Aligned Higgs couplings originated from the twisted custodial symmetry at high energies

Masashi Aiko[a] and Shinya Kanemura JHEP 02 (2021) 046 (hep-ph: 2009.04330)
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1. Introduction

Symmetry is the key for Beyond the Standard Model (BSM) physics.

Experimental facts

- Electroweak (EW) rho parameter: $\rho \simeq 1$. PDG 2020
- SM-like Higgs couplings (alignment) G. Aad et al, PRD101 (2020)

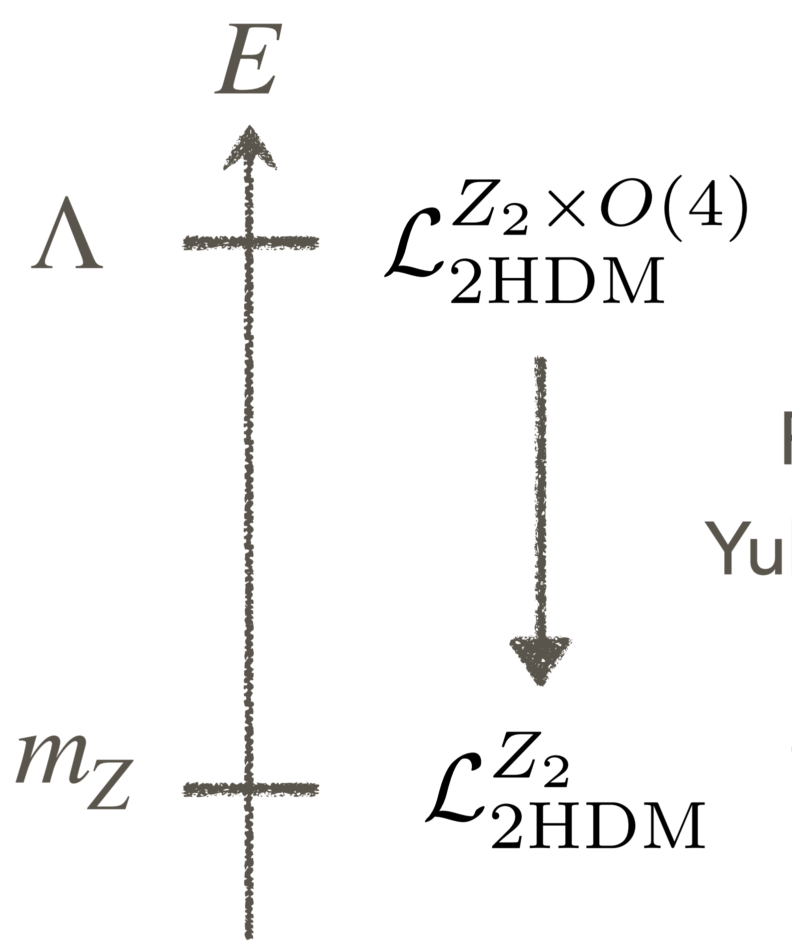
Assumption

Symmetry exists behind these experimental facts.

→ Twisted Custodial Symmetry (TCS) in two-Higgs doublet model (2HDM)
J. Gerard and M. Herquet, PRL 98 (2007)

Question: Can TCS at high energy scale explain above constraints?

