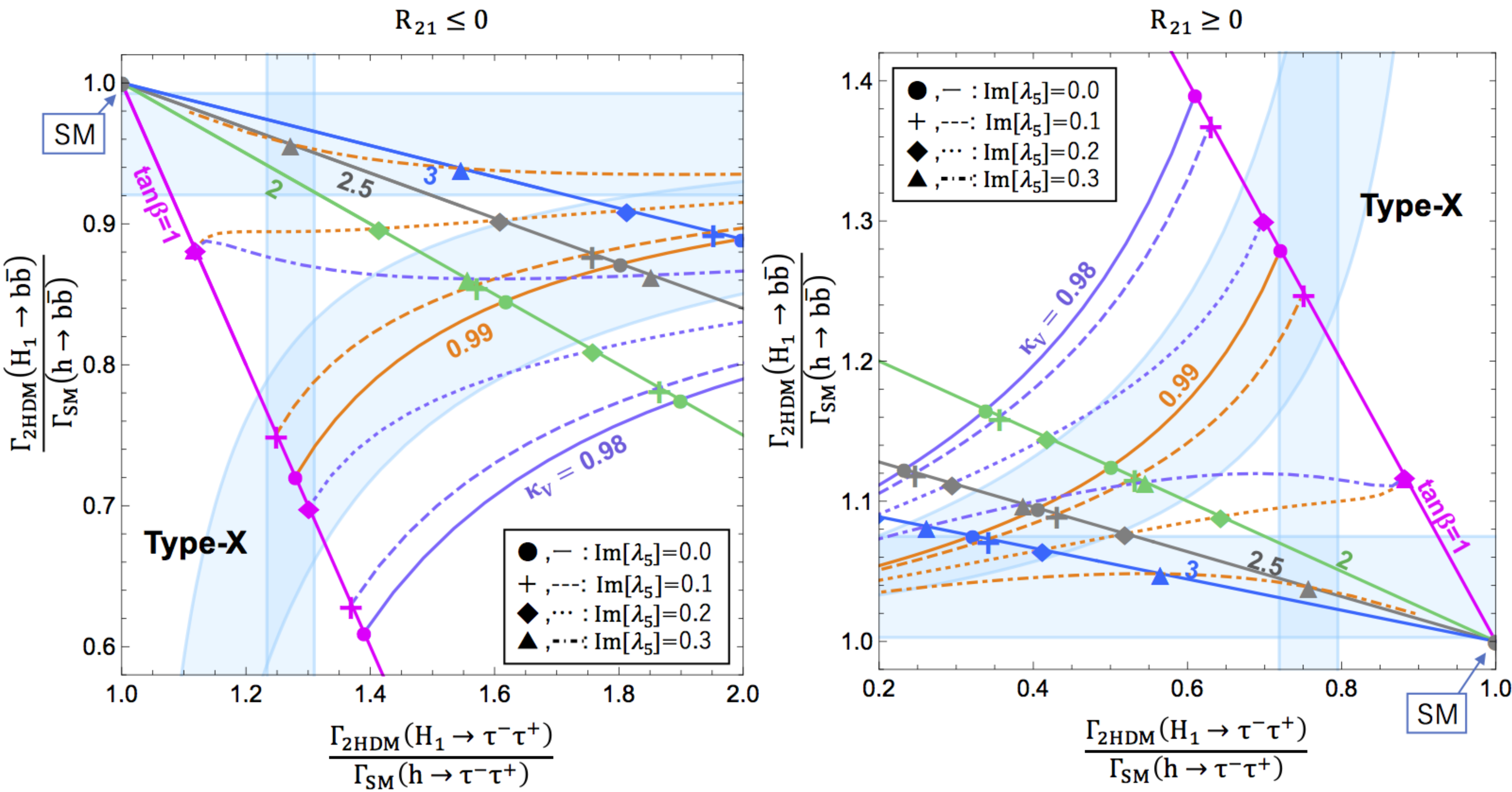
Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

Sensitivity: [K. Fujii, et al., arXiv: 1710.07621]

ILC250 (2ab^{-1})

