Naturalness and two Higgs doublet models

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Based on:

1. "Masses of physical scalars in two Higgs doublet models", **Ambalika Biswas**, Amitabha Lahiri, Phys.Rev. D91 (2015) no.11, 115012 [arXiv:1412.6187 [hep-ph] — PDF].
2. "Alignment, reverse alignment, and wrong sign Yukawa couplings in two Higgs doublet models", **Ambalika Biswas**, Amitabha Lahiri, Phys.Rev. D93 (2016) no.11, 115017 [arXiv:1511.07159 [hep-ph] — PDF].

Overview

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- Introduction

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- Veltman Conditions

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- Alignment Limit

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- Reverse Alignment Limit
- Wrong Sign Limit
- Diphoton Decay Width

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- 2HDM is one of the simplest extensions of **SM** Physics. 2HDM is embedded in **MSSM** and **SUSY**.
- The extended scalar sector provides scope for viable **dark matter** candidates and CP violating terms to explain **baryon asymmetry**.

The two Higgs Doublets

SU(2) complex scalar doublets

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$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$

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Global $U(1)$ symmetry imposed to avoid Flavour Changing Neutral Currents.

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The U(1) symmetry

- Type I: $\Phi_1 \to \exp{(i\theta)}\Phi_1$;
- Type II: $\Phi_1 \to \exp{(i\theta)}\Phi_1$,$d_R^i \to \exp{(-i\theta)}d_R^i$,$e_R^i \to \exp{(-i\theta)}e_R^i$;
- Lepton Specific: $\Phi_1 \to \exp{(i\theta)}\Phi_1$,$e_R^i \to \exp{(-i\theta)}e_R^i$;
- Flipped: $\Phi_1 \to \exp{(i\theta)}\Phi_1$,$d_R^i \to \exp{(-i\theta)}d_R^i$

Symmetries and the 2HDM Lagrangian

The scalar potential under the U(1) symmetry

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$$
\begin{aligned}
V &= \lambda_1(\Phi_1^\dagger\Phi_1 - \frac{v_1^2}{2})^2 + \lambda_2(\Phi_2^\dagger\Phi_2 - \frac{v_2^2}{2})^2 \\
&+ \lambda_3(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 - \frac{v_1^2+v_2^2}{2})^2 \\
&+ \lambda_4((\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)) \\
&+ \lambda_5|\Phi_1^\dagger\Phi_2 - \frac{v_1 v_2}{2}|^2
\end{aligned}
$$

The term, $\lambda_5 v_1 v_2 \Re(\Phi_1^\dagger\Phi_2)$ softly breaks the U(1) symmetry.

Symmetries and the 2HDM Lagrangian

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The 2HDM Yukawa Lagrangian

$$\mathcal{L}_Y = \sum_{i=1,2}\left[-\bar{l}_L\Phi_i G_e^i e_R - \bar{Q}_L\tilde{\Phi}_i G_u^i u_R - \bar{Q}_L\Phi_i G_d^i d_R + h.c.\right]$$

The Veltman Conditions

Cancelling of the quadratic divergences of the 2HDM gives rise to the below mentioned four Veltman conditions. [C. Newton and T. T. Wu, Z. Phys. C 62, 253 (1994).]

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The four VCs

$$2TrG_e^1G_e^{1\dagger} + 6TrG_u^{1\dagger}G_u^1 + 6TrG_d^1G_d^{1\dagger} = \frac{9}{4}g^2 + \frac{3}{4}g'^2 + 6\lambda_1 + 10\lambda_3 + \lambda_4 + \lambda_5$$

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Hence the *Naturalness condition*.

Some useful results:

General results involving the Yukawa couplings and fermion masses:

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$$Tr[G^{\dagger}_{1f} G_{1f}] = \frac{2}{v^2 \cos^2\beta} \sum m_f^2 \ ,$$
$$Tr[G^{\dagger}_{2f} G_{2f}] = \frac{2}{v^2 \sin^2\beta} \sum m_f^2 \ .$$

where f stands for charged leptons, up-type quarks, or down-type quarks, and the sum is taken over generations.