2. Renormalization Group Flow



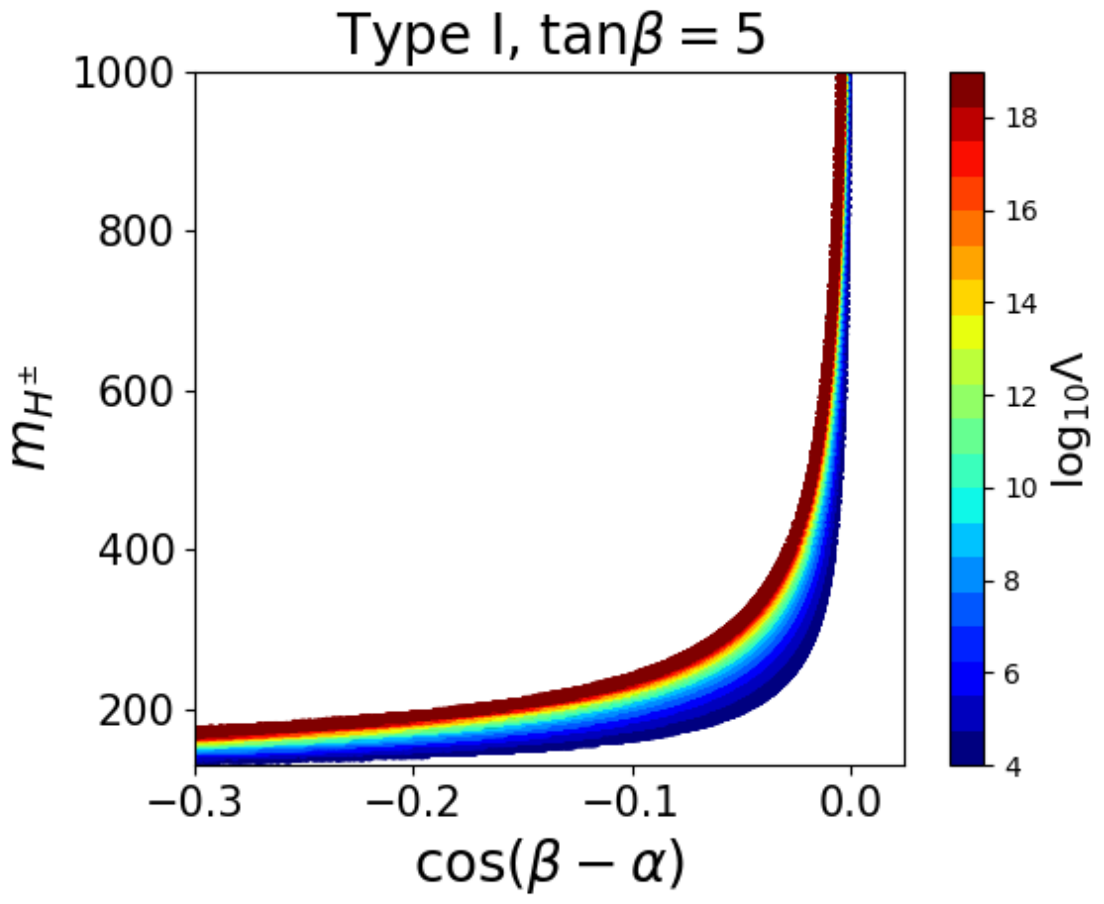
Conditions of TCS: $\lambda_1(\Lambda) = \lambda_2(\Lambda) = \lambda_3(\Lambda)$, $\lambda_4(