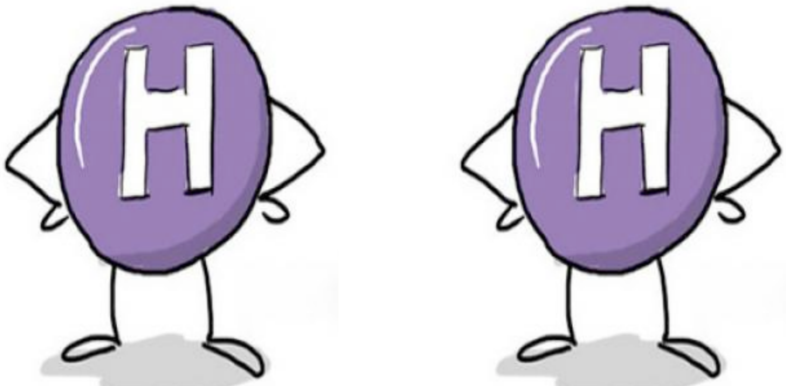
Approximate alignment without decoupling in the 2HDM naturally



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Outline

- Extended Higgs sector–motivations and constraints
- Achieving a SM-like Higgs boson in the 2HDM
- Approximate Higgs alignment via an approximate symmetry
- Possible symmetries of the 2HDM scalar potential
- Extending the symmetry to the Yukawa sector via mirror fermions
- Natural Higgs alignment without decoupling in the 2HDM
- Future work

This work is based on P. Draper, A. Ekstedt and H.E. Haber, in preparation. The central idea originated in P. Draper, H.E. Haber and J.T. Ruderman, JHEP **1606**, 124 (2016) [arXiv:1605.03237].

Why not an extended Higgs sector?

- The fermion and gauge boson sectors of the Standard Model (SM) are not of minimal form ("Who ordered that?"). So, why should the spin-0 (scalar) sector be minimal?

- Extended Higgs sectors can provide a dark matter candidate.

- Extended Higgs sectors can modify the electroweak phase transition and facilitate baryogenesis.

- Extended Higgs sectors can enhance vacuum stability.

- Models of new physics beyond the SM often require additional scalar Higgs states. E.g., two Higgs doublets are required in the minimal supersymmetric extension of the SM (MSSM).

Extended Higgs sectors are highly constrained

- The electroweak ρ parameter is very close to 1.
- One neutral Higgs scalar of the extended Higgs sector must be SM-like (and identified with the Higgs boson at 125 GeV).
- At present, only one Higgs scalar has been observed.
- Higgs-mediated flavor-changing neutral currents (FCNCs) are suppressed.
- Charged Higgs exchange at tree level (e.g. in $\bar{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$) and at one-loop (e.g. in $b \to s\gamma$) can significantly constrain the charged Higgs mass and the Yukawa couplings.
- If the scale that governs the non-SM-like Higgs bosons is close to the electroweak scale, is the naturalness problem of electroweak symmetry breaking exacerbated?

A SM-like Higgs boson in an extended Higgs sector

Les us focus on the two-Higgs doublet model (2HDM) as a prototype for an extended Higgs sector. Consider the 2HDM scalar potential,

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

The Φ_i are hypercharge $Y = 1$ doublets. After minimizing the scalar potential, $\langle\Phi_i^0\rangle = v_i/\sqrt{2}$ (for $i = 1, 2$) with $v \equiv (|v_1|^2 + |v_2|^2)^{1/2} = 2m_W/g = 246$ GeV.

Define the scalar doublet fields of the Higgs basis,

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1^*\Phi_1 + v_2^*\Phi_2}{v} , \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v} ,$$

such that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. The Higgs basis is uniquely defined up to an overall rephasing, $H_2 \to e^{i\chi}H_2$.

The Higgs basis and the alignment limit

The neutral scalar H_1^0 is *aligned* in field space with the vacuum expectation value v. If $\sqrt{2}\,H_1^0 - v$ were a mass eigenstate, then its tree-level properties would coincide with the Higgs boson of the SM.

In the Higgs basis, the scalar potential is given by:

$$\begin{aligned}\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 \\ & + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \big[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \big] H_1^\dagger H_2 + \text{h.c.} \right\} ,\end{aligned}$$

After minimizing the scalar potential, $Y_1 = -\tfrac{1}{2} Z_1 v^2$ and $Y_3 = -\tfrac{1}{2} Z_6 v^2$.

