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

Based on JHEP 02 (2021) 046 [arXiv:2009.04330]

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This work

We study the scenario where experimental data are explained as a consequence of the global symmetry of the Higgs potential at a higher scale Λ.

Assumption

Softly-broken Z_2 and twisted-custodial symmetry at a higher scale Λ

Experimental constraints

- tree-level Flavor Changing Neutral Currents (FCNCs)
- Electroweak T parameter
- SM-like Higgs couplings

Results and predictions

- The above constraints are satisfied without decoupling
- Λ can be taken at the Planck scale
- Mass spectrum of the additional Higgs bosons
- Deviations in the Higgs couplings

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.

Higgs sector

- Number and representation of Higgs fields
- The typical mass scale of new scalars
- Structure of the Higgs potential etc.

We study the global symmetry of the Higgs potential from the viewpoint of experimental constraints.

Two Higgs doublet model (2HDM)

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

Potential

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

Yukawa interaction

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

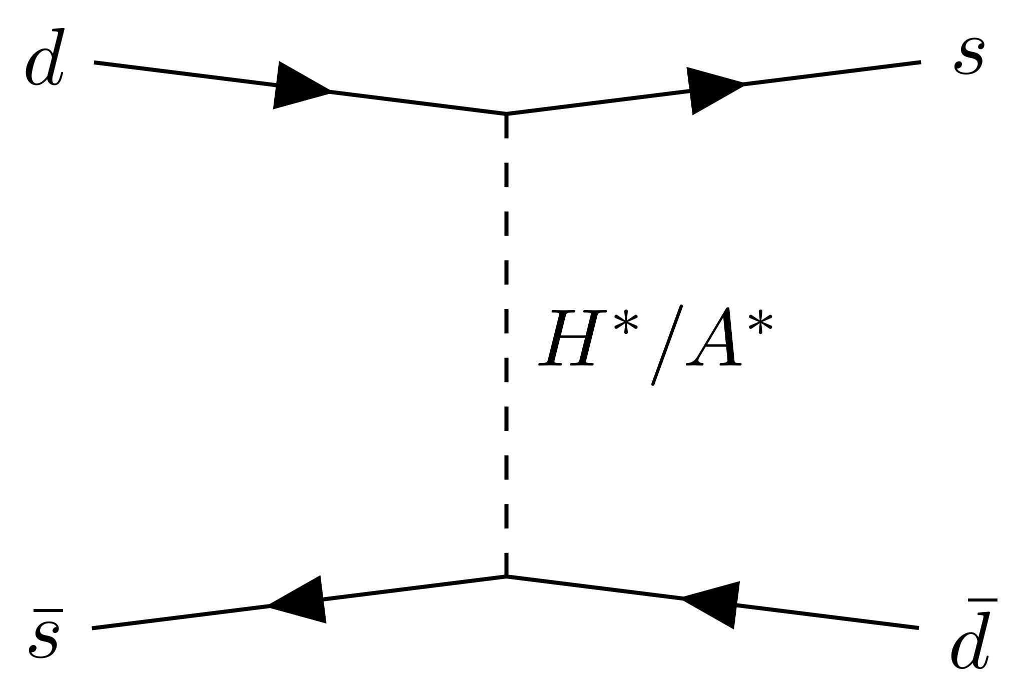
Experimental constraints

- Tree-level Flavor Changing Neutral Currents (FCNCs)
- Electroweak T parameter
- SM-like Higgs couplings

Tree-level 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 would not be diagonalized simultaneously.



Z_2 symmetry

$$\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2 \quad Y_{d,1} = 0 \text{ or } Y_{d,2} = 0$$

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 a scale $\Lambda \to y_{d,2} = 0$ at any low energy scale.

Softly-broken Z_2 symmetric 2HDM

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

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

2HDM can be classified into Type-I, II, X and Y.

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

Particles & Parameters

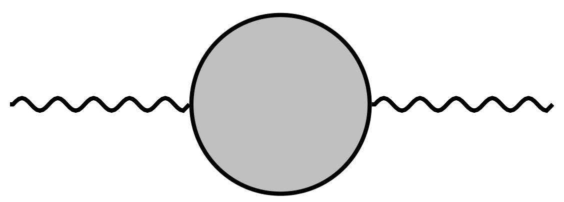
- h (SM-like Higgs boson), H, A, $H^\pm$
- v (=246 GeV), m_h (=125 GeV), m_H, m_A, $m_{H^\pm}$, $M^2 = m_{12}^2/(s_\beta c_\beta)$, $\tan\beta$, $s_{\beta-\alpha}$