\Lambda) + \lambda_5(\Lambda) = 0$

Renormalization group flow at 1-loop level

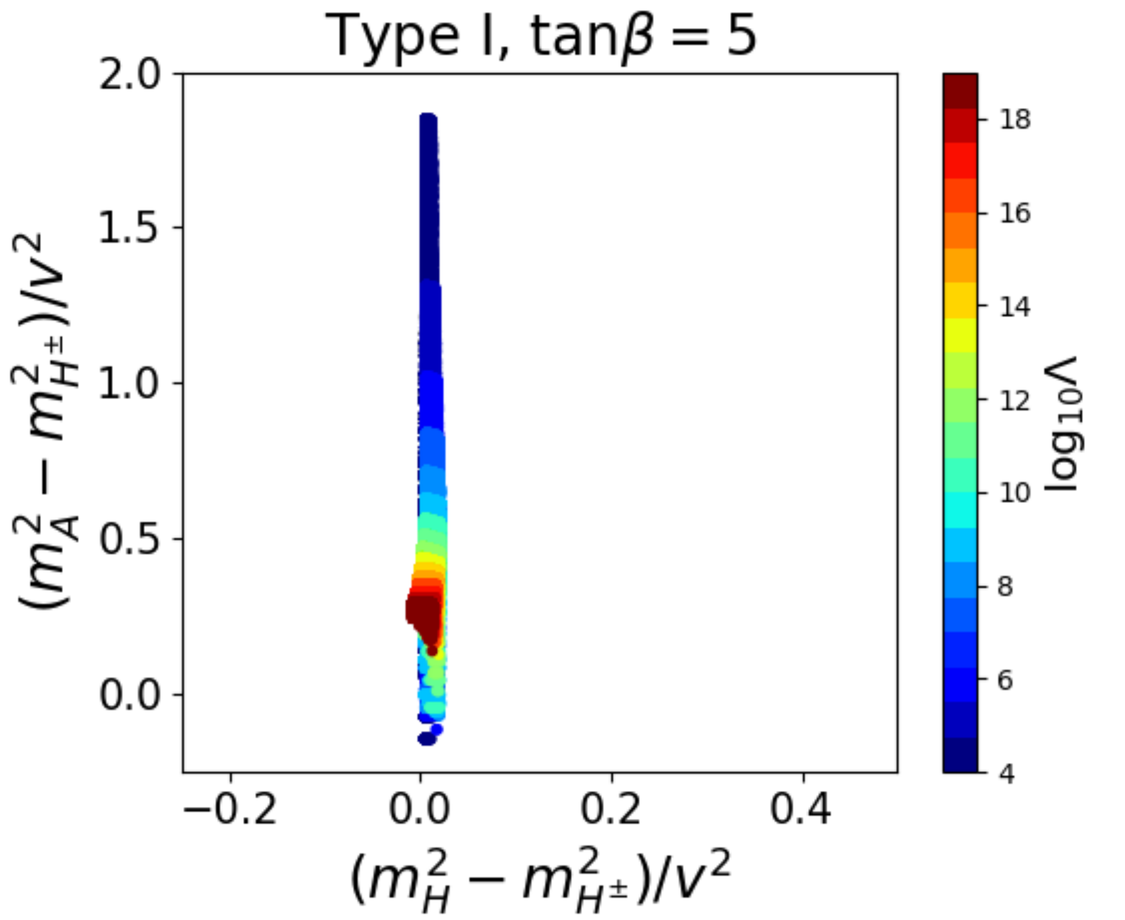
Yukawa and $U(1)_Y$ gauge couplings break TCS.