Stability and Unitarity conditions

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$$\lambda_1 + \lambda_3 > 0, 2\lambda_3 + \lambda_4 + 2\sqrt{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_3)} > 0,$$

$$\lambda_2 + \lambda_3 > 0, 2\lambda_3 + \lambda_5 + 2\sqrt{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_3)} > 0.$$

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$$\begin{aligned}
|2\lambda_3 - \lambda_4 + 2\lambda_5| &\leq 16\pi, \\
|2\lambda_3 + \lambda_4| &\leq 16\pi, \\
|2\lambda_3 + \lambda_5| &\leq 16\pi, \\
|2\lambda_3 + 2\lambda_4 - \lambda_5| &\leq 16\pi, \\
|3(\lambda_1 + \lambda_2 + 2\lambda_3) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (4\lambda_3 + \lambda_4 + \lambda_5)^2}| &\leq 16\pi, \\
|(\lambda_1 + \lambda_2 + 2\lambda_3) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_4 - \lambda_5)^2}| &\leq 16\pi, \\
|(\lambda_1 + \lambda_2 + 2\lambda_3) \pm (\lambda_1 - \lambda_2)| &\leq 16\pi.
\end{aligned}$$

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Recent bounds on $\delta\rho$ is $\delta\rho = -0.0002 \pm 0.0007$ [**Particle Data Group** Collaboration, K. Olive *et al.*, **C38** (2014)090001.].

Alignment Limit

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- $h_{ff} = h_{ff,SM}$
- $h_{VV} = h_{VV,SM}$
- $m_h = 125 \;\; \text{GeV}$

Relation between λ's and the physical Higgs boson masses in Alignment limit

[Ref: A.G.Akeroyd, A.Arhrib and E.M Naimi, Phys.Lett.B 490, 119(2000)[hep-ph/0006035]]

$$\lambda_1 = \frac{1}{2v^2 c_\beta^2} m_H^2 - \frac{\lambda_5}{4}(\tan^2\beta - 1)\,,$$

$$\lambda_2 = \frac{1}{2v^2 s_\beta^2} m_H^2 - \frac{\lambda_5}{4}\left(\frac{1}{\tan^2\beta} - 1\right)\,,$$

$$\lambda_3 = -\frac{1}{2v^2}(m_H^2 - m_h^2) - \frac{\lambda_5}{4}\,,$$

$$\lambda_4 = \frac{2}{v^2} m_\xi^2\,,$$

$$\lambda_5 = \frac{2}{v^2} m_A^2\,.$$

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$$\lambda_2 = \frac{1}{2v^2 s_\beta^2} m_H^2 - \frac{\lambda_5}{4}\left(\frac{1}{\tan^2\beta} - 1\right)\,,$$

$$\lambda_3 = -\frac{1}{2v^2}(m_H^2 - m_h^2) - \frac{\lambda_5}{4}\,,$$

$$\lambda_4 = \frac{2}{v^2} m_\xi^2\,,$$

$$\lambda_5 = \frac{2}{v^2} m_A^2\,.$$

For any 2HDM to be a perturbative quantum field theory at any scale one must impose the conditions that $|\lambda_i| \leq 4\pi\ \forall i$.

Veltman Condition (VC) 1 in Alignment limit

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RHS of VC1:

$$6M_W^2 + 3M_Z^2 + m_H^2(3\tan^2\beta - 2) + 5m_h^2 + 2m_\xi^2 - \frac{3v^2}{2}\lambda_5\tan^2\beta$$

