New scenario for aligned Higgs couplings originated from the twisted custodial symmetry at high energies

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Masashi Aiko (Osaka univ. D3)

Collaboration with: Shinya Kanemura (Osaka univ.)

大阪大学
OSAKA UNIVERSITY

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Introduction

Standard Model (SM) is amazingly consistent with the experimental data.

However, there are Beyond the Standard Model (BSM) problems:

Baryon Asymmetric Universe, Dark matter, Neutrino tiny mass etc.

One Higgs doublet is the assumption in the SM. Extended Higgs models can solve above BSM problems.

We can characterize extended Higgs models by

1. Number and representation of Higgs fields
2. Typical mass scale of new scalars
3. Structure of the Higgs potential etc.

We study the explanation of the current experimental constraints in terms of the global symmetry of the Higgs potential in two-Higgs doublet model.

two-Higgs doublet model (2HDM)

The 2HDM consists of two scalar doublets $\Phi_1,\ \Phi_2$ with $Y = 1/2$

- Higgs potential

$$
\begin{aligned}
V(\Phi_1,\ \Phi_2) = {} & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) \\
& + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + (\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2)\Phi_1^\dagger \Phi_2 + h.c. \right]
\end{aligned}
$$

- Yukawa interaction

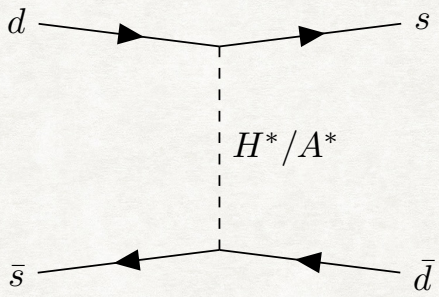
$$
\mathcal{L}_{\text{Yukawa}} = -\sum_{i=1}^{2} \left[\overline{Q}_L Y_{u,i} \tilde{\Phi}_i u_R + \overline{Q}_L Y_{d,i} \Phi_i d_R + \overline{L}_L Y_{\ell,i} \Phi_i \ell_R + h.c. \right]
$$

- Experimental constraints
  1. tree-level Flavor Changing Neutral Currents (FCNCs)
  2. Radiative corrections for electroweak T parameter ($\Delta T \simeq 0$)
  3. SM-like CP-even scalar's couplings

Experimental constraints 1

1. Suppression of FCNCs

$$\mathcal{L}^{d}_{\text{Yukawa}} = -\overline{Q}^{i}_{L}(Y^{ij}_{d,1}\Phi_1 + Y^{ij}_{d,2}\Phi_2)d^{j}_{R}$$



Yukawa matrices may not be diagonalized simultaneously.

$\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ prohibits $Y_{d,1}$ or $Y_{d,2}$

S. L. Glashow, S. Weinberg, PRD15 (1977), E. Paschos, PRD15 (1966)

This solution is scale-independent

$$16\pi^2\beta_{y_{d,2}} = \left(-8g_s^2 - \frac{9}{4}g^2 - \frac{5}{12}g'^2 + \frac{1}{2}y_{u,1}^2 + \cdots\right) y_{d,2} + (y_{u,1}y_{u,2} + 3y_{d,1}y_{d,2} + y_{\ell,1}y_{\ell,2})y_{d,1}$$

If $y_{u,1} = y_{d,2} = y_{\ell,2} = 0$ (Type-II) at some scale Λ, $\beta_{y_{d,2}} = 0 \to y_{d,2} = 0$ at any scale.

FCNC suppression can be understood from the nature of UV theory.