Check: $m_h \simeq 125$ GeV, $\sin(\beta-\alpha) \simeq 1$, $\Delta\rho \simeq 0$ ($m_H \simeq m_{H^\pm}$)

3. Results



Alignment without decoupling



Mass degeneracy $m_H \simeq m_{H^\pm}$

4. Predictions

- Mass spectrum

  $m_A \gtrsim m_H \simeq m_{H^\pm}$

  $m_A^2 - m_{H^\pm}^2$ converges if Λ is high

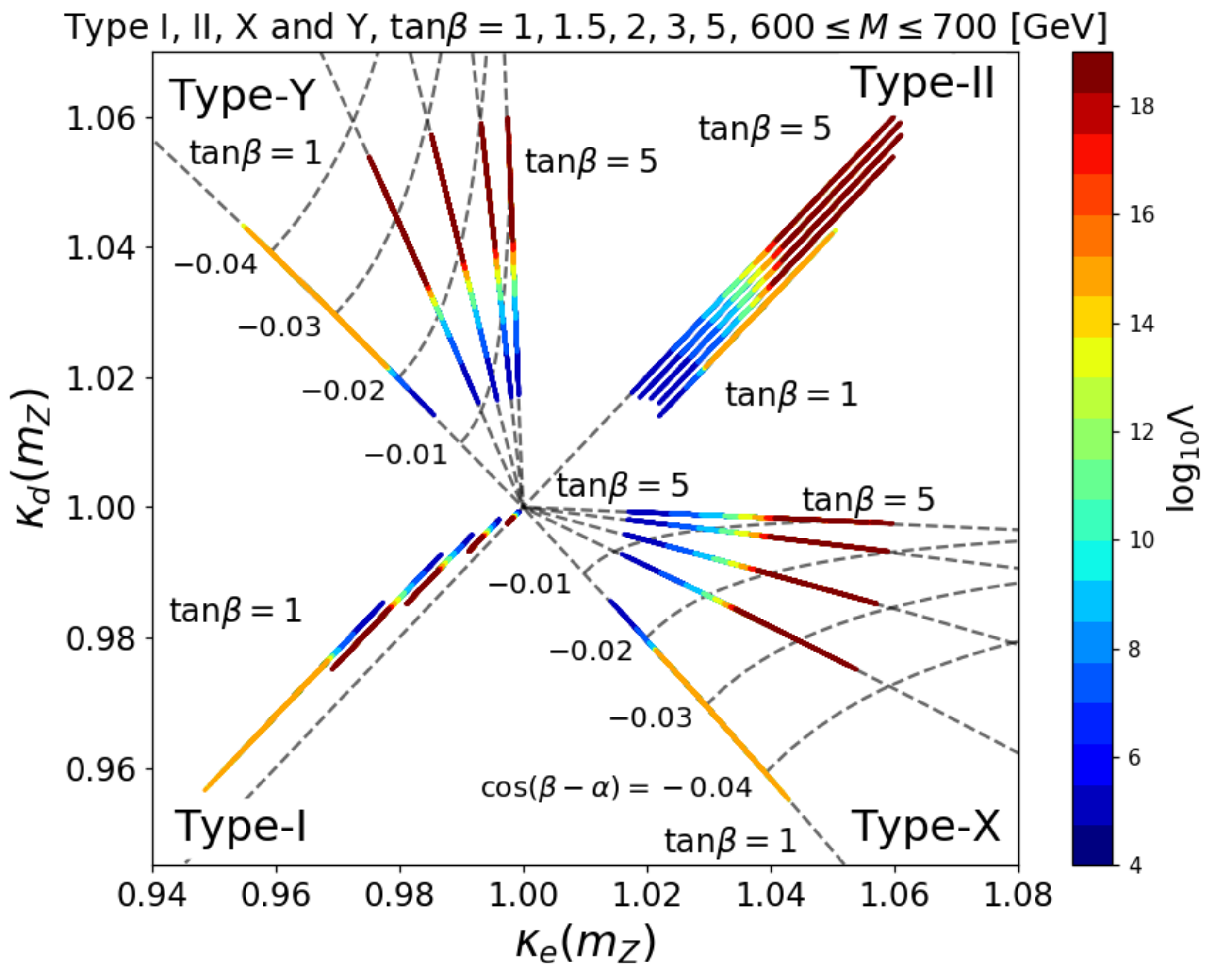
- Deviation in $hf\bar{f}$ couplings

  The directions of deviations

  → types of Yukawa interactions

  The size of deviations

  → possible high scale Λ



These features can be tested at future hadron and lepton colliders.

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• 2HDM (1/2)

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

We impose softly-broken Z_2 symmetry to avoid FCNCs at tree level.

- Higgs potential (* CP conservation is also assumed)

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

- Yukawa interaction

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

• 2HDM (2/2)

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 $\beta,\ \alpha$

There are four independent Types of Yukawa interactions

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

• TCS in 2HDM (1/2)

We work in the 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

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

with the conditions

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

• TCS in 2HDM (2/2)

Bi-doublet

$$M_i = (i\sigma_2 H_i^*, H_i),\ (i=1,2),\quad M_i' \equiv M_i\exp[-i\chi\sigma_3] = M_i{\rm diag}(e^{-i\chi}, e^{i\chi})$$

Gauge invariant quantities

$${\rm Tr}(M_1^\dagger M_1) = 2|H_1|^2,\ {\rm Tr}(M'^\dagger_2 M_2') = 2|H_2|^2,$$
$${\rm Tr}(M_1^\dagger M_2') = 2(e^{i\chi}H_1^\dagger H_2 + e^{-i\chi}H_2^\dagger H_1),$$
$${\rm Tr}(M_1^\dagger M_2'\sigma_3) = 2(e^{i\chi}H_1^\dagger H_2 - e^{-i\chi}H_2^\dagger H_1)$$ ← only breaks $SU(2)_L\times SU(2)_R$

Imposing $SU(2)_L\times SU(2)_R$, we obtain

$$\lambda_4=\lambda_5 \quad \text{for} \quad \chi = 0,\pi$$
$$\lambda_4=-\lambda_5,\ \lambda_1=\lambda_2=\lambda_3 \quad \text{for} \quad \chi=\pi/2,\ 3\pi/2$$

