High scale twisted custodial symmetry in two Higgs doublet models

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based on M. Aiko, S. Kanemura, K. Mawatari, Phys. Lett. B797 (2019) arXiv:1906.09101

and ongoing project with S. Kanemura

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Introduction

Many questions about Higgs physics

- Number of Higgs multiplets
- Representation of the Higgs fields
- Origin of the negative mass parameter
- Structure of the Higgs potential etc.

Extended Higgs sector as a solution of Beyond Standard Model phenomena

- Dark Matter
- Tiny neutrino mass
- Baryon asymmetry of the universe etc.

The direction of new physics can be revealed via detailed study of the extended Higgs models. Especially, the symmetric structure of the Higgs potential may be closely related to the nature of BSM theory.

Two Higgs doublet model (2HDM)

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.) \\
& + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.\right] + \{\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + h.c.\}
\end{aligned}
$$

2HDM like Higgs sector often appears in BSM models and provides rich phenomenology.

It is convenient to introduce Higgs basis.

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

In CP conserving case,

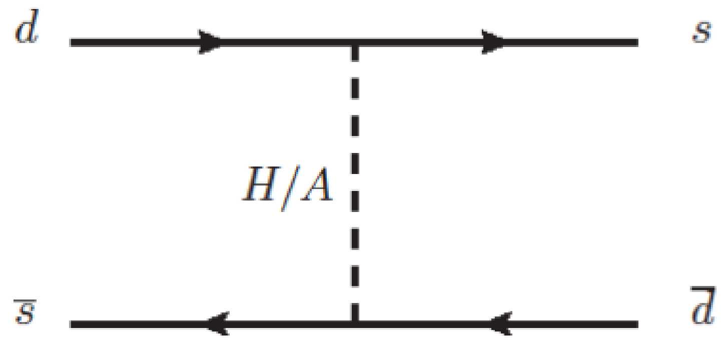
Physical states: CP-even h_1, h_2, CP-odd A and charged Higgs $H^{\pm}$

In general, we need further rotation to diagonalize CP-even states.

Experimental constraints

Suppression of flavor changing neutral current

This implies (softly) broken Z_2 symmetry



$$\Phi_1 \to \Phi_1, \;\; \Phi_2 \to -\Phi_2 \text{ sets } \lambda_6 = \lambda_7 = 0$$

S. L. Glashow, S. Weinberg, Phys. Rev. D15 (1977)

Small correction of new scalars to electroweak ρ parameter

$$\rho_0 = \frac{\rho_{obs}}{\rho_{SM}} \approx 1 + \alpha T = 1.00039$$

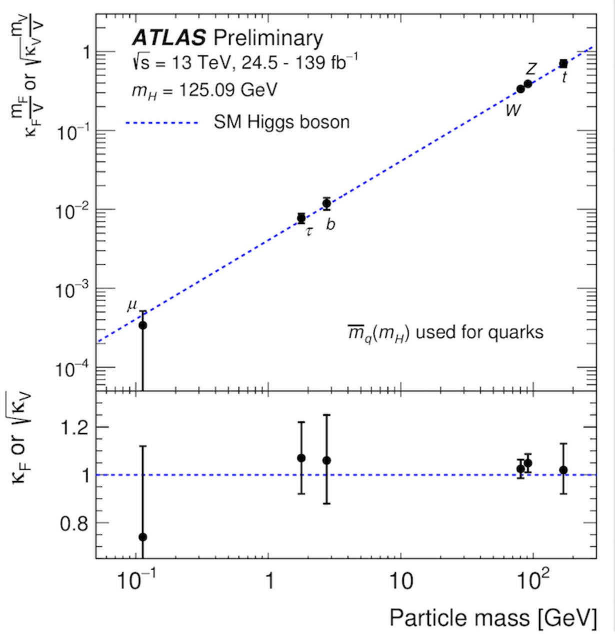
Particle Data Group (2020)

In general, T parameter suffers from non-decoupling effects in 2HDM.
If theory respects custodial symmetry, T parameter is suppressed.

