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

Based on hep-ph [2009.04330]

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Introduction

Motivation of extended Higgs models：

V. A. Kuzmin et al. Phys. Lett. B155 (1985)
C. Grojean et al. Phys. Rev. D71 (2005)
S. Kanemrua et.al Phys. Rev. D70 (2004)

1. Baryon asymmetric universe ← Electroweak baryogenesis, new CP violation
2. Dark matter ← stable scalar particle

   N. G. Deshpande and E. Ma Phys. Rev. D18 (1978)
   V. Silveria and A. Zee Phys. Lett. B161 (1985)

3. Neutrino tiny mass ← radiative mass generation etc.

   E. Ma et.al Phys. Rev. D73 (2006),
   S. Kanemura et. al. Phys. Rev. Lett 102 (2009)

Feature of Higgs sector：

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

Assumption：

UV theory controls the structure of Higgs potential

Two Higgs doublet model (2HDM)

Higgs potential

$$
\begin{aligned}
V(\Phi_1, \Phi_2) = & \; m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_3^2 (\Phi_1^\dagger \Phi_2 + h.c.) \\
& + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + h.c. \right]
\end{aligned}
$$

Scalar particles：

charged $H^{\pm}$, CP-odd A and CP-even Higgs h, H

Free parameters：

masses of Higgs bosons $m^2_{H/A/H^{\pm}}$, softly $\mathbb{Z}_2$ breaking scale M and mixing angle β, α

$v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}, \;\; m_h = 125 \text{ GeV}, \;\; \tan\beta = v_2/v_1, \;\; \alpha : \text{mixing angle of CP-even}$

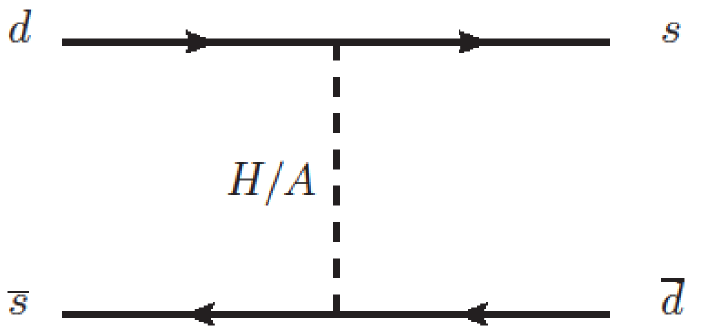
If $M \gg v$, $m_H \simeq m_A \simeq m_{H^{\pm}} \simeq M$ and additional Higgs bosons are decouple.

Some BSM physics (e.g. electroweak baryogenesis) favor non-decoupling scenario.

See also Kanemura-san's slide

Experimental constraints

1. Suppression of flavor changing neutral current (FCNC)



$$\mathcal{L}^d_{Yukawa} = -\overline{Q}^i_L(y^{ij}_{d,1}\Phi_1 + y^{ij}_{d,2}\Phi_2)d^j_R$$

→ asuume $\mathbb{Z}_2$ symmetry : $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, and prohibit $y_{d,1}$ or $y_{d,2}$

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

Why is this discrete symmetry often assumed ?

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

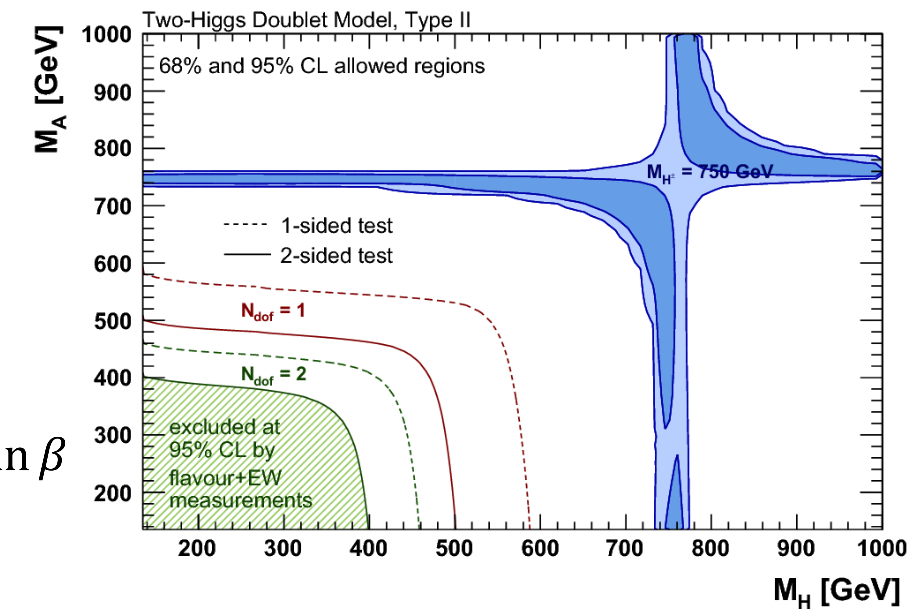
If $y_{u,1} = y_{d,2} = y_{\ell,2} = 0$ (Type-II) at some high scale Λ ($\geq m_Z$), $y_{d,2} = 0$ at any scale