Experimental constraints

- tree-level FCNCs ✔
- Electroweak T parameter
- SM-like Higgs couplings

Experimental constraints 2

Electroweak T parameter

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

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

PDG 2020

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

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

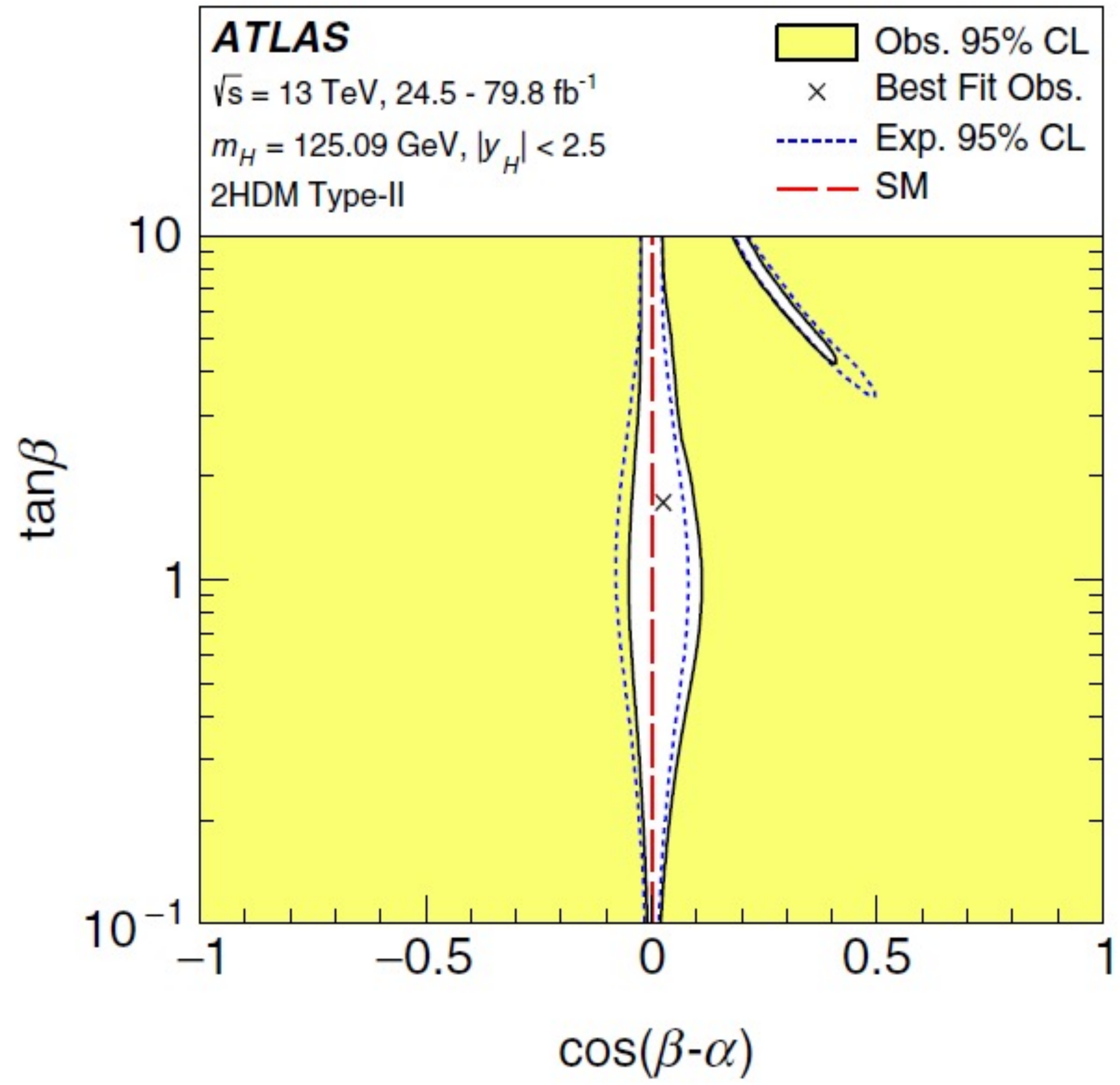
Twisted Custodial Symmetry — J. Gerard, M. Herquet, PRL 98 (2007)