Softly-broken Z_2 symmetric 2HDM

- Higgs potential

*) We also assume CP conservation in the Higgs potential

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

- Yukawa interaction

$$\mathcal{L}_{\rm Yukawa} = -\overline{Q}_L Y_u \tilde{\Phi}_u u_R - \overline{Q}_L Y_d \Phi_d d_R - \overline{L}_L Y_\ell \Phi_\ell \ell_R + h.c.$$

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

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

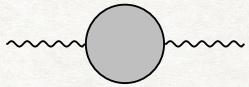
Scalar particles：charged $H^\pm$, CP-odd A and CP-even Higgs h, H

Parameters：$v = 246$ GeV, $m_h = 125$ GeV, m_H, m_A, $m_{H^\pm}$, $M = m_{12}/\sqrt{s_\beta c_\beta}$ and mixing angle β, α

- Experimental constraints
  1. tree-level Flavor Changing Neutral Currents (FCNCs) ✔
  2. Radiative corrections for electroweak T parameter ($\Delta T \simeq 0$)
  3. SM-like CP-even scalar's couplings

Experimental constraints 2

2. Smallness of ΔT



$= g^{\mu\nu}\Pi_{XY} + (q^\mu q^\nu \text{ term})$

$$\alpha_{em}T = \rho - 1 = \frac{e^2}{s_W^2 c_W^2 m_Z^2}\Big[\Pi_{11}(0) - \Pi_{33}(0)\Big], \quad \Delta T \equiv T_{\rm 2HDM} - T_{\rm SM} \simeq 0$$

PDG 2020

$$\rightarrow \begin{cases} m_A^2 = m_{H^\pm}^2 \\ m_H^2 = m_{H^\pm}^2 \quad \text{and} \quad s_{\beta-\alpha} = 1 \end{cases}$$

Custodial $O(4)$ Symmetry A. Pomarol, R. Vega NPB413 (1994)

Twisted Custodial $O(4)$ Symmetry J. Gerard and M. Herquet, PRL 98 (2007)

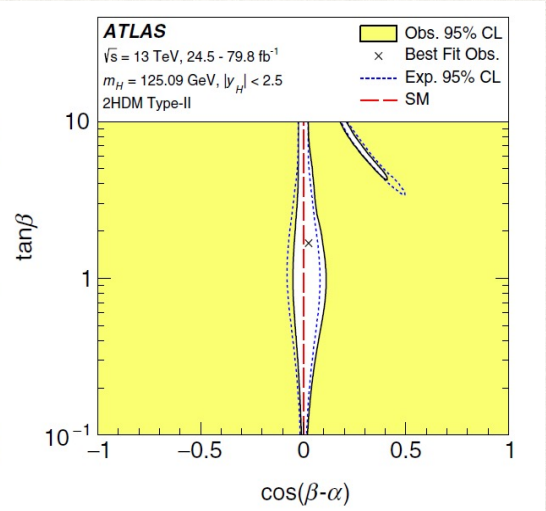
*) We need further degeneracy $M^2 = m_H^2 = m_{H^\pm}^2$

The smallness of ΔT can be understood by symmetry argument.

3. SM-like Higgs couplings

$$\mathcal{L}_{int} = \sin(\beta-\alpha)h\left(\frac{m_W^2}{v}W^{+\mu}W_\mu^- + \frac{m_Z^2}{2v}Z^\mu Z_\mu\right) - \sum_{f=u,d,e}\frac{m_f}{v}[\sin(\beta-\alpha) + \xi_f\cos(\beta-\alpha)]\bar{f}fh$$

The twisted custodial symmetry explain not only $\Delta T \simeq 0$ but also $s_{\beta-\alpha} \simeq 1$