Remark:

Exact alignment corresponds to $Z_6 = 0$, which implies no H_1^0–H_2^0 mixing.

For simplicity, assume a CP-conserving scalar potential (where all Higgs basis parameters can be chosen real). The CP-even Higgs squared-mass matrix is,

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}.$$

where m_A is the mass of the CP-odd Higgs scalar.

The CP-even Higgs bosons are h and H with $m_h \leq m_H$. Approximate alignment arises two limiting cases:

1. $m_A^2 \gg (Z_1 - Z_5)v^2$. This is the *decoupling limit*, where h is SM-like and $m_A^2 \sim m_H^2 \sim m_{H^\pm}^2 \gg m_h^2 \simeq Z_1 v^2$.

2. $|Z_6| \ll 1$. Then, h is SM-like if $m_A^2 + (Z_5 - Z_1)v^2 > 0$. Otherwise, H is SM-like. This is alignment with or without decoupling, depending on the value of m_A. The boundary between these two regions is fuzzy.

In particular, the CP-even neutral scalar mass eigenstates are:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & -s_{\beta-\alpha} \\ s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}\, H_1^0 - v \\ \sqrt{2}\,\mathrm{Re}\, H_2^0 \end{pmatrix},$$

where $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$ and $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$ are defined in terms of the mixing angle α that diagonalizes the CP-even Higgs squared-mass matrix when expressed in the Φ_1–Φ_2 basis of scalar fields, $\{\sqrt{2}\,\mathrm{Re}\,\Phi_1^0 - v_1\,,\ \sqrt{2}\,\mathrm{Re}\,\Phi_2^0 - v_2\}$, and $\tan\beta \equiv v_2/v_1$.

Since the SM-like Higgs boson must be approximately $\sqrt{2}\,\mathrm{Re}\ H_1^0 - v$, it follows that

- h is SM-like if $|c_{\beta-\alpha}| \ll 1$ (alignment with or without decoupling, depending on the value of m_A),
- H is SM-like if $|s_{\beta-\alpha}| \ll 1$ (alignment without decoupling).

The alignment limit in equations

The CP-even Higgs squared-mass matrix yields,

$$\begin{aligned}
Z_1 v^2 &= m_h^2 s^2_{\beta-\alpha} + m_H^2 c^2_{\beta-\alpha}\,,\\
Z_6 v^2 &= (m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha}\,,\\
Z_5 v^2 &= m_H^2 s^2_{\beta-\alpha} + m_h^2 c^2_{\beta-\alpha} - m_A^2\,.
\end{aligned}$$

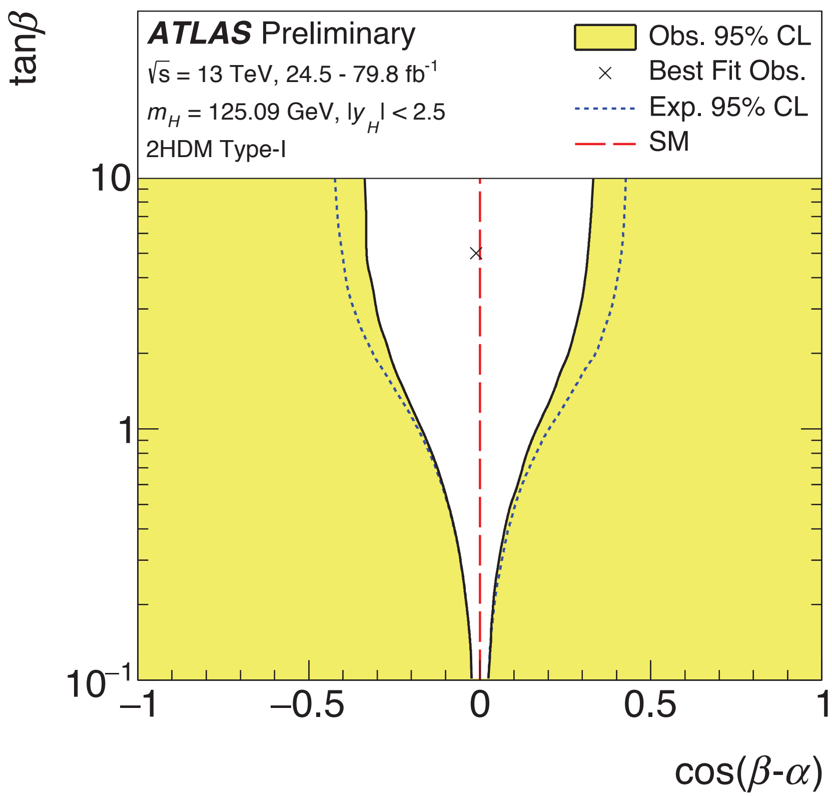
If h is SM-like, then $m_h^2 \simeq Z_1 v^2$ (i.e., $Z_1 \simeq 0.26$) and