$$\mathcal{L}_{UV}(\Lambda) \Rightarrow \mathcal{L}^{Z_2}_{2HDM}(\Lambda) \Rightarrow \mathcal{L}^{Z_2}_{2HDM}(m_Z)$$

FCNC suppression can be understood from the nature of UV theory (e.g. R-parity etc.)

Experimental constraints

The Gfitter Group, Eur. Phys. J. C78 (2018)



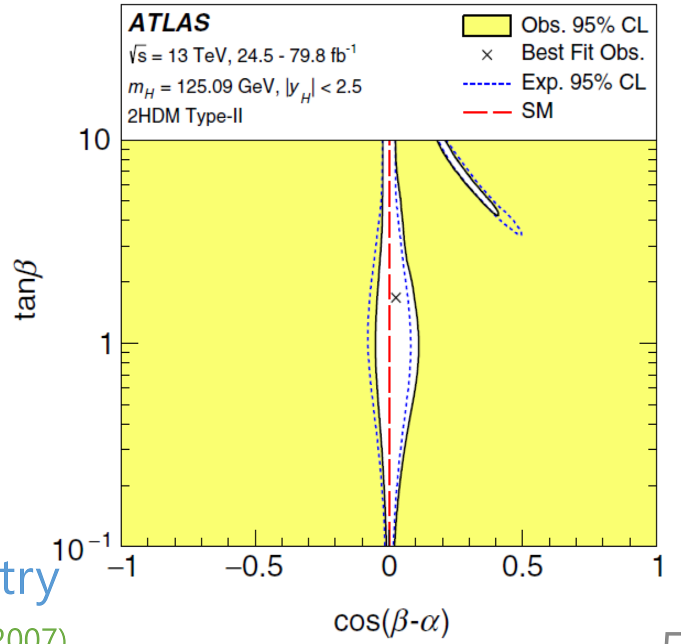
2. Smallness of ΔT PDG2020

The difference between $T_{2\mathrm{HDM}}$ and T_{SM} should be small

$$\Delta T \equiv T_{2\mathrm{HDM}} - T_{\mathrm{SM}} \approx 0$$

3. SM-like Higgs couplings $\xi_f = \cot\beta$ or $-\tan\beta$

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



G. Aad et al, Phys. Rev. D101 (2020)

2. and 3. imply

$$m_A^2 = m_{H^\pm}^2 \quad \text{and} \quad \sin(\beta-\alpha) = 1$$

or

$$m_H^2 = m_{H^\pm}^2 \quad \text{and} \quad \sin(\beta-\alpha) = 1$$

The latter conditions are required by twisted custodial $O(4)$ symmetry

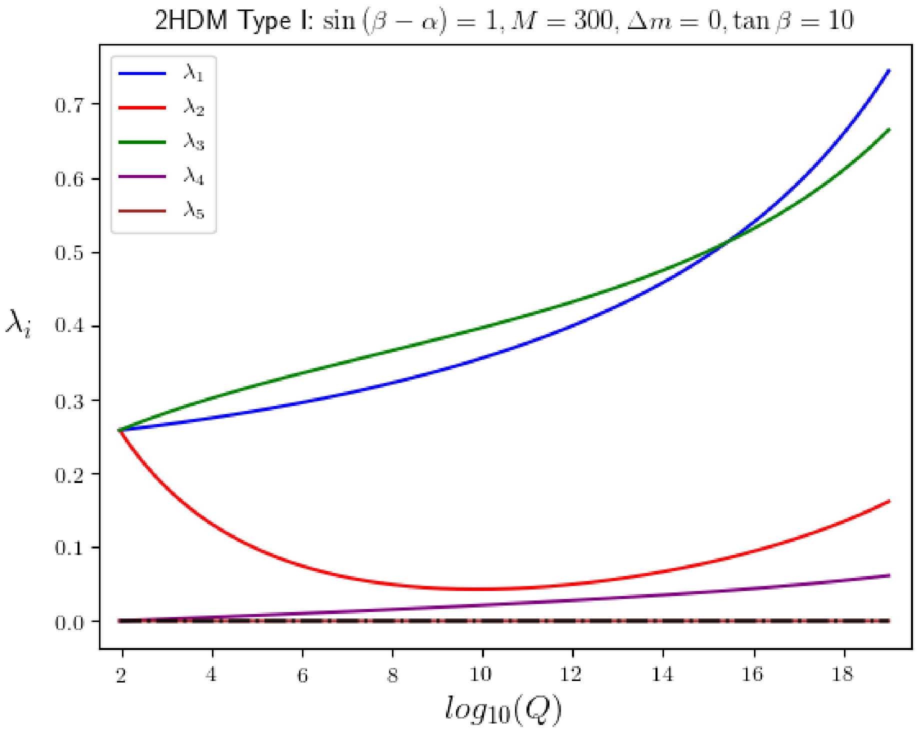
J. Gerard and M. Herquet, Phys. Rev. Lett 98 (2007)

Artificiality of exact global symmetry at EW scale