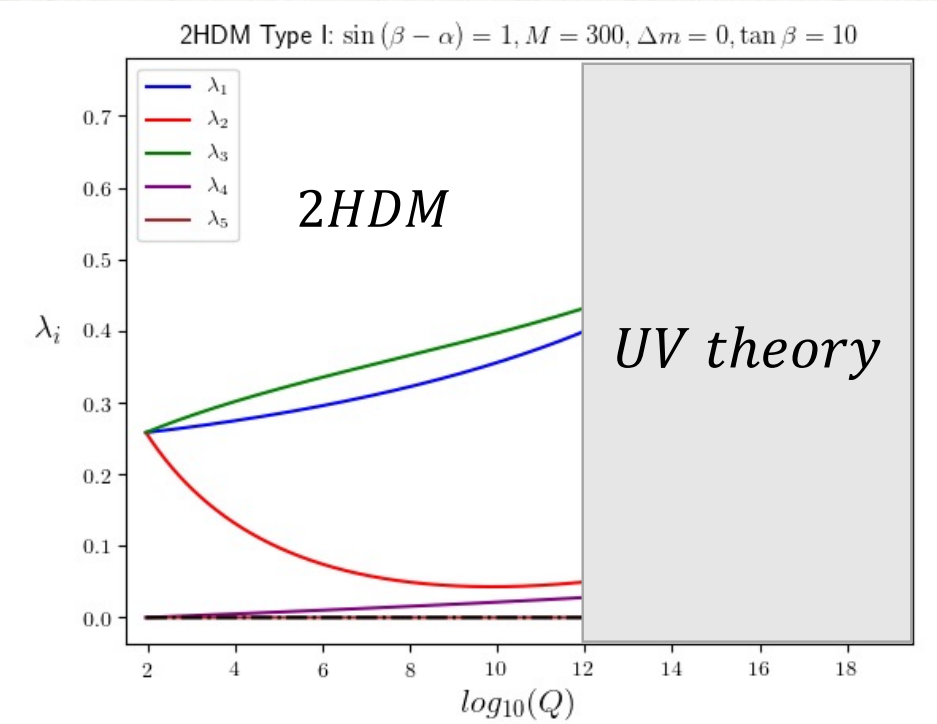


G. Aad et al, PRD101 (2020)

Violation of twisted-custodial symmetry

$Z_2 \times O(4)$ symmetry at the EW scale can explain experimental constraints.

$$\lambda_1(m_Z) = \lambda_2(m_Z) = \lambda_3(m_Z),\ \lambda_4(m_Z) = -\lambda_5(m_Z)$$



$O(4)$ symmetry is violated by the Yukawa and $U(1)_Y$ gauge couplings.

→ Adjustment of $\lambda_i(\Lambda)$ is needed to realize twisted-custodial symmetry at EW scale.

When we consider the scenario

$$\mathcal{L}_{\rm UV}(\Lambda) \Rightarrow \mathcal{L}_{\rm 2HDM}(\Lambda)$$

It would be natural to assume the twisted-custodial symmetry is realized at Λ.

Twisted custodial symmetry at high scale Λ

- Assumption

Higgs potential respects the twisted-custodial symmetry at Λ

$$\lambda_1(\Lambda) = \lambda_2(\Lambda) = \lambda_3(\Lambda),\ \ \lambda_4(\Lambda) = -\lambda_5(\Lambda)$$