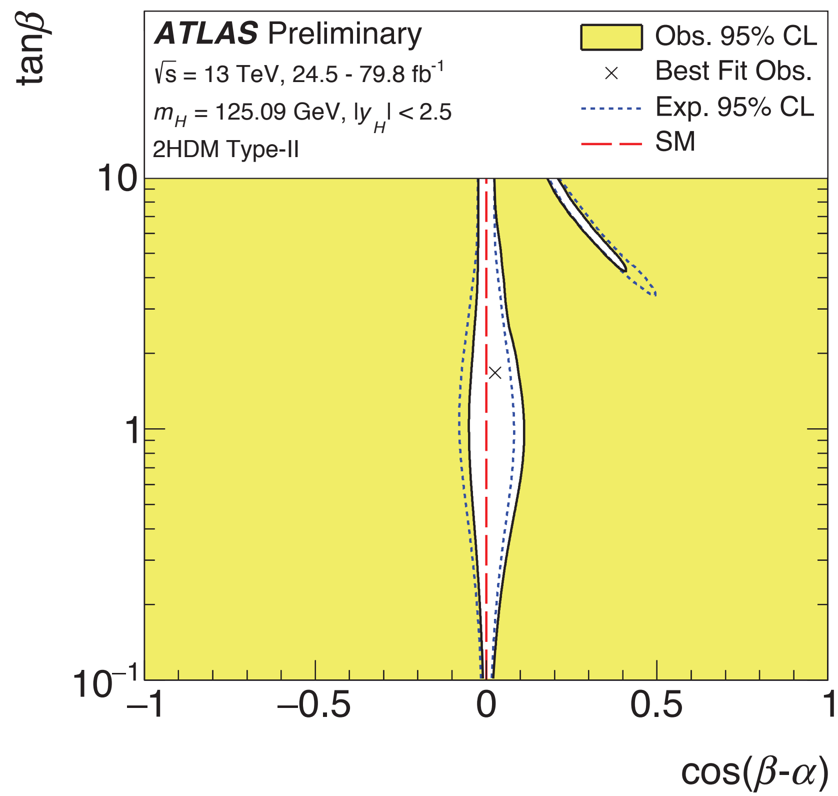
$$|c_{\beta-\alpha}| = \frac{|Z_6| v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1\,,$$

If H is SM-like, then $m_H^2 \simeq Z_1 v^2$ (i.e., $Z_1 \simeq 0.26$) and

$$|s_{\beta-\alpha}| = \frac{|Z_6| v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}} \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1\,.$$

LHC constraints on alignment in the 2HDM





Taken from ATLAS-CONF-2019-005 (March 20, 2019), under the assumption that $h(125)$ is the lighter of the two CP-even scalars.

Achieving a SM-like Higgs boson in the 2HDM

- In the decoupling limit, $m_h \ll m_H, m_A, m_{H^\pm}$. The SM is the effective low energy theory below the mass scale of the Higgs basis field H_2, and h is the SM-like Higgs boson.

- The inert doublet model (IDM): There is a $\mathbb{Z}_2$ symmetry in the Higgs basis such that $H_2 \to -H_2$ is the only $\mathbb{Z}_2$-odd field. Then $Z_6 = 0$, and the tree-level properties of $\sqrt{2}\,\mathrm{Re}H_1^0 - v$ coincide with the SM Higgs boson. That is, tree-level alignment is exact. Deviations from SM behavior can appear at loop level due to the virtual exchange of the scalar states that reside in H_2. The lightest of the $\mathbb{Z}_2$-odd scalars is a dark matter candidate.

