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

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[arXiv: 1808.08770]

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.

We consider the two Higgs doublet model (2HDM) and analyze a difference between the Higgs coupling constants $(hVV, h\tau\tau, hbb, hcc)$ in the CP-conserving case and the CP-violating case.

The 2HDM with CP-violation

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

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

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

◆ Vacuum expectation value

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

The redefinition of the phases can get θ_j to disappear.

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

Stationary condition

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

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

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

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

$$2\,\mathrm{Im}(\mu_3^2) = v_1 v_2\,\mathrm{Im}(\lambda_5)$$

◆ Parameters in this model

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

◆ Neutral scalar mixing

Higgs basis

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

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

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

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

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

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

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

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

◆ Higgs couplings

H_1: 125 GeV Higgs

f : u, d and e

V : W and Z

$$\mathcal{L}_{H_1VV}^{2HDM} = R_{11} g_{hVV}^{SM} V_\mu V^\mu H_1$$

$$\mathcal{L}_{H_1ff}^{2HDM} = -g_{hff}^{SM}(c_f^s \bar{f}f + c_f^p i\bar{f}\gamma_5 f)H_1$$

$$c_f^s = R_{11} + R_{21}\xi_f$$

$$c_f^p = (-2I_f)R_{31}\xi_f \quad I_u = 1/2,\ I_d = I_e = -1/2$$

	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	$+\cot\beta$	$-\tan\beta$	$+\cot\beta$

References

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

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

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

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

[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)]

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

Result

◆ Input parameters

v	$= 246$ GeV
m_{H_1}	$= 125$ GeV
$\tilde{m}_H$	$= 200$ GeV
$\tilde{m}_A$	$= 250$ GeV

$\tilde{m}_H, \tilde{m}_A$ $(\mathrm{Im}[\lambda_5] \to 0)$ $\to$ mass eigenvalues

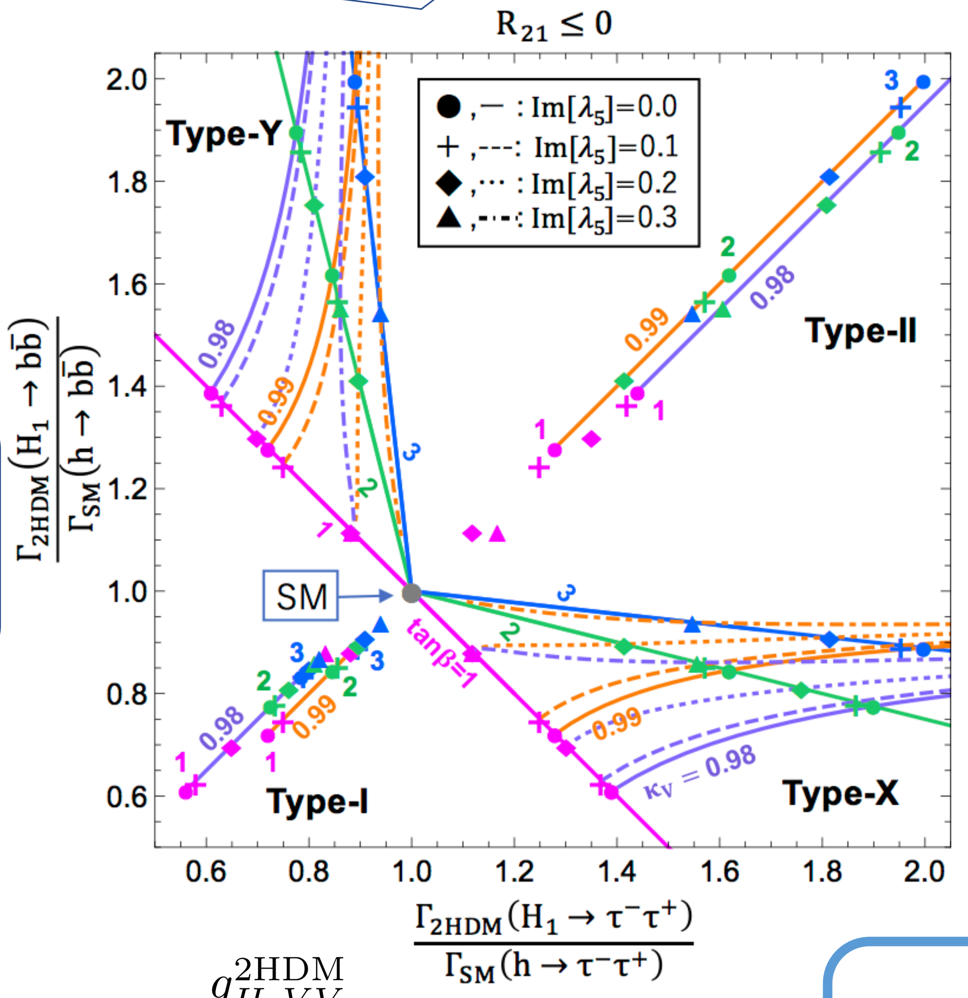
[Kanemura, Yagyu, Phys.Lett. B751 (2015) 289-296]