These relations are violated under the RG evolution.
However, the conditions

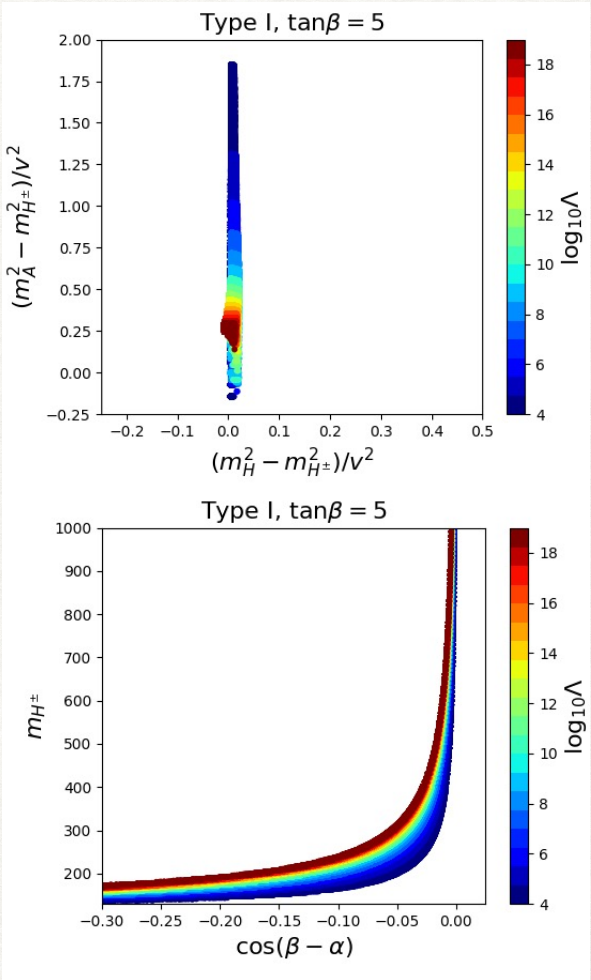
$$m_H^2 \simeq m_{H^\pm}^2 \quad \text{and} \quad s_{\beta-\alpha} \simeq 1$$

are realized at the EW scale without decoupling of additional Higgs bosons.
We can take Λ to the Planck scale.

- Predictions

$m_A \geq m_H \simeq m_{H^\pm}$ and $m_A^2 - m_{H^\pm}^2$ tends to converge if Λ is high.

These features can be tested at LHC and HL-LHC



MA, S. Kanemura, JHEP (2021)

Twisted custodial symmetry at high scale Λ

MA, S. Kanemura, JHEP (2021)

- Deviation in the Higgs couplings

1. hVV couplings

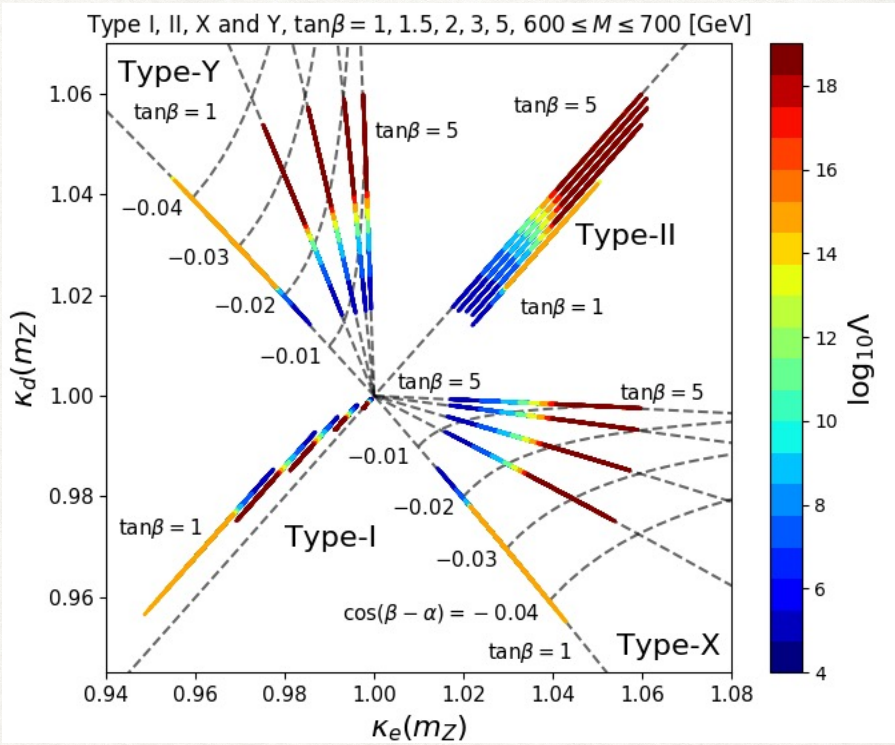
$$\mathcal{L}_{int} = \sin(\beta-\alpha) h \left(\frac{m_W^2}{v} W^{+\mu} W_\mu^- + \frac{m_Z^2}{2v} Z^\mu Z_\mu \right)$$

proportional to $s_{\beta-\alpha} \rightarrow \mathcal{O}(0.1)\%$

2. $hf\bar{f}$ couplings

$$\mathcal{L}_{int} = -\sum_{f=u,d,e} \frac{m_f}{v} [\sin(\beta-\alpha) + \xi_f(\beta)\cos(\beta-\alpha)] \bar{f} f h$$