- Approximate alignment without decoupling. If present,
  - is this a result of an accidental choice of model parameters?
  - is this a consequence of an approximate (softly-broken) symmetry? (The latter is not possible in the IDM.)

Family and Generalized CP symmetries of the 2HDM

Higgs family symmetries

$\mathbb{Z}_2$: $\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$

Π_2 : $\Phi_1 \longleftrightarrow \Phi_2$

U(1)$_{\rm PQ}$ [Peccei-Quinn]: $\Phi_1 \to e^{-i\theta}\Phi_1, \quad \Phi_2 \to e^{i\theta}\Phi_2$

SO(3): $\Phi_a \to U_{ab}\Phi_b\,, \quad U \in {\rm U}(2)/{\rm U}(1)_Y$

Generalized CP (GCP) transformations

$$\text{GCP1}: \quad \Phi_1 \to \Phi_1^*, \qquad \Phi_2 \to \Phi_2^*$$

$$\text{GCP2}: \quad \Phi_1 \to \Phi_2^*, \qquad \Phi_2 \to -\Phi_1^*$$

$$\text{GCP3}: \quad \Phi_1 \to \Phi_1^* c_\theta + \Phi_2^* s_\theta, \qquad \Phi_2 \to -\Phi_1^* s_\theta + \Phi_2^* c_\theta, \qquad \text{for } 0 < \theta < \tfrac{1}{2}\pi$$

where $c_\theta \equiv \cos\theta$ and $s_\theta \equiv \sin\theta$.

Possible symmetries of the 2HDM scalar potential

A complete classification of possible Higgs family and generalized CP symmetries of the scalar potential (in the Φ_1–Φ_2 basis) has been obtained.[1]

symmetry	m_{22}^2	m_{12}^2	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
$\mathbb{Z}_2$		0					0	0
Π_2	m_{11}^2	real	λ_1			real		λ_6^*
U(1)		0				0	0	0
SO(3)	m_{11}^2	0	λ_1		$\lambda_1 - \lambda_3$	0	0	0
CP		real				real	real	real
GCP2	m_{11}^2	0	λ_1					$-\lambda_6$
GCP3	m_{11}^2	0	λ_1			$\lambda_1 - \lambda_3 - \lambda_4$ (real)	0	0

Remarks:

1. Π_2 symmetry is equivalent to $\mathbb{Z}_2$ symmetry in a different basis.
2. Simultaneous $\mathbb{Z}_2$ and Π_2 $\Longleftrightarrow$ GCP2 in a different basis.
3. Simultaneous $\mathrm{U}(1)_{\mathrm{PQ}}$ and Π_2 $\Longleftrightarrow$ GCP3 in a different basis.

[1] I.P. Ivanov, Phys. Rev. D **77**, 015017 (2008) [arXiv:0710.3490]; P.M. Ferreira, H.E. Haber and J.P. Silva, Phys. Rev. D **79**, 116004 (2009) [arXiv:0902.1537].

A symmetry origin for alignment without decoupling

Consider the CP-conserving 2HDM. The scalar potential parameters in the Φ_1–Φ_2 basis are related to the corresponding Higgs basis parameters; e.g.,

$$Y_3 = \tfrac{1}{2}(m_{22}^2 - m_{11}^2)s_{2\beta} - m_{12}^2 c_{2\beta}\,.$$

If $m_{11}^2 = m_{22}^2$ and $m_{12}^2 = 0$, then $Y_3 = 0$. The scalar potential minimum condition ($Y_3 = -\tfrac{1}{2}Z_6 v^2$) then yields $Z_6 = 0$, i.e. exact alignment.[2] This leads to three possible symmetry choices:

symmetry	m_{22}^2	m_{12}^2	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
GCP2	m_{11}^2	0	λ_1					$-\lambda_6$
GCP3	m_{11}^2	0	λ_1			$\lambda_1-\lambda_3-\lambda_4$ (real)	0	0
SO(3)	m_{11}^2	0	λ_1		$\lambda_1-\lambda_3$	0	0	0

Unfortunately, none of these symmetries can be extended to the Yukawa interactions without generating a massless quark or some other phenomenologically untenable feature.[3]

[2] See, e.g., P.S. Bhupal Dev and A. Pilaftsis, JHEP **1412**, 024 (2014) [Erratum: JHEP **1511**, 147 (2015)].
[3] P.M. Ferreira and J.P. Silva, Eur. Phys. J. C **69**, 45 (2010).