P. Sikivie, L. Susskind, M. B. Voloshin, V. I. Zakharov, Nucl. Phys. B173 (1980)

SM like $h(125)$ couplings

This implies alignment condition for mixing angle among two CP-even states: $\sin(\beta-\alpha) \approx 1$



ATLAS-CONF-2019-005

This limit can be realized by

1. Decoupling $(M \gg v)$ — J. Gunion and H. Haber, Phys. Rev. D67 (2003)
2. Global symmetry in Higgs potential — P.S. Dev and A. Pilaftsis, JHEP12 (2014)

Twisted custodial symmetry guarantees both small T parameter and alignment without decoupling.

J. Gerard and M. Herquet, Phys. Rev. Lett. 98 (2007)
H. E. Haber, D. O'Neil, Phys. Rev. D83 (2011)

$$V(H_1,H_2) = Y_1^2|H_1|^2 + Y_2^2|H_2|^2 + \frac{1}{2}Z_1(|H_1|^2+|H_2|^2)^2 + Z_5[(H_1^\dagger H_2)-(H_2^\dagger H_1)]^2$$

This potential is invariant under $SU(2)_L \times SU(2)_R$ transformation

$$M_1 \to L M_1 R^\dagger, \quad M_2 \to L M_2 P R^\dagger P^{-1}, \quad P \equiv \mathrm{diag}(-i,i), \; M_i = (i\sigma_2 H_i^*, H_i)$$

High scale twisted custodial symmetry

We assume that twisted custodial symmetric Higgs potential emerges from unknown UV physics at some high scale Λ.

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

$$\text{Coefficients of } V(\Phi_1, \Phi_2) \text{ satisfy } \lambda_1 = \lambda_2 = \lambda_3 \text{ and } \lambda_4 = -\lambda_5 \text{ at } \mu = \Lambda$$

This global symmetry is not the symmetry of the whole theory.

→ Twisted custodial symmetry would be broken under renormalization group evolution due to Yukawa and $U(1)_Y$ couplings.

<u>Question</u>

Can high scale twisted custodial symmetry explain electroweak scale observables?

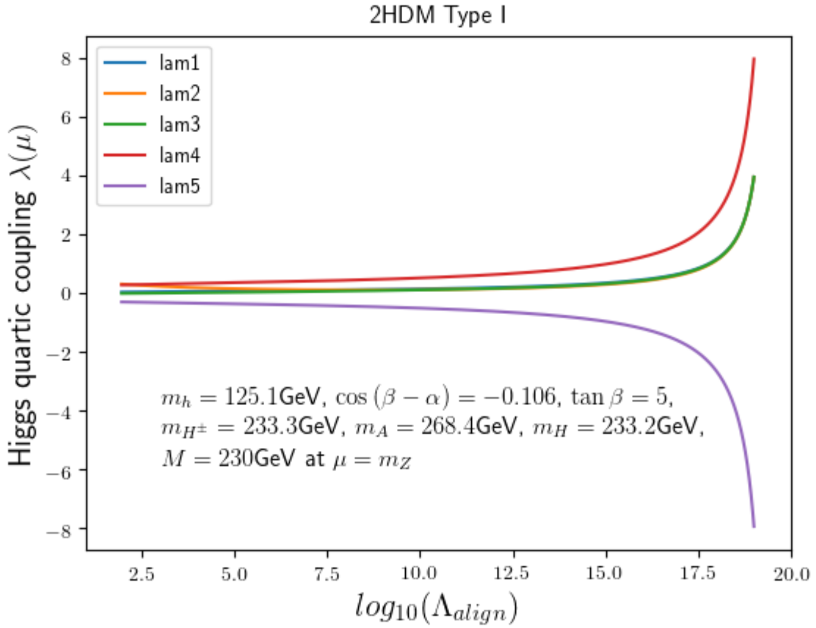
The answer is Yes!