The smallness of ΔT is understood by symmetry ✔

SM-like Higgs couplings

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

The twisted custodial symmetry ensures $s_{\beta-\alpha} = 1$ ✔

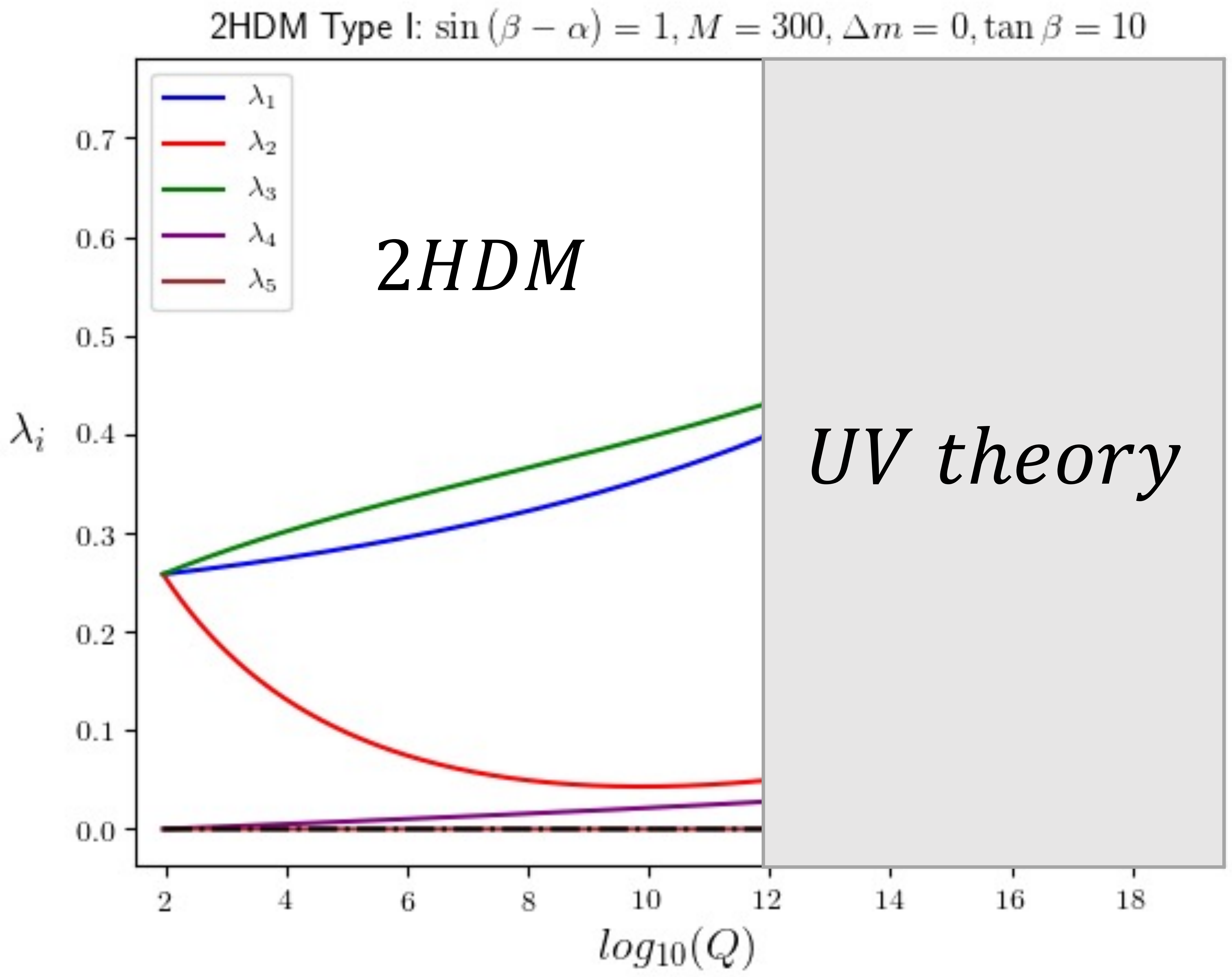


G. Aad et al, PRD101 (2020)

Violation of twisted-custodial symmetry

$Z_2 \times O(4)$ symmetry

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