The GCP-symmetric 2HDM with mirror fermions

The 2HDM with a GCP2 [GCP3]-symmetric scalar potential can be realized in another basis as a $\mathbb{Z}_2 \otimes \Pi_2$ $[\mathrm{U}(1)_{\mathrm{PQ}} \otimes \Pi_2]$ discrete symmetry, where

$$m_{11}^2 = m_{22}^2\,, \quad \lambda_1 = \lambda_2\,, \quad \lambda_5 \text{ real } [\lambda_5 = 0]\,, \quad m_{12}^2 = \lambda_6 = \lambda_7 = 0\,.$$

To extend this symmetry to the Yukawa sector, we introduce mirror fermions U and $\overline{U}$. SM two-component fermions are denoted by lower case letters (e.g. doublet fields $q = (u, d)$ with $Y = 1/3$ and singlet fields $\bar{u}$ with $Y = -4/3$); mirror singlet two-component fermions by upper case letters. Note that $Y_{\bar{u}} = Y_{\bar{U}} = -Y_U$. Under the symmetries,[4]

symmetry	Φ_1	Φ_2	q	$\bar{u}$	$\overline{U}$	U
$\mathbb{Z}_2$	Φ_1	$-\Phi_2$	q	$-\bar{u}$	$\overline{U}$	U
Π_2	Φ_2	Φ_1	q	$\overline{U}$	$\bar{u}$	U
U(1)	$e^{-i\theta}\Phi_1$	$e^{i\theta}\Phi_2$	q	$e^{-i\theta}\bar{u}$	$e^{i\theta}\overline{U}$	$e^{-i\theta}U$

[4] The down-type fermions and leptons can also be included by introducing the appropriate mirror fermions.

The Yukawa couplings consistent with the $\mathbb{Z}_2 \otimes \Pi_2$ $[\mathrm{U}(1)_{\mathrm{PQ}} \otimes \Pi_2]$ symmetry and the SU(2)×U(1)$_{\mathrm{Y}}$ gauge symmetry are

$$\mathscr{L}_{\mathrm{Yuk}} \supset y_t \left(q\Phi_2\bar{u} + q\Phi_1\overline{U}\right) + \mathrm{h.c.}$$

The model is not phenomenologically viable due to

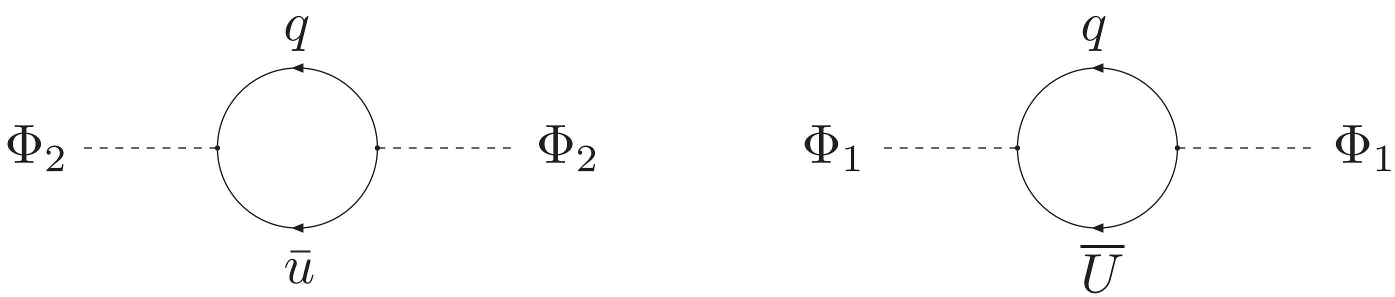
- experimental limits on mirror fermion masses
- existence of a massless scalar if U(1)$_{\mathrm{PQ}}$ is spontaneously broken

Thus, we introduce SU(2)×U(1)$_{\mathrm{Y}}$ preserving mass terms associated with mirror fermions,

$$\mathscr{L}_{\mathrm{mass}} \supset M_U\overline{U}U + M_u\bar{u}U + \mathrm{h.c.}$$

The $\mathbb{Z}_2$ [U(1)$_{\mathrm{PQ}}$] symmetry is preserved by the $\overline{U}U$ mass term, whereas it is explicitly broken by the $\bar{u}U$ mass term. The Π_2 discrete symmetry is also explicitly broken if $M_U \neq M_u$. In all cases the symmetry breaking is soft, so that corrections to the scalar potential squared-mass parameters are protected from quadratic sensitivity to the cutoff scale Λ of the theory.