Type of 2HDM	**The corresponding LHS of VC 1**
Type-I $G_{1e} = 0; G_{1d} = 0; G_{1u} = 0$	0
Type-II $G_{1u} = 0$	$4[(m_e^2 + m_\mu^2 + m_\tau^2)$ $+3(m_d^2 + m_s^2 + m_b^2)]\sec^2\beta$
Lepton Specific $G_{1d} = 0; G_{1u} = 0$	$4(m_e^2 + m_\mu^2 + m_\tau^2)\sec^2\beta$
Flipped 2HDM $G_{1e} = 0; G_{1u} = 0$	$12(m_d^2 + m_s^2 + m_b^2)\sec^2\beta$

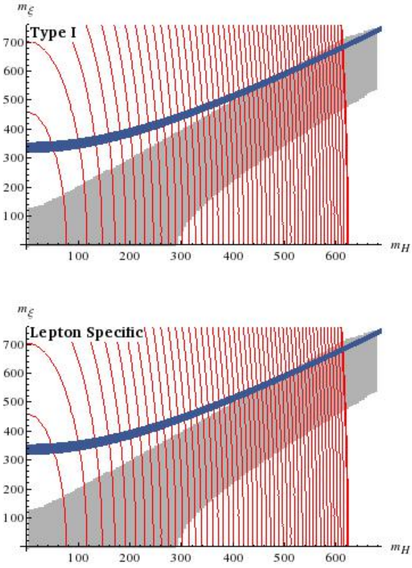
Veltman Condition (VC) 2 in Alignment limit

Veltman Condition (VC) 2 in Alignment limit

RHS of VC2:
$6M_W^2 + 3M_Z^2 + m_H^2(\frac{3}{\tan^2\beta} - 2) + 5m_h^2 + 2m_\xi^2 - \frac{3v^2}{2}\frac{\lambda_5}{\tan^2\beta}$

Type of 2HDM	The corresponding LHS of VC 2
Type-I	$4[(m_e^2 + m_\mu^2 + m_\tau^2)$ $+3(m_u^2 + m_c^2 + m_t^2)$ $+3(m_d^2 + m_s^2 + m_b^2)]\csc^2\beta$
Type-II $G_{2e} = 0; G_{2d} = 0$	$12(m_u^2 + m_c^2 + m_t^2)\csc^2\beta$
Lepton Specific $G_{2e} = 0$	$12[(m_u^2 + m_c^2 + m_t^2)$ $+(m_d^2 + m_s^2 + m_b^2)]\csc^2\beta$
Flipped 2HDM $G_{2d} = 0$	$4[(m_e^2 + m_\mu^2 + m_\tau^2)$ $+3(m_u^2 + m_c^2 + m_t^2)]\csc^2\beta$

The allowed mass range plot for the physical Higgs bosons



Results for SM-like limit

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- Direct searches have shown that $m_\xi > 100\ \mathrm{GeV}$ and our results agree with this lower bound. [K.A. Olive et al. (Particle Data Group), Chin. Phys. C38 , 090001 (2014)]
- The degeneracy in the masses of the physical Higgs bosons for large enough $\tan\beta$ is evident from our plots.

Reverse Alignment Limit

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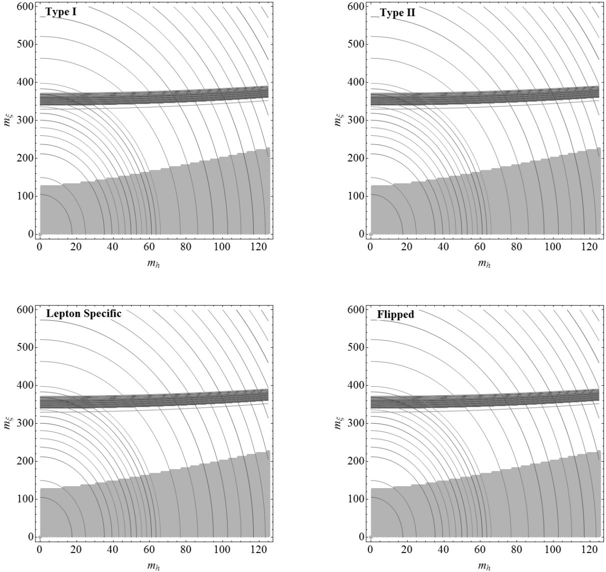
- $m_H = 125$ GeV

The allowed mass range plot for the physical Higgs bosons



Results for Reverse alignment limit

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As seen from the plots in figure we find that there is no common region of intersection which obeys all the constraints. Thus *Reverse alignment limit* is not a consistent limit with the *Naturalness condition* for 2HDMs.