[Keus, King, Moretti, Yagyu, JHEP 04, 048 (2016)]

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

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

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



$$\kappa_V = \frac{g_{H_1VV}^{2HDM}}{g_{hVV}^{SM}} = R_{11}$$

$$\frac{\Gamma_{2HDM}(H_1 \to f\bar{f})}{\Gamma_{SM}(h \to f\bar{f})} \simeq (c_f^s)^2 + (c_f^p)^2$$

EDM constraint

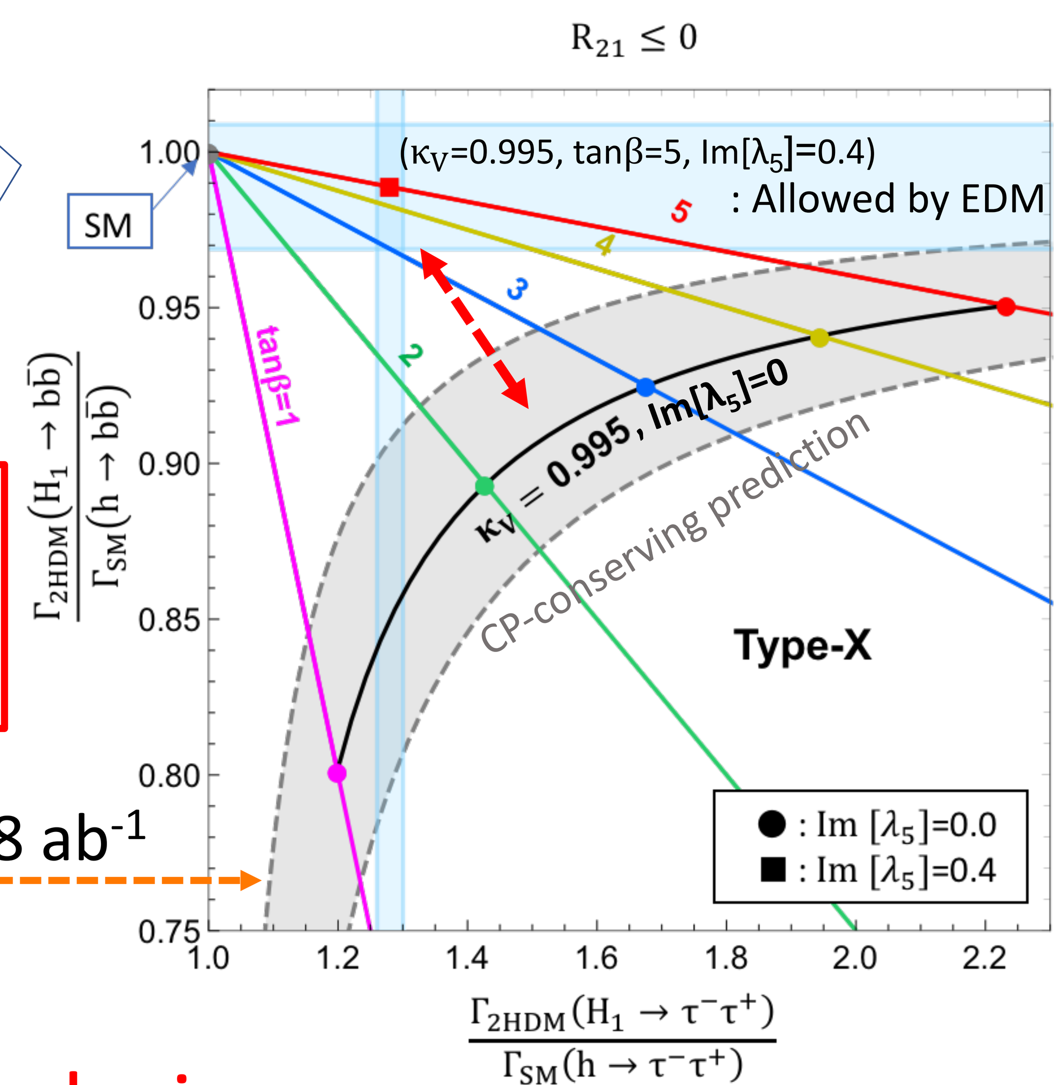
[Cheung, Lee, Senaha, Tseng, JHEP 06, 149 (2014)]

[Keus, King, Moretti, Yagyu, JHEP 04, 048 (2016)]

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

ILC250 (2 ab[-1]) κ_Z: 0.38% κ_b: 1.8% κ_τ: 1.9%

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



Conclusion

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