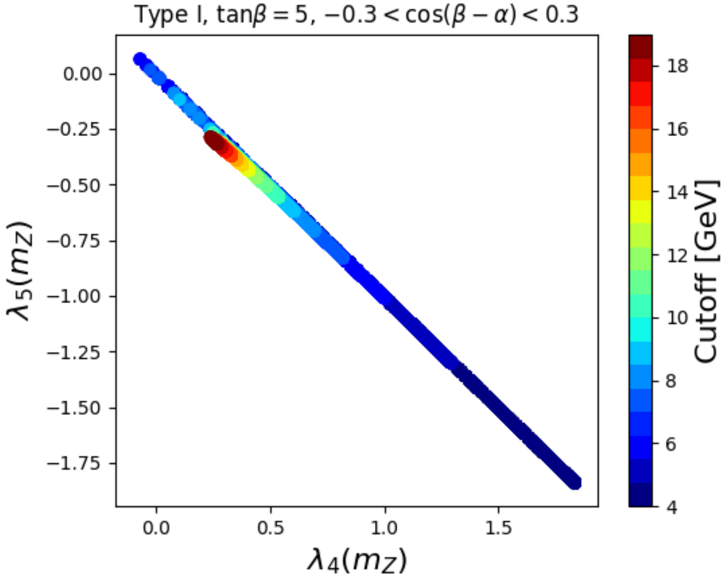
We searched parameters which satisfy

1. $\lambda_1 = \lambda_2 = \lambda_3$ and $\lambda_4 = -\lambda_5$ at $\mu = \Lambda$
2. $m_h = 125.1\mathrm{GeV}$ at $\mu = m_Z$

by using one-loop β function.

We checked that parameter sets satisfy theoretical constraints during RG flow and also satisfy experimental constraints.





What we found

▷ This scenario can be valid up to Planck scale

▷ $\lambda_4 = -\lambda_5$ is approximately realized at EW scale.

▷ λ_4 closes to fixed value when scale Λ is high

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▷ $\lambda_1 = \lambda_2 = \lambda_3$ is violated at EW scale

This causes mixing among CP-even states

→ $h(125)$ couplings deviate from SM values

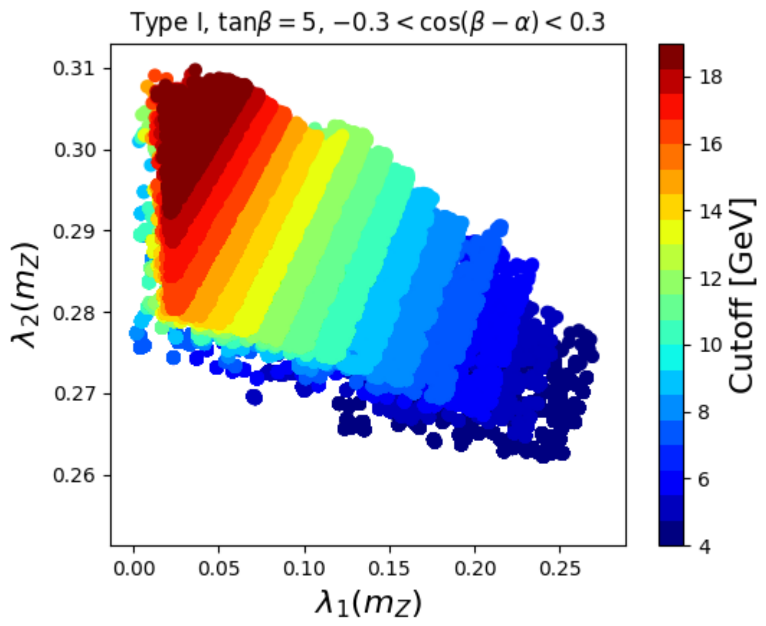
However,

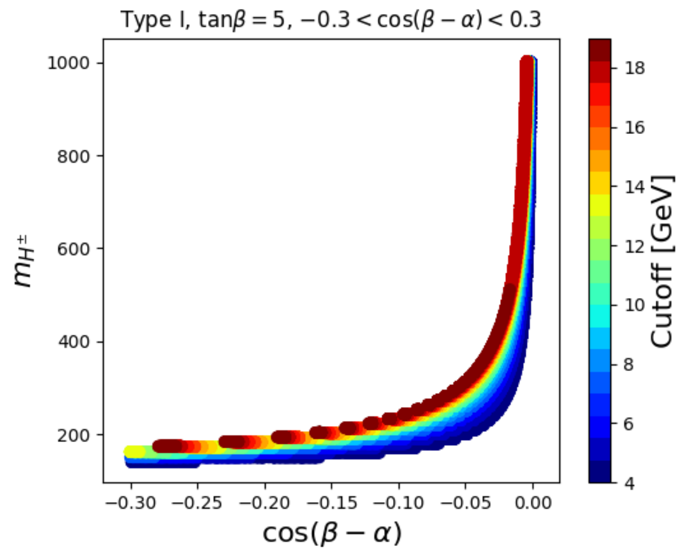
▷ Alignment can be realized without decoupling

$$\left|\sin(\beta-\alpha)\cos(\beta-\alpha)\right| = \frac{\mathcal{M}_{12}^2}{m_H^2 - m_h^2}$$