If Higgs potential respects $\mathbb{Z}_2 \times O(4)$ symmetry at EW scale, previous experimental data can be explained.

$$m_H^2 = m_{H^\pm}^2 = M^2 \quad \text{and} \quad \sin(\beta - \alpha) = 1$$

$$\Rightarrow \lambda_1(m_Z) = \lambda_2(m_Z) = \lambda_3(m_Z), \quad \lambda_4(m_Z) + \lambda_5(m_Z) = 0$$



<u>Violation of above conditions</u>

twisted custodial symmetry is not the symmetry of whole theory

→ Yukawa interaction and $U(1)_Y$ gauge coupling break it under RG evolution

→ We need to adjust $\lambda_i(\Lambda)$ to derive twisted-custodial symmetric Higgs potential at EW scale.

It looks artificial

Twisted custodial symmetry at high scale Λ

hep-ph: 2009.04330

Assumption: UV theory derives twisted-custodial symmetric Higgs potential

$$\lambda_1(\Lambda) = \lambda_2(\Lambda) = \lambda_3(\Lambda), \quad \lambda_4(\Lambda) + \lambda_5(\Lambda) = 0$$

These relations are violated under the RG evolution.

However, the conditions,

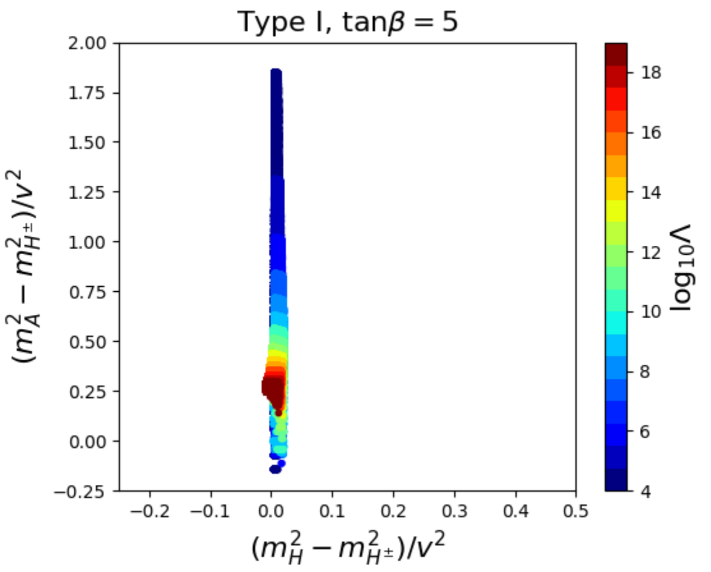
$$m_H^2 \simeq m_{H^\pm}^2 \quad \text{and} \quad \sin(\beta - \alpha) \simeq 1,$$