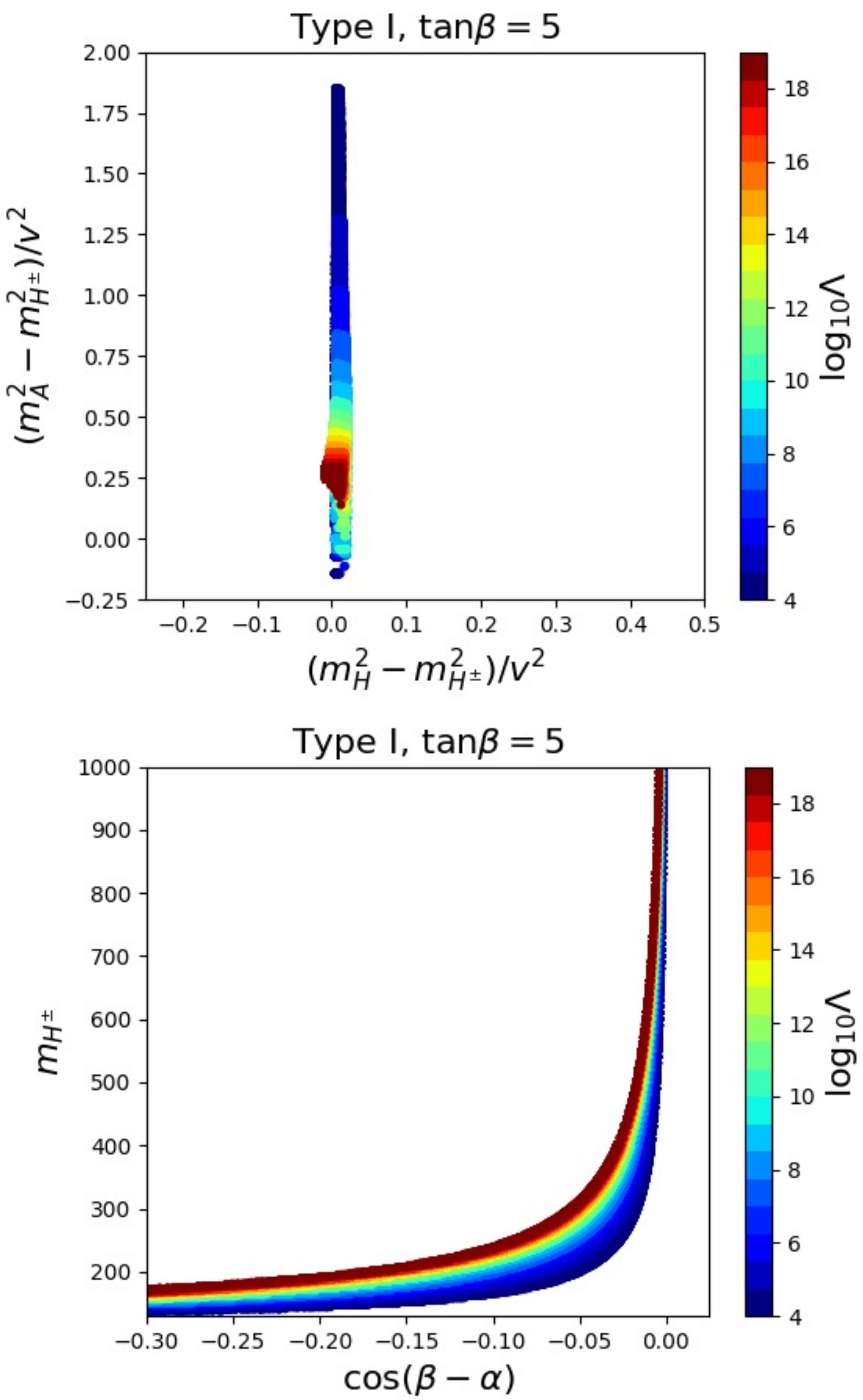


Violation in RGE

The Yukawa and $U(1)_Y$ gauge couplings violate $O(4)$ symmetry.

Scenario

- Twisted custodial symmetry at EW
  - $\lambda_i(\Lambda)$ should be adjusted.
- Twisted custodial symmetry at a high scale
  - Can we explain the experimental constraint?



MA, S. Kanemura, JHEP (2021)