$m_H \gtrsim 300$ GeV causes decoupling like behavior because $\mathcal{M}_{12}$ is generated by RG evolution and it's enough small.

▷ Small T parameter and alignment without decoupling can be realized as a consequence of high scale global symmetry!





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Prediction of EW observables

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- $\lambda_4 = -\lambda_5 \geq 0 \rightarrow$ charactaristic mass spectrum

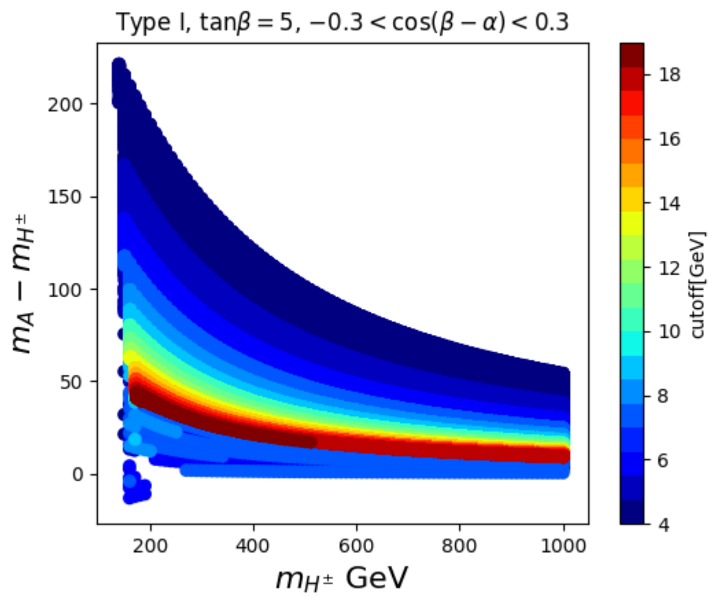
$$m_A \geq m_H \approx m_{H^\pm}$$

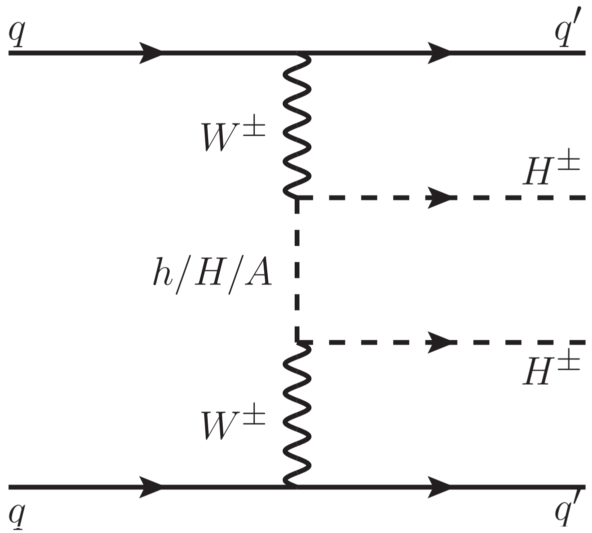
High scale validity of this scenario requires nonzero mass difference.

If Λ is close to EW scale and there is sizable mass difference ($m_A - m_{H^\pm} \gtrsim 150$ GeV), we can study this scenario via same-sign pare production of charged Higgs bosons process.

M. Aiko, S. Kanemura, K. Mawatari, Phys. Lett. B797 (2019)

Even for small mass difference, branching ratio of $h(125)$ will be deviated from SM value through radiative correction → ILC is important!





Summary

- Smallness of T parameter and alignment without decoupling can be realized as a consequence of high scale twisted custodial symmetry.
- This scenario can be valid up to Planck scale and characteristic mass spectrum is predicted.
- We can study this scenario by future hadron and linear collider.