Possible deviations depend on ξ_f ($\cot\beta$ or $-\tan\beta$)
maximally 6% deviations are expected



- The directions of deviations → types of Yukawa interactions

S. Kanemura, et al, PRD90 (2014)

- The size of deviations → possible scale Λ

These % level deviations can be tested at future lepton collider

Summary

We investigate the scenario where current experimental data can be explained as a consequence of the global symmetry of the Higgs potential at some higher scale Λ.

- Assumption
  Twisted-custodial symmetry are imposed at higher scale Λ

- Results and predictions
  Λ can be taken at the Planck scale without conflicting with the experimental data.
  Mass spectrum of the additional Higgs bosons ($m_A \geq m_H \simeq m_{H^\pm}$) and deviations in the Higgs couplings are predicted as a function of Λ

- Message
  In this scenario, masses of the additional Higgs bosons can be taken around EW scale.
  We can test the predictions in the current and future colliders.

Backup

Custodial symmetry in the 2HDM 1/3

- Higgs basis

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}, \quad \langle H_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle H_2 \rangle = 0$$

- Higgs Potential

$$\begin{aligned} V(H_1, H_2) = {} & Y_1^2 |H_1|^2 + Y_2^2 |H_2|^2 - Y_3^2 (H_1^\dagger H_2 + H_2^\dagger H_1) \\ & + \frac{1}{2} Z_1 |H_1|^4 + \frac{1}{2} Z_2 |H_2|^4 + Z_3 |H_1|^2 |H_2|^2 + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + Z_5 [(H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2] + [Z_6 |H_1|^2 + Z_7 |H_2|^2](H_1^\dagger H_2 + H_2^\dagger H_1) \end{aligned}$$

- Z_6 and Z_7 satisfy

$$\begin{aligned} Z_6 + Z_7 &= -\frac{1}{2}(Z_1 - Z_2) \tan 2\beta \\ Z_6 - Z_7 &= -\frac{1}{4}[Z_1 + Z_2 - 2(Z_3 + Z_4 + Z_5)] \tan 4\beta \end{aligned}$$

Custodial symmetry in the 2HDM 2/3

- Bi-doublet

$$M_i = (i\sigma_2 H_i^*, H_i), \ (i = 1, 2)$$

$$M_i' \equiv M_i \exp[-i\chi\sigma_3] = M_i \mathrm{diag}(e^{-i\chi}, e^{i\chi})$$

- Transformation of M_i under $O(4) \simeq SU(2)_L \times SU(2)_R$

$$M_1 \to L M_1 R^\dagger, \ M_2' \to L M_2' R^\dagger$$

- Gauge invariant quantities

$$\mathrm{Tr}(M_1^\dagger M_1) = 2|H_1|^2,$$
$$\mathrm{Tr}(M'^\dagger_2 M_2') = 2|H_2|^2,$$
$$\mathrm{Tr}(M_1^\dagger M_2') = 2(e^{i\chi} H_1^\dagger H_2 + e^{-i\chi} H_2^\dagger H_1),$$
$$\mathrm{Tr}(M_1^\dagger M_2' \sigma_3) = 2(e^{i\chi} H_1^\dagger H_2 - e^{-i\chi} H_2^\dagger H_1)$$