Wrong Sign Limit

Wrong Sign Limit

Region of 2HDM parameter space where,

- $\frac{h\overline{D}D}{hVV} < 0$ or,
- $\frac{h\overline{U}U}{hVV} < 0$

Here h is the SM-like Higgs. [P. M. Ferreira *et al.* arxiv: 1410.1926v1 [hep-ph].]

Wrong Sign Limit and Alignment Limit

Type-II Higgs-fermion Yukawa couplings normalized w.r.t. SM:

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$$h\overline{D}D \quad : \quad -\frac{\sin\alpha}{\cos\beta} = -\sin(\beta+\alpha) + \cos(\beta+\alpha)\tan\beta$$

$$h\overline{U}U \quad : \quad \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta$$

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- $\sin(\beta+\alpha) = 1 \Rightarrow h\overline{D}D = -1$ and $h\overline{U}U = +1$.

Wrong Sign Limit and Alignment Limit

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- $\sin(\beta+\alpha) = 1 \Rightarrow h\overline{D}D = -1$ and $h\overline{U}U = +1$.
- Wrong Sign + Alignment limit $\Rightarrow \sin(\beta+\alpha) \sim 1$ and $\sin(\beta-\alpha) \sim 1$.

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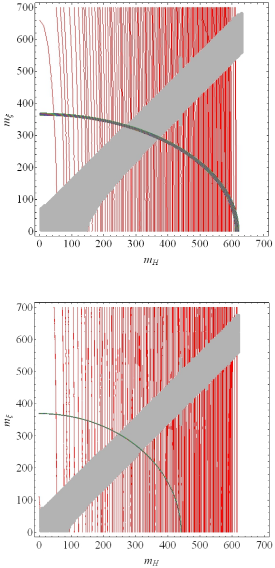
- $\sin(\beta+\alpha) = 1 \Rightarrow h\overline{D}D = -1$ and $h\overline{U}U = +1$.
- Wrong Sign + Alignment limit $\Rightarrow \sin(\beta+\alpha) \sim 1$ and $\sin(\beta-\alpha) \sim 1$.
- The wrong sign limit approaches the alignment limit for $\tan\beta \approx 17$

[P. M. Ferreira *et al.* arxiv: 1410.1926v1 [hep-ph].]


700
600
500
400
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200
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Results for Wrong sign limit and alignment limit

- For $\tan\beta = 17$ the range of physical Higgs bosons are:
  - $m_H \approx$ (250, 330) GeV

Results for Wrong sign limit and alignment limit

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  - $m_H \approx$ (250, 330) GeV
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Results for Wrong sign limit and alignment limit

- For $\tan\beta = 17$ the range of physical Higgs bosons are:
  - $m_H \approx$ (250, 330) GeV
  - $m_\xi \approx$ (260, 310) GeV.
- At higher values of $\tan\beta$, both ranges become narrower and move down on the mass scale.

Diphoton Decay width

Diphoton decay width in Wrong sign and Alignment limits

Diphoton Decay width

Diphoton decay width in Wrong sign and Alignment limits

$$\Gamma(h \to \gamma\gamma) = \frac{G_\mu \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \Big| \sum_f N_c Q_f^2 g_{hff} A_{1/2}^h(\tau_f) + g_{hVV} A_1^h(\tau_W) + \frac{m_W^2 \lambda_{h\xi^+\xi^-}}{2c_W^2 M_{\xi^\pm}^2} A_0^h(\tau_{\xi^\pm}) \Big|^2$$

Diphoton Decay width

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where, $g_{htt} = \frac{\cos\alpha}{\sin\beta}$, $g_{hbb} = -\frac{\sin\alpha}{\cos\beta}$ and $g_{hWW} = \sin(\beta - \alpha)$
and

$$\begin{aligned} \lambda_{h\xi^+\xi^-} &= \cos 2\beta \sin(\beta+\alpha) + 2c_W^2 \sin(\beta-\alpha) \\ &= \lambda_{hAA} + 2c_W^2 g_{hVV} \end{aligned}$$

where $c_W = \cos\theta_W$, θ_W being the Weinberg angle.