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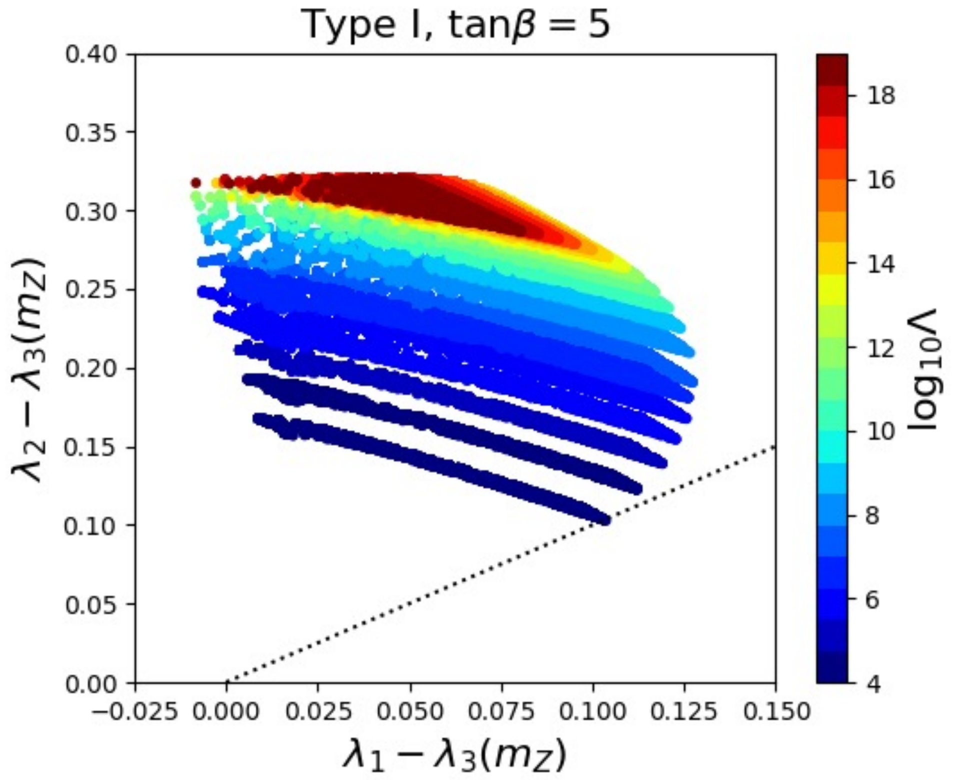
• Violation of TCS at EW (1/2)

Conditions of TCS for Higgs quartic couplings

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

Yukawa and $U(1)_Y$ couplings break these conditions under RG flow.

Especially, first condition is violated at the EW scale because only Φ_2 couples to the top quark.

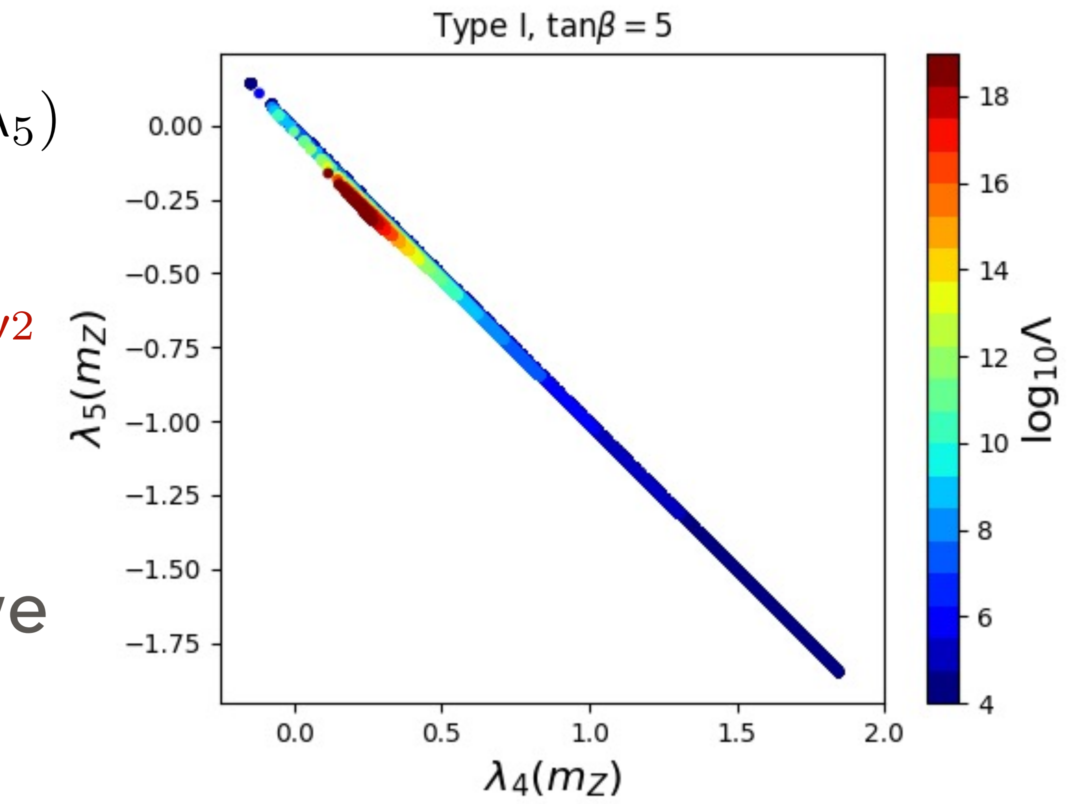


• Violation of TCS at EW (2/2)