Effects of the broken symmetries



$$\Delta m^2 \equiv m_{22}^2 - m_{11}^2 \sim \kappa(M_U^2 - M_u^2) - \frac{3y_t^2(M_U^2 - M_u^2)}{4\pi^2} \ln(\Lambda/M) \,,$$

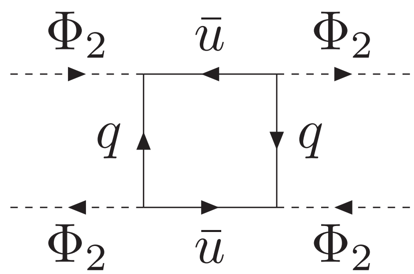
where $M \equiv (M_U^2 + M_u^2)^{1/2}$. The above result includes a finite threshold corrections proportional to κ. Note that when $M_U = M_u$, the Π_2 discrete symmetry is unbroken and hence the relation $m_{11}^2 = m_{22}^2$ is protected. Likewise,

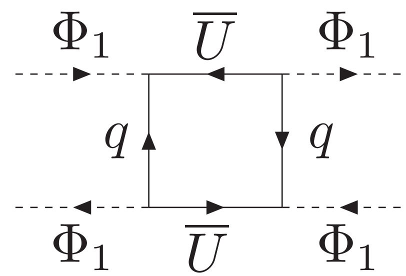
$$m_{12}^2 \sim \kappa_{12} M_U M_u + \frac{3y_t^2 M_U M_u}{4\pi^2} \ln(\Lambda/M) \,,$$

which includes a finite threshold corrections proportional to κ_{12}.

Integrating out the mirror fermions below the scale M, one generates a splitting between λ_1 and λ_2 and nonzero values of $\lambda_{5,6,7}$.

For example, above the scale M, the diagrams





contribute equally to $\lambda_2(\Phi_2^\dagger\Phi_2)^2$ and $\lambda_1(\Phi_1^\dagger\Phi_1)^2$, respectively. Below the scale M, the diagrams with internal U lines decouple, which then yields

$$\Delta\lambda \equiv |\lambda_1 - \lambda_2| \sim \frac{3y_t^4}{4\pi^2}\left(\frac{M_U^2 - M_u^2}{M_U^2 + M_u^2}\right)\log(M/m_t) \sim \mathcal{O}(0.1)\,,$$

for $M \sim \mathcal{O}(1\ \mathrm{TeV})$. This is a small correction, which in first approximation can be neglected in our analysis.

Likewise, explicit breaking of the $\mathbb{Z}_2$ [U(1)$_{\mathrm{PQ}}$] symmetry will generate small nonzero values of [λ_5], λ_6 and λ_7.

Top quark–mirror quark mixing

After electroweak symmetry breaking, the fermion mass eigenstates are obtain by Takagi-diagonalization of the following 4×4 mass matrix.

$$-\mathscr{L}_{\rm mass} = \tfrac{1}{2}(u \quad U \quad \bar{u} \quad \overline{U}) \begin{pmatrix} 0 & 0 & m_2 & m_1 \\ 0 & 0 & M_u & M_U \\ m_2 & M_u & 0 & 0 \\ m_1 & M_U & 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ U \\ \bar{u} \\ \overline{U} \end{pmatrix} + \text{h.c.}\,,$$

where $m_1 \equiv y_t v_1/\sqrt{2}$ and $m_2 \equiv y_t v_2/\sqrt{2}$. States with the same electric charge, i.e. $\{u, U\}$ and $\{\bar{u}, \overline{U}\}$, can separately mix (with mixing angles θ_L and θ_R, respectively). This yields two Dirac fermions–the top quark t and its mirror T, with squared-masses,

$$\begin{Bmatrix} M_T^2 \\ m_t^2 \end{Bmatrix} = \tfrac{1}{2}\left[m^2 + M^2 \pm \sqrt{(m^2 + M^2)^2 - 4(m_1 M_u - m_2 M_U)^2}\right]\,,$$

where $m \equiv y_t v/\sqrt{2}$ and $M^2 \equiv M_U^2 + M_u^2$.

