Masses of physical scalars in two Higgs doublet models

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Overview

- Introduction
- Aim of the work
- Calculations
- Results and conclusion
Motivations for 2HDMs:
- Supersymmetry
- Axion models
- Dark Matter

The 2HDM Yukawa Lagrangian:

\[ L_{Y} = \sum_{i=1}^{2} h^{\dagger} L_{i} G_{i} e_{R} + h : c : + \sum_{i=1}^{2} Q_{i} G_{i} u_{R} + \sum_{i=1}^{2} d_{R} G_{i} \]

where \( L_{i} ; Q_{i} \) are 3-vectors of isodoublets in the space of generations, \( e_{R} ; u_{R} ; d_{R} \) are 3-vectors of singlets, \( G_{1} e \) etc. are complex 3x3 matrices in generation space containing the Yukawa coupling constants, and \( \tilde{i} = i \).
Motivations for 2HDMs:

- Supersymmetry
- Axion models
- Dark Matter

The 2HDM Yukawa Lagrangian:

$$L_{Y} = \sum_{i=1}^{2} h_{i} l_{i}^{T} Q_{L} G_{i} e_{R} + h.c.$$

where $l_{L}$; $Q_{L}$ are 3-vectors of isodoublets in the space of generations, $e_{R}$; $u_{R}$; $d_{R}$ are 3-vectors of singlets, $G_{1}$; etc. are complex $3 \times 3$ matrices in generation space containing the Yukawa coupling constants, and $\sim_{i} = i_{2} i_{3} i_{1}$.
Motivations for 2HDMs:
- Supersymmetry
- Axion models
- Dark Matter

The 2HDM Yukawa Lagrangian:

\[ \mathcal{L}_Y = \sum_{i=1,2} \left[ -\bar{l}_L \tilde{h}_i G^i e_R - \bar{Q}_L \tilde{h}_i G^i u_R - \bar{Q}_L \tilde{h}_i G^i d_R + h.c. \right] \]
Introduction

Motivations for 2HDMs:
- Supersymmetry
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- Dark Matter

The 2HDM Yukawa Lagrangian:
\[ L_Y = \sum_{i=1,2} \left[ -\bar{l}_L \Phi^i G^i_{e e_R} - \bar{Q}_L \Phi^i G^i_{u u_R} - \bar{Q}_L \Phi^i G^i_{d d_R} + h.c. \right] \]

where \( l_L, Q_L \) are 3-vectors of isodoublets in the space of generations, \( e_R, u_R, d_R \) are 3-vectors of singlets, \( G^i_{e}, \ldots \) etc. are complex 3 \( \times \) 3 matrices in generation space containing the Yukawa coupling constants, and \( \Phi^i = i\tau_2 \Phi^*_i \).
Symmetries and the scalar potential

The $Z_2$ symmetry FCNCs are avoided by imposing $Z_2$ symmetry.

$Z_2$ symmetry implies:

\[
1 \neq 1
\]

The scalar potential under the $Z_2$ symmetry is:

\[
V = \left(y_1 v_1^2 + y_2 v_2^2\right)^2 + \left(y_1 v_1 + y_2 v_2\right)^2 + \left(y_1 v_2 + y_2 v_1\right)^2 + \left(y_1 y_2 v_1 v_2\right)^2 + \left(12(v_1 v_2)^2\right)^2 + \left(12i(y_1 y_2 v_1 v_2\right)^2
\]
Symmetries and the scalar potential

The $Z_2$ symmetry

FCNCs are avoided by imposing $Z_2$ symmetry.

$Z_2$ symmetry implies:

$\Phi_1 \to -\Phi_1$

$\Phi_2 \to \Phi_2$
Symmetries and the scalar potential

The $Z_2$ symmetry

FCNCs are avoided by imposing $Z_2$ symmetry.

\[ Z_2 \text{ symmetry implies:} \]
\[ \Phi_1 \rightarrow -\Phi_1 \]
\[ \Phi_2 \rightarrow \Phi_2 \]

The scalar potential under the $Z_2$ symmetry

\[ V = \lambda_1 (\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2})^2 + \lambda_2 (\Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2})^2 \]
\[ + \lambda_3 (\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 - \frac{v_1^2 + v_2^2}{2})^2 \]
\[ + \lambda_4 ((\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) - (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)) \]
\[ + \lambda_5 (\frac{1}{2}(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 - v_1 v_2))^2 + \lambda_6 (\frac{1}{2i}(\Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1))^2 \]
In this paper we will consider the implications of a global $U(1)$ symmetry which generalizes the $Z_2$ symmetry mentioned earlier. Here we show only those fields that *flip* sign under $U(1)$ symmetry:

- **Type I:**
  - $1 \to \exp(i\theta) 1$
  - $d_i R \to \exp(i\theta) d_i R$
  - $e_i R \to \exp(i\theta) e_i R$

- **Type II:**
  - $1 \to \exp(i\theta) 1$
  - $d_i R \to \exp(i\theta) d_i R$
  - $e_i R \to \exp(i\theta) e_i R$

- **Lepton Specific:**
  - $1 \to \exp(i\theta) 1$
  - $e_i R \to \exp(i\theta) e_i R$

- **Flipped:**
  - $1 \to \exp(i\theta) 1$
  - $d_i R \to \exp(i\theta) d_i R$

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Physical Higgs masses from VCs
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### The $U(1)$ symmetry

- **Typel**: $\Phi_1 \to \exp(i\theta)\Phi_1$;
- **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**: $\Phi_1 \to \exp(i\theta)\Phi_1, d_R^i \to \exp(-i\theta)d_R^i$
The scalar potential under the $U(1)$ symmetry

The $U(1)$ symmetry implies $\lambda_5 = \lambda_6$ and hence the scalar potential takes the form:

$$V = \lambda_1 (\Phi^+_1 \Phi_1 - \frac{v_1^2}{2})^2 + \lambda_2 (\Phi^+_2 \Phi_2 - \frac{v_2^2}{2})^2$$

$$+ \lambda_3 (\Phi^+_1 \Phi_1 + \Phi^+_2 \Phi_2 - \frac{v_1^2 + v_2^2}{2})^2$$

$$+ \lambda_4 ((\Phi^+_1 \Phi_1)(\Phi^+_2 \Phi_2) - (\Phi^+_1 \Phi_2)(\Phi^+_2 \Phi_1))$$

$$+ \lambda_5 |\Phi^+_1 \Phi_2 - \frac{v_1 v_2}{2}|^2$$
The two Higgs Doublets

$$\begin{align*}
\mathbf{\Phi} &= \mathbf{w} + \mathbf{a}(x) + \mathbf{v}_a + \mathbf{h}_a(x) + \mathbf{iz}_a(x) \\
\mathbf{\Phi}^2 &= \mathbf{a} \\
\tan\beta &= \frac{v_2}{v_1} \\
v &= \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}
\end{align*}$$

Obtaining the mass eigenstates

The physical Higgs fields and the Goldstone bosons are hence obtained:

$$\begin{align*}
\mathbf{h} &= \mathbf{c}_s\mathbf{s}\mathbf{c}_w \mathbf{h}_1 \mathbf{h}_2 \\
\mathbf{A} &= \mathbf{c}_s\mathbf{s}\mathbf{c}_z \mathbf{z}_1 \mathbf{z}_2 \\
\mathbf{H} &= \mathbf{c}_s\mathbf{s}\mathbf{c}_h \mathbf{h}_1 \mathbf{h}_2
\end{align*}$$
The two Higgs Doublets

SU(2) complex scalar doublets

\[ \Phi_a = \left( \begin{array}{c} w_a^+(x) \\ (v_a + h_a(x) + iz_a(x)) \end{array} \right) \frac{1}{\sqrt{2}}; \quad a = 1, 2 \]

\[ \tan \beta = \frac{v_2}{v_1}, \quad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV} \]
The two Higgs Doublets

SU(2) complex scalar doublets

\[ \Phi_a = \left( \frac{w_a^+(x)}{(v_a + h_a(x) + iz_a(x))} \right)^{\frac{1}{\sqrt{2}}}; \quad a = 1, 2 \]

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Obtaining the mass eigenstates

The physical Higgs fields and the Goldstone bosons are hence obtained:

\[ \begin{pmatrix} \omega^\pm \\ \xi^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix}, \]

\[ \begin{pmatrix} \zeta \\ \Lambda \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}, \]

\[ \begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \]
A different angle of rotation

\[
\begin{pmatrix}
H^0 \\
R
\end{pmatrix} = \begin{pmatrix}
c_\beta & s_\beta \\
-s_\beta & c_\beta
\end{pmatrix}
\begin{pmatrix}
h_1 \\
h_2
\end{pmatrix}
\]
A different angle of rotation

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

Now,

- \( H^0 \) has the exact Standard Model couplings with the fermions and gauge bosons.