← only breaks $SU(2)_L \times SU(2)_R$

Custodial symmetry in the 2HDM 3/3

- Higgs potential

$$
\begin{aligned}
V(M_1, M_2') = &\frac{1}{2}Y_1^2 \mathrm{Tr}(M_1^\dagger M_1) + \frac{1}{2}Y_2^2 \mathrm{Tr}(M'^\dagger_2 M_2') - \mathrm{Re}(Y_3^2 e^{-i\chi})\mathrm{Tr}(M_1^\dagger M_2') \\
&+ \frac{1}{8}Z_1\,\mathrm{Tr}^2(M_1^\dagger M_1) + \frac{1}{8}Z_2\,\mathrm{Tr}^2(M'^\dagger_2 M_2') + \frac{1}{4}Z_3\,\mathrm{Tr}(M_1^\dagger M_1)\mathrm{Tr}(M'^\dagger_2 M_2') \\
&+ \frac{1}{4}[Z_4 + \mathrm{Re}(Z_5 e^{-2i\chi})]\mathrm{Tr}^2(M_1^\dagger M_2') \\
&+ \frac{1}{2}[\mathrm{Re}(Z_6 e^{-i\chi})\,\mathrm{Tr}(M_1^\dagger M_1) + \mathrm{Re}(Z_7 e^{-i\chi})\,\mathrm{Tr}(M'^\dagger_2 M_2')]\mathrm{Tr}(M_1^\dagger M_2') \\
&- i\,\mathrm{Im}(Y_3^2 e^{-i\chi})\,\mathrm{Tr}(M_1^\dagger M_2'\sigma_3) - \frac{1}{4}[Z_4 - \mathrm{Re}(Z_5 e^{-2i\chi})]\mathrm{Tr}^2(M_1^\dagger M_2'\sigma_3) \\
&- \frac{i}{2}\mathrm{Im}(Z_5 e^{-2i\chi})\,\mathrm{Tr}(M_1^\dagger M_2')\mathrm{Tr}(M_1^\dagger M_2'\sigma_3) \\
&- \frac{i}{2}[\mathrm{Im}(Z_6 e^{-i\chi})\,\mathrm{Tr}(M_1^\dagger M_1) + \mathrm{Im}(Z_7 e^{-i\chi})\,\mathrm{Tr}(M'^\dagger_2 M_2')]\mathrm{Tr}(M_1^\dagger M_2'\sigma_3).
\end{aligned}
$$

- Imposing $SU(2)_L \times SU(2)_R$

$$
\begin{aligned}
&\mathrm{Im}(Y_3^2 e^{-i\chi}) = \mathrm{Im}(Z_5 e^{-2i\chi}) = \mathrm{Im}(Z_6 e^{-i\chi}) = \mathrm{Im}(Z_7 e^{-i\chi}) = 0, \\
&\qquad Z_4 = \mathrm{Re}(Z_5 e^{-2i\chi}).
\end{aligned}
\quad \longrightarrow \quad
\begin{aligned}
&\lambda_4 = \lambda_5 && \text{for} \quad \chi = 0, \pi \\
&\quad \text{or} \\
&\lambda_4 = -\lambda_5,\ \lambda_1 = \lambda_2 = \lambda_3 && \text{for} \quad \chi = \pi/2,\ 3\pi/2
\end{aligned}
$$