Assumption

- 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

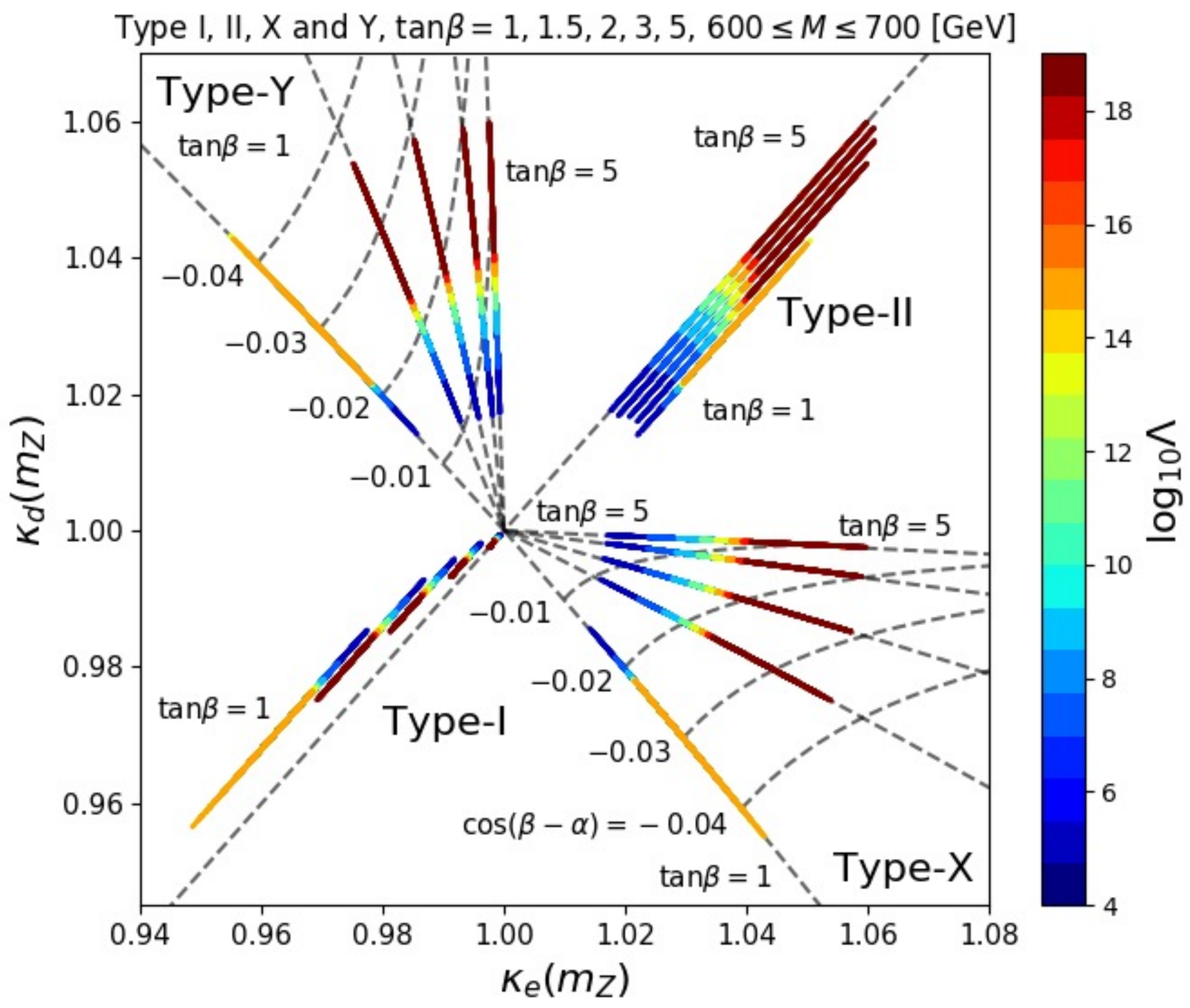
Results

- $m_H^2 \simeq m_{H^\pm}^2$ and $s_{\beta-\alpha} \simeq 1$ at EW scale without decoupling
- The scale Λ can be taken to the Planck scale

Predictions

- $m_A \geq m_H \simeq m_{H^\pm}$
- $m_A^2 - m_{H^\pm}^2$ takes a fixed value if Λ is high.

These features can be tested at LHC and HL-LHC



MA, S. Kanemura, JHEP (2021)

Deviation in the Higgs couplings

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

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

- Deviations in $hf\bar{f}$ couplings depend on ξ_f

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

Predictions

- The directions of deviations S. Kanemura, et al, PRD90 (2014)
  $\to$ types of Yukawa interactions
- The size of deviations $\to$ possible scale Λ

These % level deviations can be tested at future lepton collider

Summary

We have found the scenario where experimental data are explained as a consequence of the global symmetry of the Higgs potential at a higher scale Λ.

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Experimental constraints

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Results and predictions

- The above constraints are satisfied without decoupling
- Λ can be taken at the Planck scale
- Mass spectrum of the additional Higgs bosons
- Deviations in the Higgs couplings $\rightarrow$ detectable at the ILC

Back up

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 invariants

$$\mathrm{Tr}(M_1^\dagger M_1) = 2|H_1|^2,$$

$$\mathrm{Tr}(M'^\dagger_2 M_2') = 2|H_2|^2,$$

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

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

Custodial symmetry in the 2HDM 3/3

Higgs potential

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

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

$$
\begin{aligned}
\mathrm{Im}(Y_3^2 e^{-i\chi}) = \mathrm{Im}(Z_5 e^{-2i\chi}) = \mathrm{Im}(Z_6 e^{-i\chi}) = \mathrm{Im}(Z_7 e^{-i\chi}) = 0, \\
Z_4 = \mathrm{Re}(Z_5 e^{-2i\chi}).
\end{aligned}
$$

$\lambda_4 = \lambda_5$ for $\chi = 0, \pi$

→ or

$\lambda_4 = -\lambda_5,\ \lambda_1 = \lambda_2 = \lambda_3$ for $\chi = \pi/2,\ 3\pi/2$