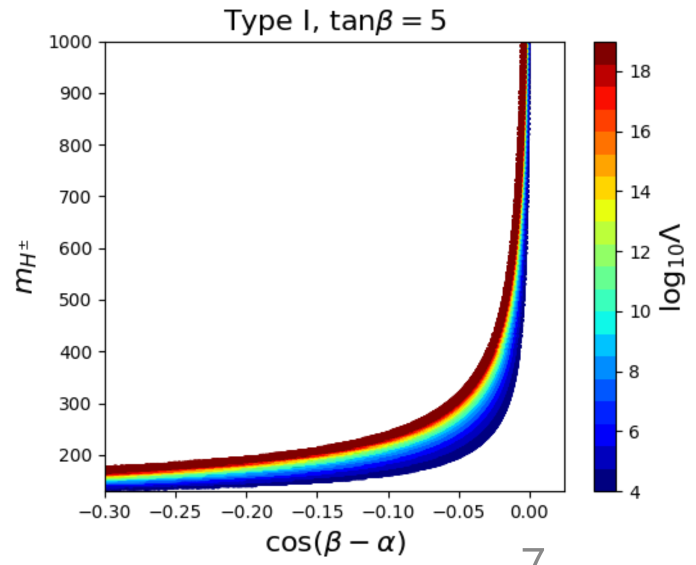
are approximately realized at the EW scale without decoupling of additional Higgs bosons.

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





Twisted custodial symmetry at high scale Λ

Deviation in the Higgs couplings   S. Kanemura, et al, Phys. Rev. D90 (2014)

1. hWW, hZZ

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

proportional to $\sin(\beta-\alpha) \to O(0.1)\%$

2. hff

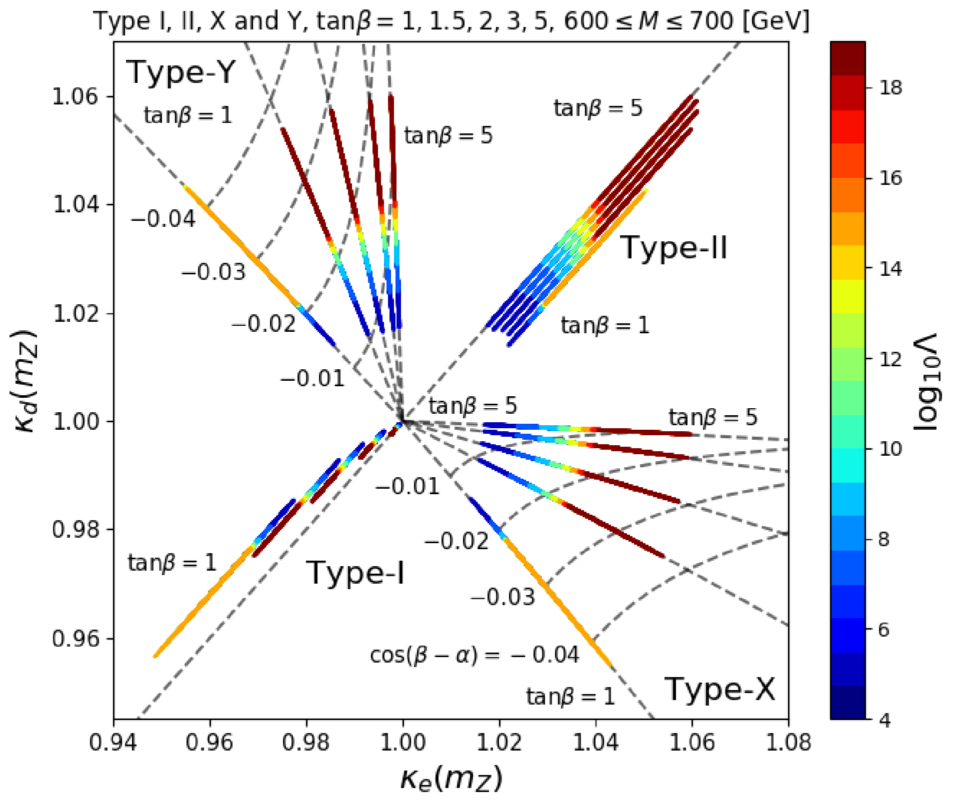
$$\mathcal{L}_{int} = -\sum_{f=u,d,e} \frac{m_f}{v} [\sin(\beta-\alpha) + \xi_f(\beta)\cos(\beta-\alpha)] \bar{f} f h$$

Possible deviations depend on ξ_f ($\cot\beta$ or $-\tan\beta$)

maximally 6% deviations are expected

The directions of deviations → types of Yukawa interactions

The size of deviations → possible scale Λ



hep-ph: 2009.04330

These percent-level deviations can be tested at ILC

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 Planck scale.
- Characteristic mass spectrum ($m_A \geq m_H \simeq m_{H^\pm}$) and deviations of Higgs couplings are predicted as a function of Λ.

Message

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