κ_Z: 0.38%
κ_b: 1.8%
κ_τ: 1.9%

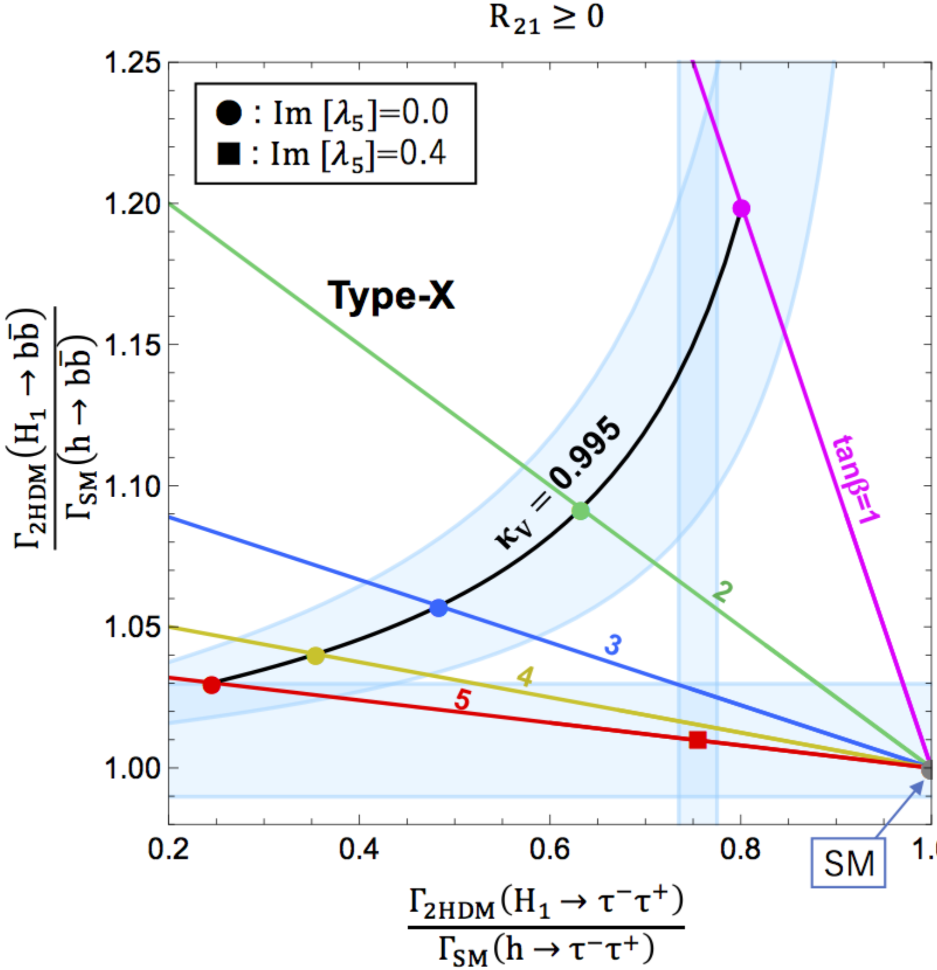


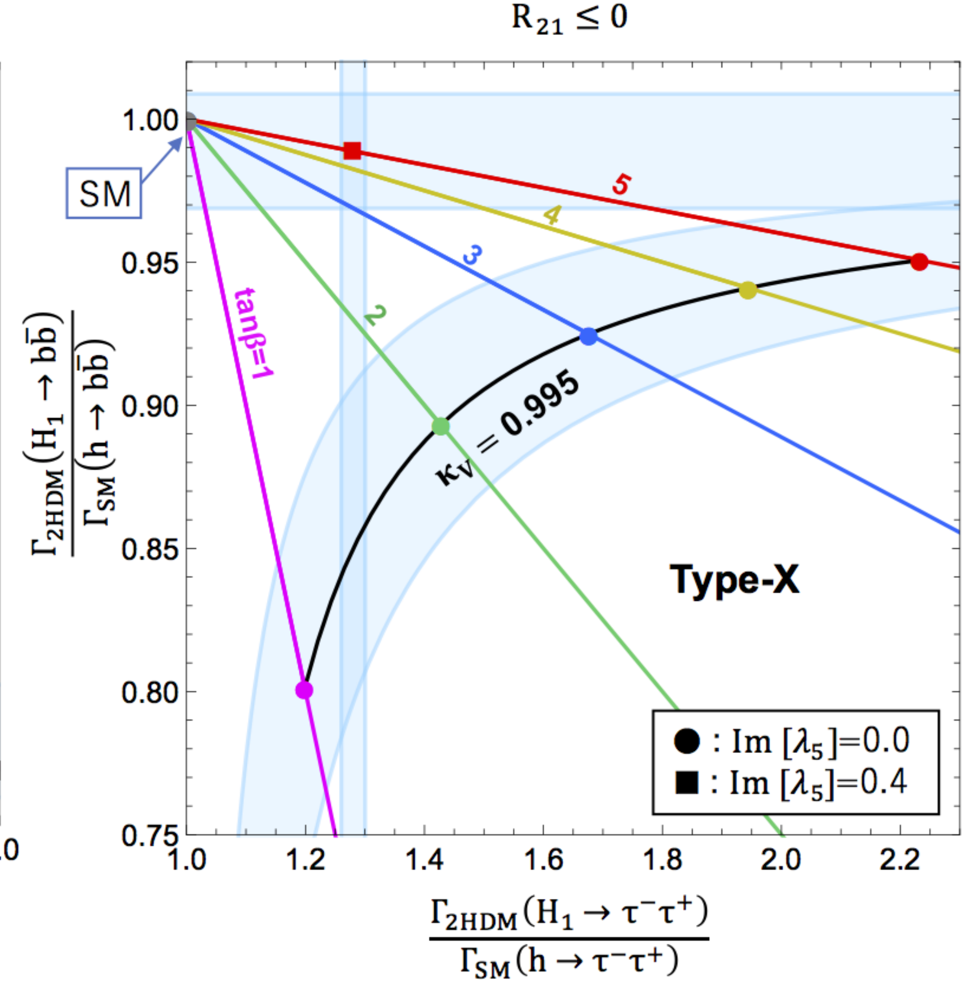
Type-X

Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

κ_V: 0.2%
$\kappa_{b,\tau}$: 1 %





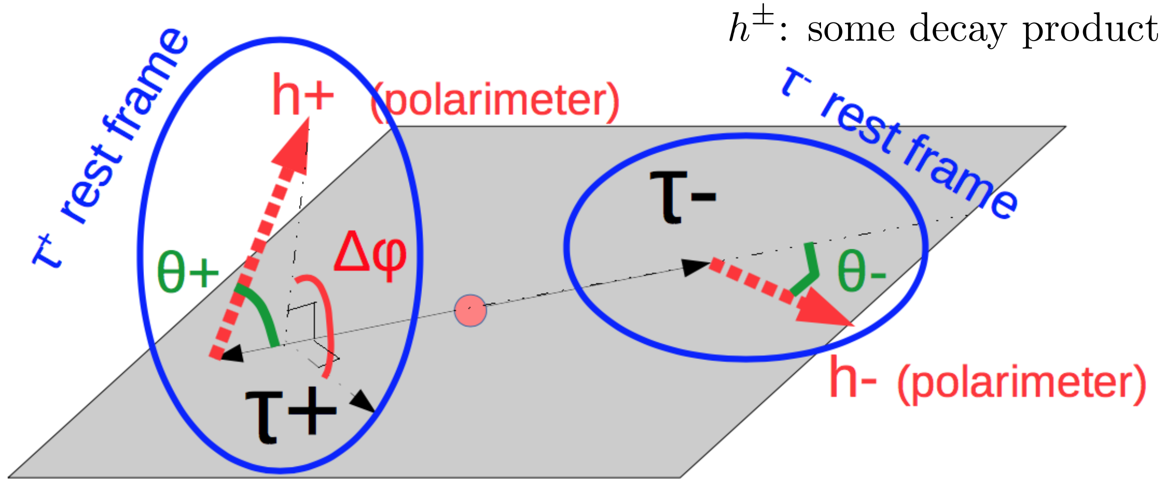
Type-X

Angular distribution of $h \to \tau\tau$

Yukawa coupling: $\mathcal{L}_{h\tau\tau} = g\bar{\tau}(\cos\psi_{CP} + i\gamma_5 \sin\psi_{CP})\tau h$

$$h \to \tau^+\tau^- \to h^+\bar{\nu}h^-\nu$$

$h^{\pm}$: some decay product



[From D. Jeans's slide(ACWS2016)]

$$dN/(d\cos\theta^+ d\cos\theta^- d\phi^+ d\phi^-) \propto (1 + \cos\theta^+ \cos\theta^-) - \sin\theta^+ \sin\theta^- \cos(\Delta\phi - 2\psi_{\rm CP}).$$

ILC250, 2ab^{-1} : $\Delta\psi_{CP}$=4.3°

[Jeans and Wilson, PRD98, 013007 (2018)]

Result

[M. Aoki, K. Hashino, D. Kaneko, S. Kanemura, MK, arXiv: 1808.08770]

ILC250, 2ab^{-1} : $\Delta\psi_{CP}$=4.3°

[Jeans and Wilson, PRD98, 013007 (2018)]

◆ Angular distribution of $h \to \tau\tau$

For $\kappa_V = 0.995, \tan\beta = 5$,

$(\mathrm{Im}\lambda_5, \psi_{CP}) = (0.0, 0°)$,
$(0.4, -26°)$ for $R_{21} \leq 0$,
$(0.4, -30°)$ for $R_{21} \geq 0$.

$\tan\psi_{CP} \equiv c_\tau^p / c_\tau^s$