Results for $\lambda_i(m_Z)$

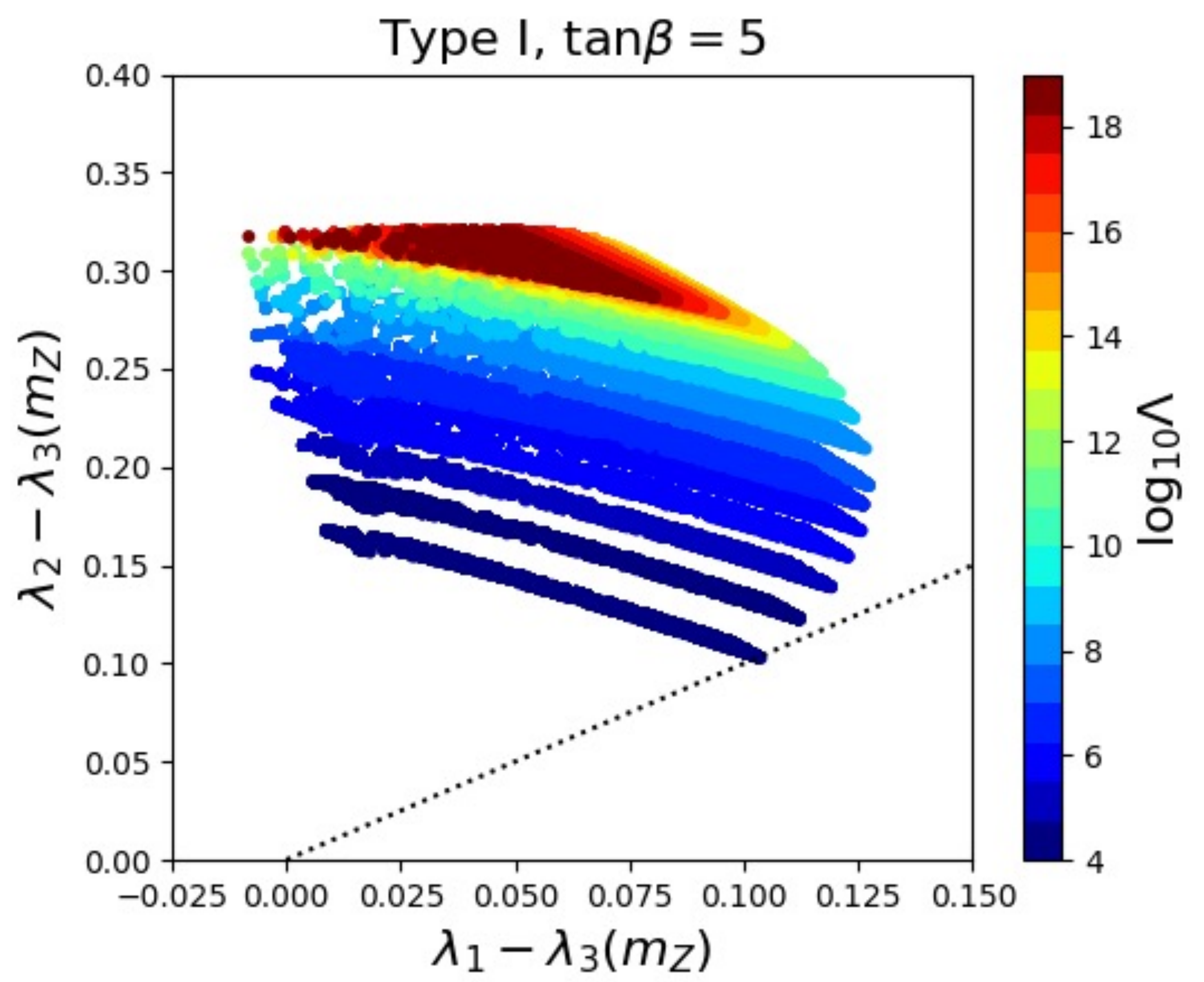
Assumption

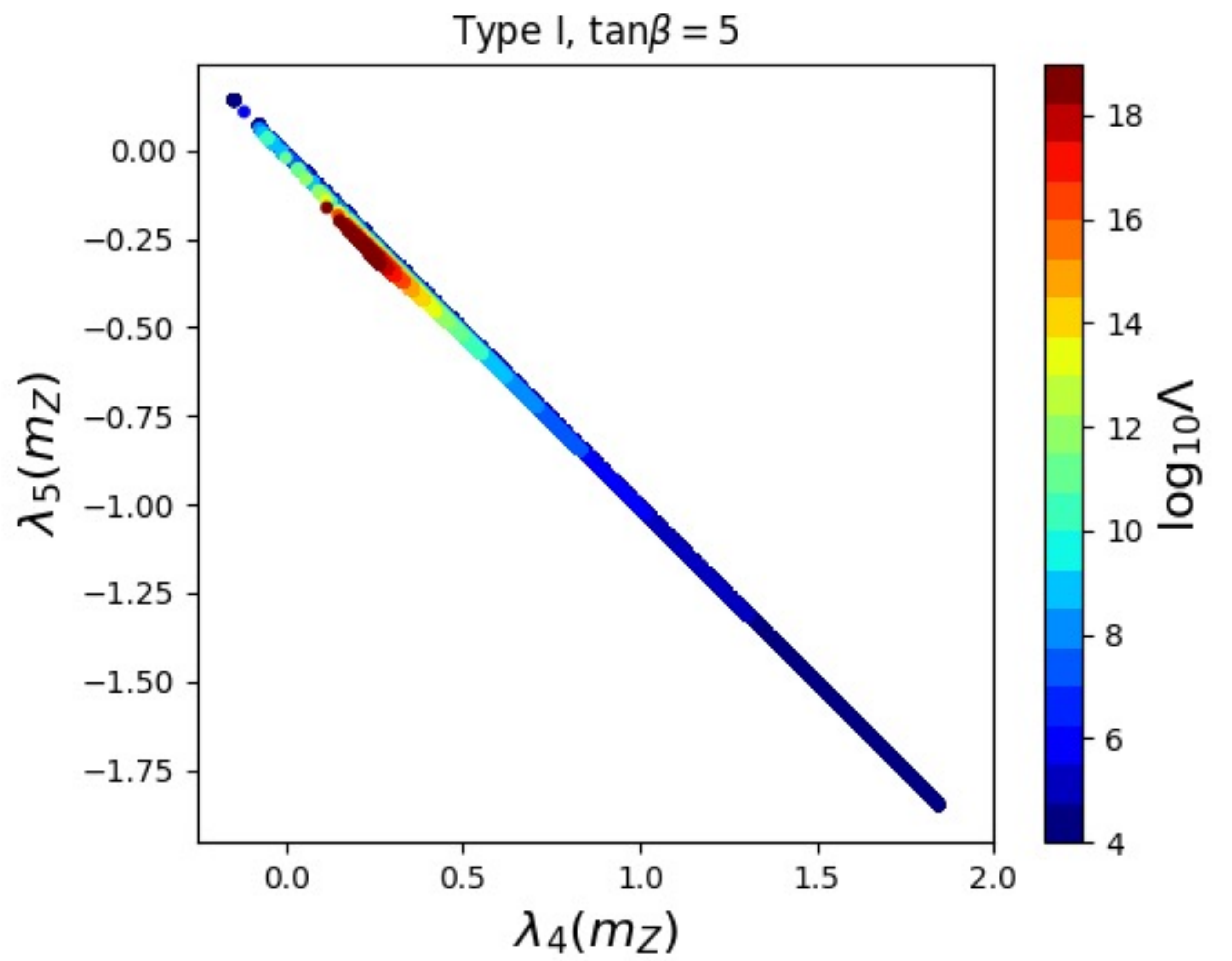
- Twisted-custodial symmetry at Λ

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

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