The Higgs sector of the softly-broken GCP-symmetric 2HDM

The important parameters of the scalar potential are:

$$m^2 \equiv \tfrac{1}{2}(m_{11}^2 + m_{22}^2)\,, \qquad \Delta m^2 \equiv m_{22}^2 - m_{11}^2\,, \qquad R \equiv \frac{\lambda_{345}}{\lambda}\,, \qquad m_{12}^2\,,$$

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$. We impose $\lambda > 0$ and $R > -1$ to ensure that the vacuum is bounded from below. Solving for the potential minimum yields,

$$2m^2 = \bar{m}^2 - \tfrac{1}{2}\lambda v^2(1+R)\,, \qquad \Delta m^2 = \epsilon\left(\bar{m}^2 + \tfrac{1}{2}\lambda v^2(1-R)\right)\,,$$

where $\bar{m}^2 \equiv 2m_{12}^2/\sin 2\beta$ and

$$\tan\beta \equiv \frac{v_2}{v_1} = \sqrt{\frac{1-\epsilon}{1+\epsilon}}\,, \qquad \text{where} \quad \epsilon \equiv \cos 2\beta\,.$$

The positivity of v_1^2 and v_2^2 requires $|\epsilon| < 1$.

Approximate alignment without decoupling

The relevant Higgs basis parameters are given by,

$$\begin{aligned} Z_1 &= \tfrac{1}{2}\lambda\big[1 + R + \epsilon^2(1-R)\big]\,, \\ m_A^2 + Z_5 v^2 &= 2m^2 + \lambda v^2\big[1 - \tfrac{1}{2}\epsilon^2(1-R)\big]\,, \\ Z_6 &= \tfrac{1}{2}\lambda(R-1)\epsilon\sqrt{1-\epsilon^2}\,, \end{aligned}$$

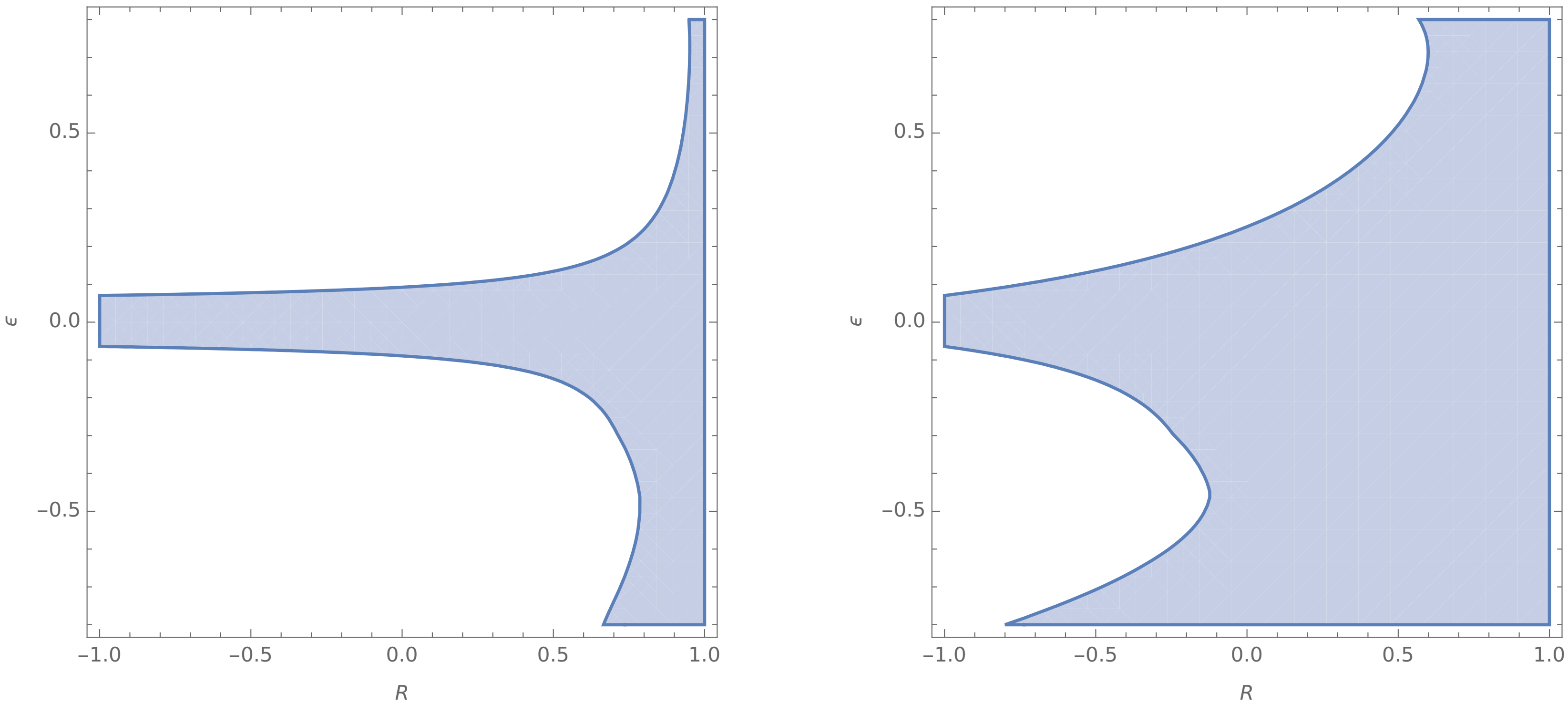
Approximate alignment without decoupling requires that $|Z_6| \ll 1$ and $m^2 \sim \mathcal{O}(v^2)$. To avoid $\tan\beta$ very large or very small, we consider two limiting cases: $|\epsilon| \ll 1$ and $|R-1| \ll 1$.