On the other hand, $\lambda_4(m_Z) = -\lambda_5(m_Z)$ is approximately realized even at the EW scale.

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

In type-I and X, gauge coupling only breaks this condition. (In type-II and Y, we also have $y_t^2 y_b^2$)



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

Mass matrix of neutral scalars in Higgs basi

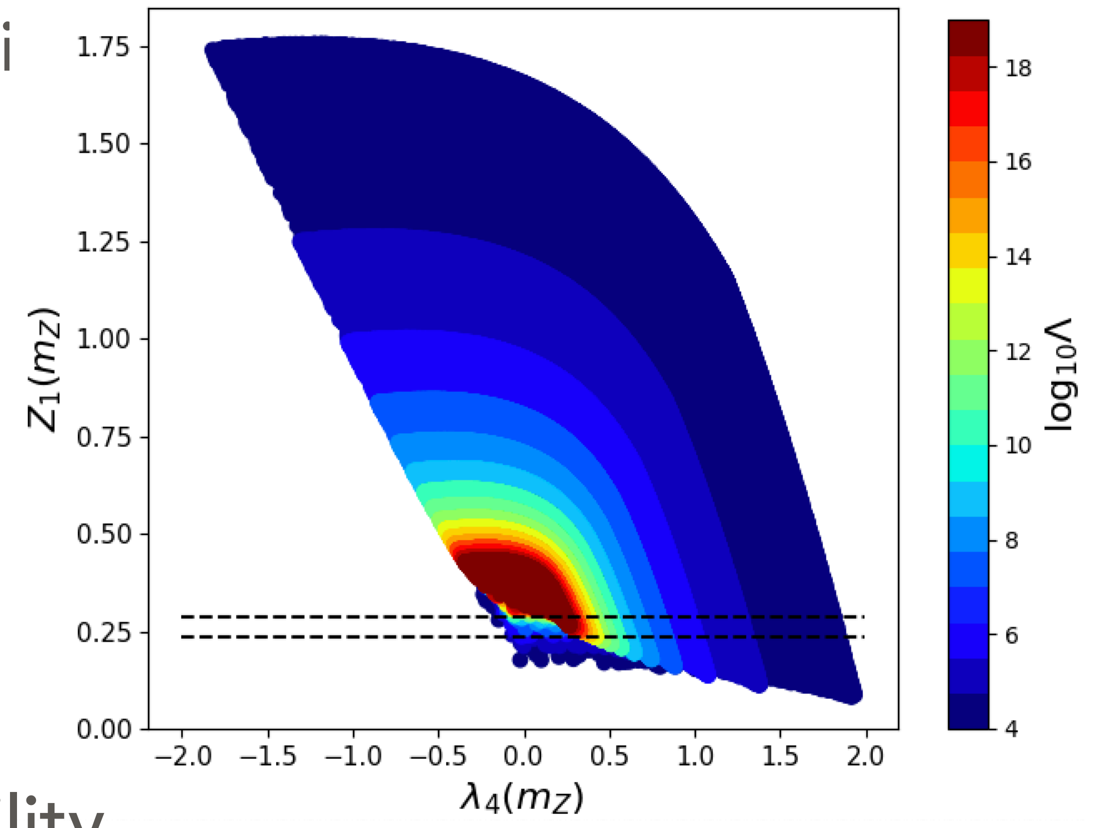
$$\mathcal{M} = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & Y_2^2 + \frac{1}{2} Z_{345} v^2 \end{pmatrix} \begin{matrix} h_1 \\ h_2 \end{matrix}$$

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

$m_h = 125$ GeV is determined only by

$$Z_1 v^2 \rightarrow Z_1 \simeq 0.26$$

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



• Mass difference

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

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

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 $\tan\beta$.