The following conditions are approximately realized in this scenario.

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

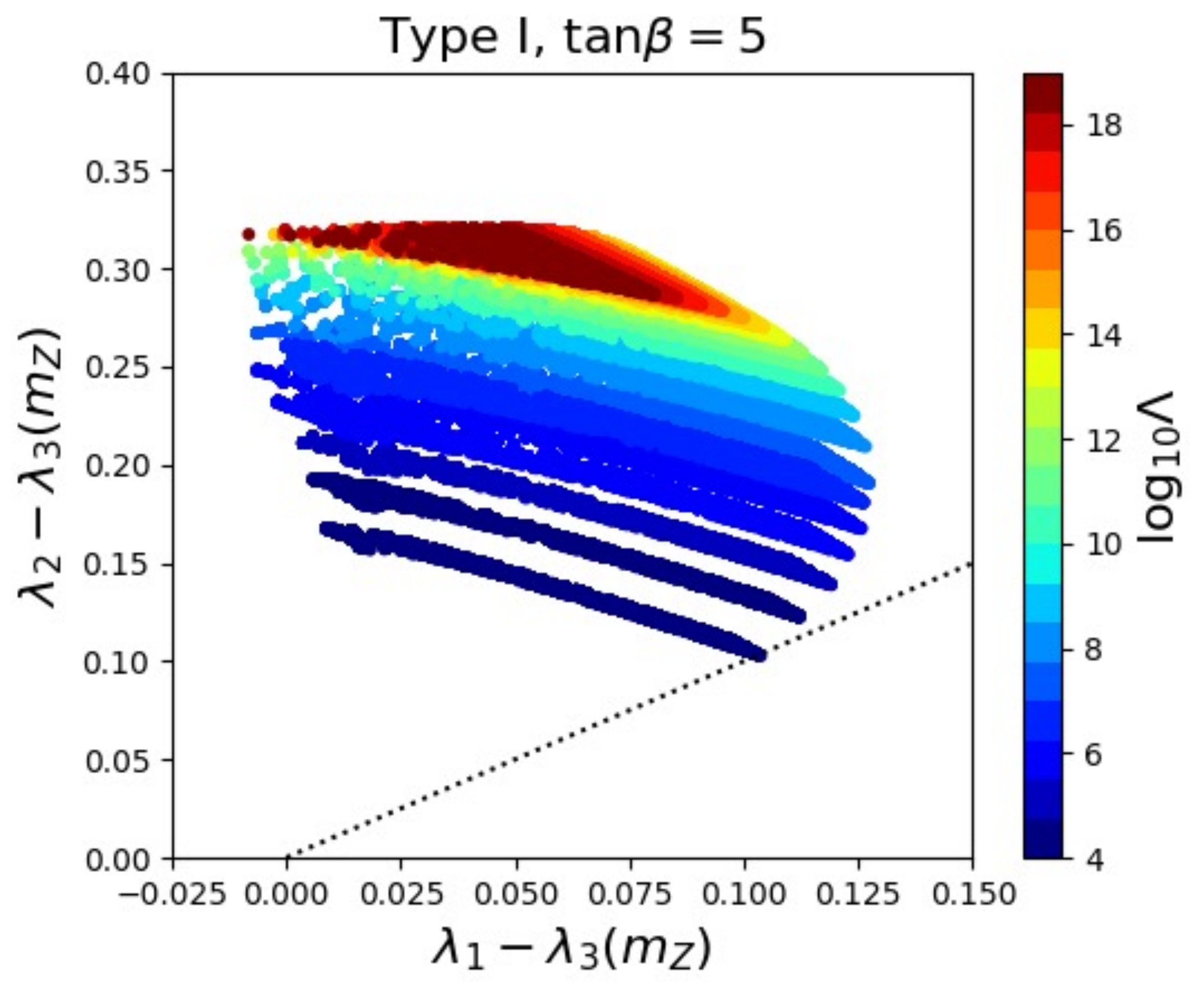
The mass squared differences among the additional Higgs bosons can be simplified as