Diphoton decay width contd...

The amplitudes A_i at lowest order for the spin 1, spin $\frac{1}{2}$ and spin 0 particle contributions are given by:

$$\begin{aligned}
A^h_{1/2} &= -2\tau[1+(1-\tau)f(\tau)] \\
A^h_1 &= 2+3\tau+3\tau(2-\tau)f(\tau) \\
A^h_0 &= \tau[1-\tau f(\tau)]
\end{aligned}$$

Diphoton decay width contd...

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$$\tau_x = 4m_x^2/m_h^2$$

and

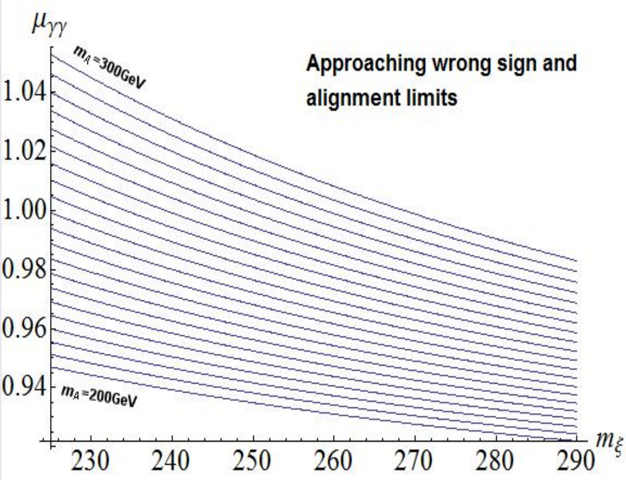
$$f(\tau) = \begin{cases} \arcsin^2\sqrt{1/\tau}\,, & \tau \geq 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2, & \tau < 1 \end{cases}$$

Diphoton Decay

Plot for diphoton decay in alignment and wrong sign limits

Diphoton Decay

Plot for diphoton decay in alignment and wrong sign limits



Results for diphoton decay width

Results for diphoton decay width

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Results for diphoton decay width

- The relative diphoton decay width increases as m_A increases.
- Maximum value of about 6% as compared to the SM value.
- Throw light on BSM Physics.

Thank you!

Appendix : A

Appendix : A

Alignment and Reverse Alignment limits

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

H^0 has exactly the Standard Model Higgs couplings with the fermions and gauge bosons.

$$h = \sin(\beta - \alpha) H^0 + \cos(\beta - \alpha) R$$

Thus in order for h to be the Higgs boson of the Standard Model, we require $\sin(\beta - \alpha) \approx 1 \Rightarrow (\beta - \alpha) \approx \frac{\pi}{2}$, which has been called the SM-like or alignment limit.

$$H = H^0 \cos(\beta - \alpha) - R \sin(\beta - \alpha)$$

Thus in order for H to be the Higgs boson of the Standard Model, we require $\cos(\beta - \alpha) \approx 1 \Rightarrow \beta \approx \alpha \; or \; \beta \approx \pi + \alpha$, which is the reverse alignment limit.

NB: $0 \leq \beta \leq \frac{\pi}{2}$ **and** $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$.