Results for $\lambda_i(m_Z)$

- Assumption

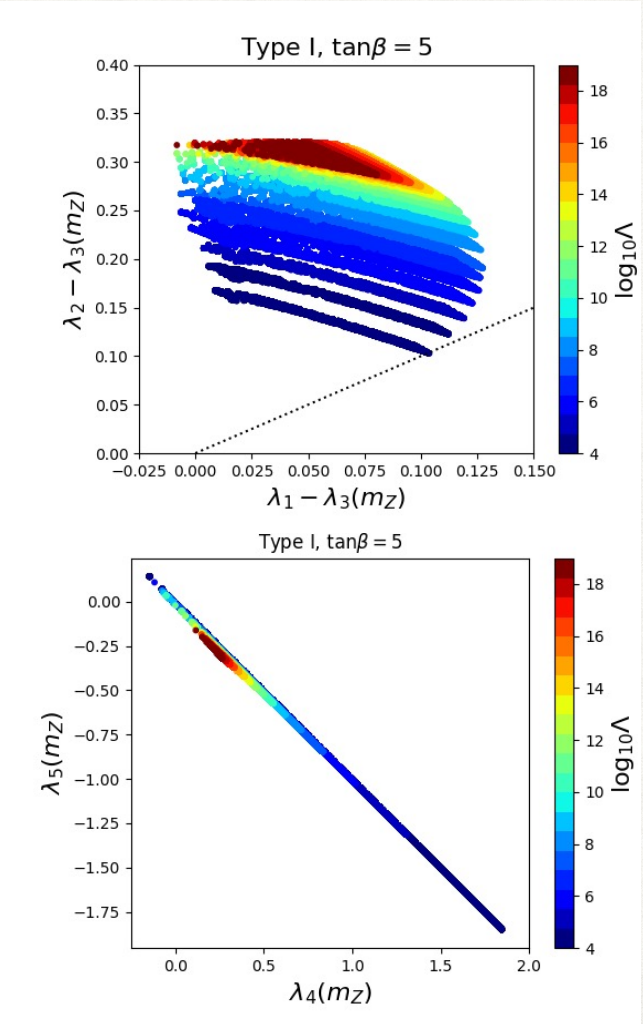
Higgs potential respects the twisted-custodial symmetry at Λ

$$\lambda_1(\Lambda) = \lambda_2(\Lambda) = \lambda_3(\Lambda),\ \ \lambda_4(\Lambda) = -\lambda_5(\Lambda)$$

First relation is violated under the RG evolution.

However, $\lambda_4(m_Z) = -\lambda_5(m_Z)$ is approximately realized.

$$16\pi^2 \frac{d(\lambda_4+\lambda_5)}{d\ln\mu} = 2(\lambda_1+\lambda_2+4\lambda_3+2\lambda_4+4\lambda_5)(\lambda_4+\lambda_5)$$
$$- 3(3g^2+g'^2)(\lambda_4+\lambda_5)$$
$$+ 2(3y_t^2+3y_b^2+y_\tau^2)(\lambda_4+\lambda_5) + 3g^2g'^2$$



Mass differences

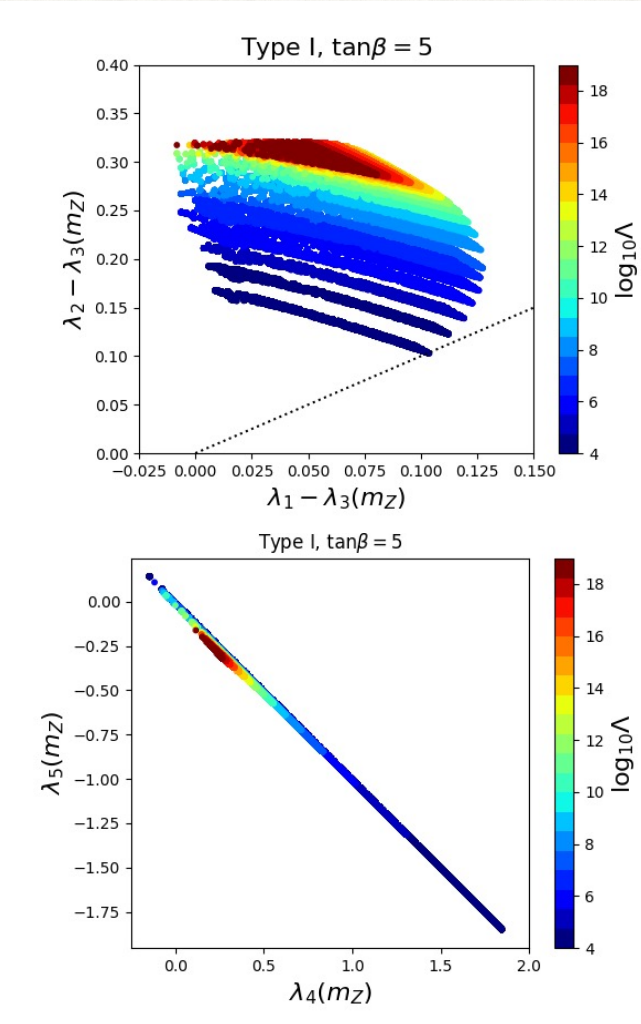
- We have seen that following conditions are approximately realized in this scenario.