In the limit of $|\epsilon| \ll 1$,

$$m_h^2 = \tfrac{1}{2}\lambda v^2(1+R)\,, \qquad m_H^2 = 2m^2 + \lambda v^2\,, \qquad c_{\beta-\alpha} = \frac{\lambda v^2(1-R)\epsilon}{4m^2 + \lambda v^2(1-R)}\,.$$

In the limit of $|R-1| \ll 1$,

$$m_h^2 = \lambda v^2\,, \qquad m_H^2 = 2m^2 + \lambda v^2\,, \qquad c_{\beta-\alpha} = \frac{\lambda v^2(1-R)\epsilon\sqrt{1-\epsilon^2}}{4m^2}\,.$$



Allowed regions of the R vs. ϵ parameter space with $m = 50$ GeV (left) and $m = 150$ GeV (right) with softly broken GCP symmetry, taking the precision $h(125)$ LHC data into account.

We impose constraints from precision Higgs data, which favors a SM-like $h(125)$. The allowed regions above correspond to those of a Type-I 2HDM. For $m = 150$ GeV, typical values of m_H and m_A are around 250 GeV.

Regions of approximate alignment without decoupling

To be consistent with current LHC data, we shall also impose:

- Non-SM Higgs bosons in the parameter regime of alignment without decoupling should have so far evaded LHC detection.

- Constraints on the charged Higgs mass from flavor constraints in the Type-I 2HDM.

- Vector-like top quark bounds [we choose $M_T \gtrsim 1.2$ TeV]

- Constraints on mixing between the top quark and its mirror partner[5] [$\sin\theta_L \lesssim 0.12$]

- Avoid excessive fine-tuning to keep size of the effects due to soft-GCP-symmetry breaking terms small. This will provide upper limits on the values of M/m_t and Λ/M.

[5] See, e.g., A. Arhrib et al., Phys. Rev. D 97, 095015 (2018).

Future work

- Adding in the mirror fermions corresponding to the down-type quarks and leptons.
- A detailed phenomenological study of the softly-broken GCP model to see the interplay between the spectrum of mirror fermions and the deviations from the alignment limit.
- Correlating the properties of the non-SM Higgs bosons with those of the mirror fermions.
- If mirror fermions are discovered, how to use data to identify the presence of an approximate GCP symmetry and to distinguish between GCP2 and GCP3.
- Assessing the extent of the fine-tuning of parameters in models of approximate alignment without decoupling (in the presence of an approximate symmetry), beyond the one fine-tuning required to set the electroweak symmetry breaking scale.