Appendix : B

Appendix : B

Yukawa Couplings for Different 2HDMs

2HDMs	$h\bar{U}U$	$h\bar{D}D$	$H\bar{U}U$	$H\bar{D}D$
Type I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
Type II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
Lepton Specific	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
Flipped	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$

Appendix : C

Appendix : C

Wrong Sign and Reverse Alignment Limit

HVV is $\cos(\beta-\alpha)$ times the corresponding SM value. In the convention where $\cos(\beta-\alpha) \geq 0$, the HVV couplings in the 2HDM are always non-negative. For type-II and Flipped 2HDMs:

$$
\begin{aligned}
H\bar{D}D: \quad & \frac{\cos\alpha}{\cos\beta} &=& \quad \cos(\beta+\alpha) + \sin(\beta+\alpha)\tan\beta\,, \\
H\bar{U}U: \quad & \frac{\sin\alpha}{\sin\beta} &=& \quad -\cos(\beta+\alpha) + \sin(\beta+\alpha)\cot\beta\,.
\end{aligned}
$$

When $\cos(\beta+\alpha) = -1$, the $H\bar{D}D = -1$ and $H\bar{U}U = +1$ normalized w.r.t. SM. Thus in this case, when the reverse alignment limit is taken in conjunction with the wrong sign limit, we have $\alpha \approx \beta \approx \frac{\pi}{2}$. In this case there is no common region of intersection when the Veltman conditions are considered in conjunction with other constraints.
When $\cos(\beta+\alpha) = 1$, the $H\bar{U}U = -1$ and $H\bar{D}D = +1$ normalized w.r.t. SM. In this limiting case, $\cos(\beta-\alpha) = \cos 2\beta$, which implies that the wrong-sign $H\bar{U}U$ couplings can only be achieved for $\tan\beta < 1$ for the type II and Flipped 2HDMs.
In the type-I and lepton specific 2HDMs, both the $H\bar{D}D$ and $H\bar{U}U$ couplings are given by $\frac{\sin\alpha}{\sin\beta}$. Thus, for $\cos(\beta+\alpha) = 1$, both the normalized $H\bar{D}D$ and $H\bar{U}U$ couplings are equal to -1, which is only possible if $\tan\beta < 1$.

Since $\tan\beta > 1$, we see that the wrong-sign Yukawa coupling is incompatible with the reverse alignment limit in all of the four types of 2HDMs.

Appendix : D

Appendix : D

Wrong Sign and Alignment Limit

hVV is $\sin(\beta-\alpha)$ times the corresponding SM value. Then in the convention where $\sin(\beta-\alpha)\geq 0$, the hVV couplings in the 2HDM are always non-negative. For type-II and Flipped 2HMDs:

$$h\bar{D}D: \quad -\frac{\sin\alpha}{\cos\beta} = -\sin(\beta+\alpha)+\cos(\beta+\alpha)\tan\beta\,, \tag{1}$$

$$h\bar{U}U: \quad \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha)+\cos(\beta+\alpha)\cot\beta\,. \tag{2}$$

When $\sin(\beta+\alpha)=1$, the $h\bar{D}D=-1$ and $h\bar{U}U=+1$ normalized w.r.t. SM. In this limiting case, $\sin(\beta-\alpha)=-\cos 2\beta$, which implies that the wrong-sign $h\bar{D}D$ Yukawa coupling can only be achieved for values of $\tan\beta>1$.

When $\sin(\beta+\alpha)=-1$, the $h\bar{U}U=-1$ and $h\bar{D}D=+1$ normalized w.r.t. SM. Then $\sin(\beta-\alpha)=\cos 2\beta$, which implies that the wrong-sign $h\bar{U}U$ couplings can occur only if $\tan\beta<1$. In the type-I and lepton specific 2HDM, both the $h\bar{D}D$ and $h\bar{U}U$ couplings are given by $\frac{\cos\alpha}{\sin\beta}$. Thus for $\sin(\beta+\alpha)=-1$, both the normalized $h\bar{D}D$ and $h\bar{U}U$ couplings are equal to -1, which is only possible if $\tan\beta<1$. Thus realistically only the $h\bar{D}D$ coupling of the type-II and flipped 2HDM can be of the wrong sign, since $\tan\beta>1$.