$$s_{\beta-\alpha} \simeq 1 \quad \text{if } m_{H^\pm} \gtrsim 300 \text{ GeV}$$
$$\lambda_4 + \lambda_5 \simeq 0 \quad \text{at EW scale}$$

- The mass squared differences among the additional Higgs bosons can be simplified as

$$\frac{m_A^2 - m_{H^\pm}^2}{v^2} \simeq \lambda_4 \gtrsim 0,$$
$$\frac{m_H^2 - m_{H^\pm}^2}{v^2} \simeq (\lambda_1 + \lambda_2 - 2\lambda_3)\cot^2\beta \left(\frac{1}{1+\cot^2\beta}\right)^2$$

The mass difference between H and $H^\pm$ is generated via violation effects for $\lambda_1 = \lambda_2 = \lambda_3$. However, it is suppressed via $\tan\beta$.



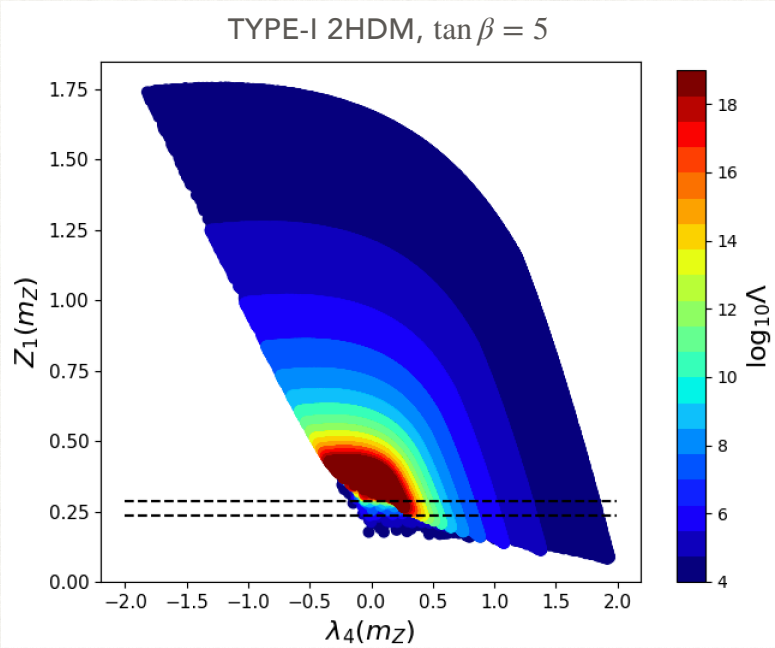
Positivity of $m_A^2 - m_{H^\pm}^2 = \lambda_4 v^2$

- Higgs basis

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}, \quad \langle H_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle H_2 \rangle = 0$$

- Mass matrix of neutral scalars in Higgs basis

$$\mathcal{M} = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & Y_2^2 + \frac{1}{2} Z_{345} v^2 \end{pmatrix} \begin{matrix} h_1 \\ h_2 \end{matrix}$$



Observed data : $Z_6 v^2 \simeq 0$, $(\beta - \alpha \simeq \pi/2)$

$m_h = 125$ GeV is determined only by $Z_1 v^2 \to Z_1 \simeq 0.26$

$\lambda_4 < 0$ is almost rejected by vacuum stability