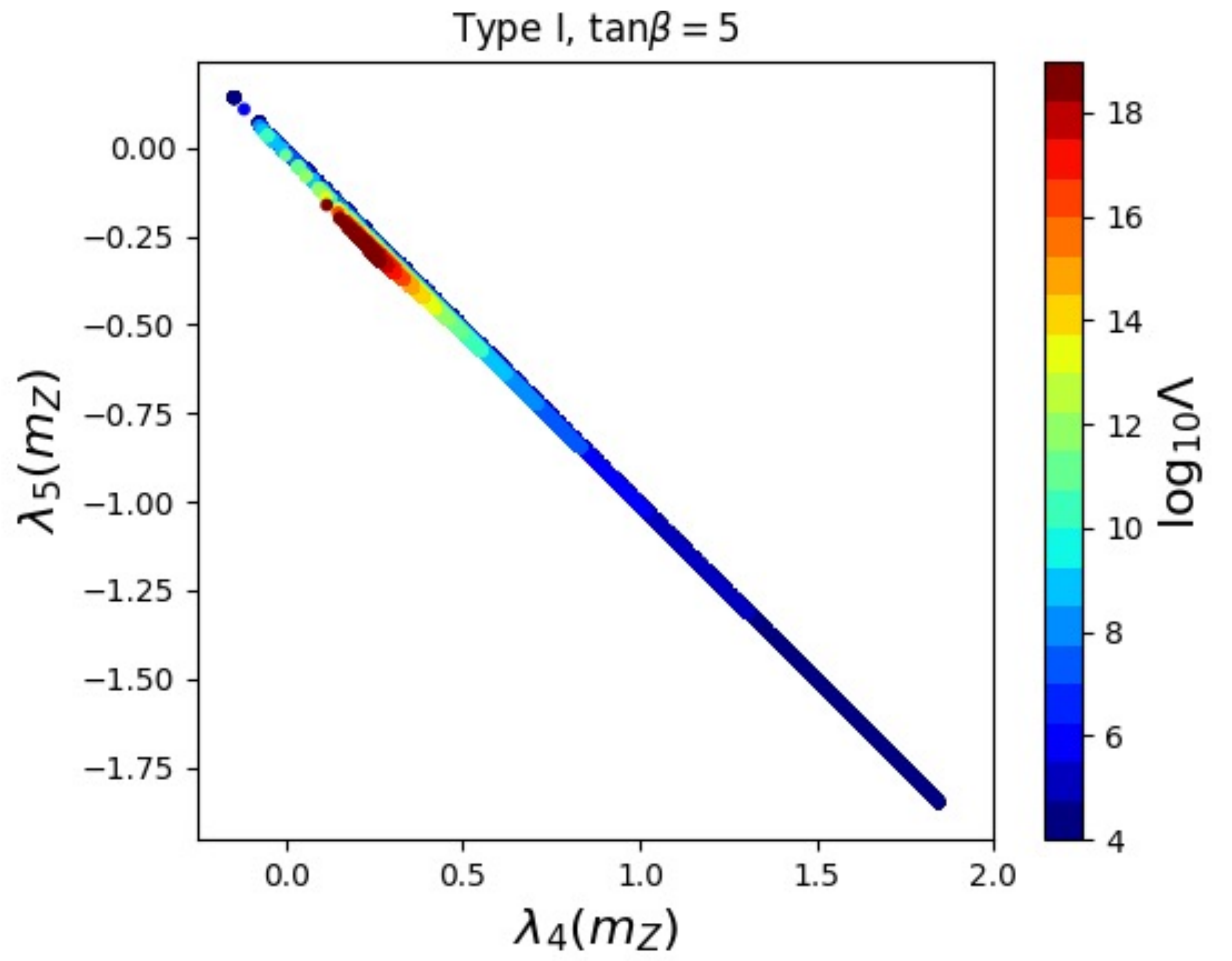
$$\frac{m_A^2 - m_{H^\pm}^2}{v^2} \simeq \lambda_4 \gtrsim 0,$$

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

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

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

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