[Ref: G.C.Branco, W.Grimus and L.Lavoura, Phys.Lett.B 380, 119 (1996)[hep-ph/9601383].]
Decoupling Limit

A different angle of rotation

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

Now,

- $H^0$ has the exact Standard Model couplings with the fermions and gauge bosons.

  [Ref: G.C.Branco, W.Grimus and L.Lavoura, Phys.Lett.B 380, 119 (1996)[hep-ph/9601383].]

- The field $R$ does not have any cubic gauge coupling at the tree level. It can however have flavor changing Yukawa couplings.
Decoupling limit contd...

Relation between the lighter CP even mass eigenstate $h$, $H^0$ and $R$

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

Relation between the lighter CP even mass eigenstate $h$, $h^0$ and $R$

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

Thus in order for $h$ to be the Higgs boson of the Standard Model, we require,

$$\sin(\beta - \alpha) \approx 1$$

$$\Rightarrow \beta - \alpha = \frac{\pi}{2}$$
Relation between the lighter CP even mass eigenstate $h$, $\Phi^0$ and $R$

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

Thus in order for $h$ to be the Higgs boson of the Standard Model, we require,

$$\sin(\beta - \alpha) \approx 1$$

$$\Rightarrow \beta - \alpha = \frac{\pi}{2}$$

which has been referred to as the \textit{decoupling limit}

[Ref. J. F. Gunion and H. E. Haber, Phys. Rev. D 67, 075019 (2003)].
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).]

The four VCs

\[
2 Tr G_1^1 G_1^1 + 6 Tr G_1^1 G_1^2 + 6 Tr G_1^1 G_1^1 = \frac{9}{4} g_2^2 + \frac{3}{4} g'^2 + 6 \lambda_1 + 10 \lambda_3 + \lambda_4 + \lambda_5
\]

\[
2 Tr G_2^2 G_2^1 + 6 Tr G_2^2 G_2^2 + 6 Tr G_2^2 G_2^1 = \frac{9}{4} g_2^2 + \frac{3}{4} g'^2 + 6 \lambda_2 + 10 \lambda_3 + \lambda_4 + \lambda_5
\]

\[
2 Tr G_1^1 G_2^2 + 6 Tr G_1^1 G_2^2 + 6 Tr G_1^1 G_2^1 = 0
\]

\[
2 Tr G_1^2 G_2^1 + 6 Tr G_1^2 G_1^2 + 6 Tr G_1^2 G_1^1 = 0
\]
Aim of the work

- Expressing the VCs in terms of the fermion, the Higgs boson and the gauge boson masses

  ↓

- Fermion and the gauge boson masses are plugged in

  ↓

- Left with some equations in terms of the physical Higgs bosons masses

  ↓

- Inference of the mass ranges of the physical Higgs bosons.
General results involving the Yukawa couplings and fermion masses:

By diagonalising the Yukawa matrices we obtain the following results.

\[
\text{Tr} \left[ G_{1f}^\dagger G_{1f} \right] = \left( \frac{\sqrt{2}}{v} \right)^2 \cos^2 \beta \sum m_f^2
\]
\[
\text{Tr} \left[ G_{2f}^\dagger G_{2f} \right] = \left( \frac{\sqrt{2}}{v} \right)^2 \sin^2 \beta \sum m_f^2
\]

for each of the cases where \( f \) stands for charged leptons, up-type quarks, or down-type quarks, and the sum is taken over generations.
\( \lambda_1 = \frac{1}{2v^2c^2_\beta} m_H^2 - \frac{\lambda_5}{4} (\tan^2 \beta - 1) \),

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

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

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

\( \lambda_5 = \frac{2}{v^2} m_A^2 \).
\[ \lambda_1 = \frac{1}{2v^2 c^2_\beta} m_H^2 - \frac{\lambda_5}{4} (\tan^2 \beta - 1), \]
\[ \lambda_2 = \frac{1}{2v^2 s^2_\beta} m_H^2 - \frac{\lambda_5}{4} \left( \frac{1}{\tan^2 \beta} - 1 \right), \]
\[ \lambda_3 = -\frac{1}{2v^2} (m_H^2 - m_h^2) - \frac{\lambda_5}{4}, \]
\[ \lambda_4 = \frac{2}{v^2} m_\xi^2, \]
\[ \lambda_5 = \frac{2}{v^2} m_A^2. \]

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**

RHS of VC1:

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

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

RHS of VC2:

$$6 \mathcal{M}_W^2 + 3 \mathcal{M}_Z^2 + m_H^2 \left( \frac{3}{\tan^2 \beta} - 2 \right) + 5 m_h^2 + 2 m_\xi^2 - \frac{3v^2}{2} \frac{\lambda_5}{\tan^2 \beta}$$

| Type of 2HDM   | The corresponding LHS of VC 2                                      |
|----------------|------------------------------------------------------------------|
| Type-I         | $4[(m_e^2 + m_\mu^2 + m_\tau^2) + 3(m_u^2 + m_c^2 + m_t^2) + 3(m_d^2 + m_s^2 + m_b^2)] \sin^2 \beta$ |
| Type-II        | $12(m_u^2 + m_c^2 + m_t^2) \sin^2 \beta$                         |
| $\mathcal{G}_{2e} = 0; \mathcal{G}_{2d} = 0$ |                                                                |
| Lepton Specific| $12[(m_u^2 + m_c^2 + m_t^2) + (m_d^2 + m_s^2 + m_b^2)] \sin^2 \beta$ |
| $\mathcal{G}_{2e} = 0$ |                                                                |
| Flipped 2HDM   | $4[(m_e^2 + m_\mu^2 + m_\tau^2) + 3(m_u^2 + m_c^2 + m_t^2)] \sin^2 \beta$ |
| $\mathcal{G}_{2d} = 0$ |                                                                |
Stability and Unitarity conditions

Scalar potential being bounded from below:

\[ \text{Ref: M. Sher, Phys. Rept. 179 (1989) 273} \]

\[ 1 + 3 > 0; \quad 2 + 3 + 4 + 2q(1 + 3)(2 + 3) > 0; \]

\[ 2 + 3 > 0; \quad 2 + 3 + 5 + 2q(1 + 3)(2 + 3) > 0; \]

Perturbative unitarity:

\[ \text{Ref: J. Maalampi, J. Sirkka and I. Vilja, Phys. Lett. B 265, 371 (1991)} \]

\[ j^2 + 3 + 4j^{16}; \quad j^2 + 3 + 5j^{16}; \quad j^2 + 3 + 2 + 4j^{16}; \]

\[ j(1 + 2 + 2^3)q^9(1 + 2); \quad 2(4 + 3 + 4 + 5)j^{16}; \quad j(1 + 2 + 2^3)q^9(1 + 2); \]

\[ j(1 + 2 + 2^3)(1 + 2 + 2^3)j^{16}; \]
Stability and Unitarity conditions

Scalar potential being bounded from below: [Ref: M. Sher, Phys. Rept. 179 (1989) 273]

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

\[
\lambda_2 + \lambda_3 > 0, 2\lambda_3 + \lambda_5 + 2\sqrt{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_3)} > 0.
\]
Stability and Unitarity conditions

Scalar potential being bounded from below: [Ref:M.Sher,Phys.Rept.179(1989)273]

\[ \lambda_1 + \lambda_3 > 0, \quad 2\lambda_3 + \lambda_4 + 2\sqrt{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_3)} > 0, \]
\[ \lambda_2 + \lambda_3 > 0, \quad 2\lambda_3 + \lambda_5 + 2\sqrt{(\lambda_1 + \lambda_3)(\lambda_2 + \lambda_3)} > 0. \]

Perturbative unitarity: [Ref:J.Maalampi, J.Sirkka and I.Vilja, Phys.Lett.B 265,371(1991)]

\[ |2\lambda_3 - \lambda_4 + 2\lambda_5| \leq 16\pi, \]
\[ |2\lambda_3 + \lambda_4| \leq 16\pi, \]
\[ |2\lambda_3 + \lambda_5| \leq 16\pi, \]
\[ |2\lambda_3 + 2\lambda_4 - \lambda_5| \leq 16\pi, \]
\[ |3(\lambda_1 + \lambda_2 + 2\lambda_3) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (4\lambda_3 + \lambda_4 + \lambda_5)^2}| \leq 16\pi, \]
\[ |(\lambda_1 + \lambda_2 + 2\lambda_3) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_4 - \lambda_5)^2}| \leq 16\pi, \]
\[ |(\lambda_1 + \lambda_2 + 2\lambda_3) \pm (\lambda_1 - \lambda_2)| \leq 16\pi. \]
Restrictions on the physical Higgs masses
Restrictions on the physical Higgs masses

\[ 0 \leq (m_H^2 - m_A^2)(\tan^2 \beta + \cot^2 \beta) + 2m_h^2 \leq \frac{32\pi v^2}{3}. \]
Restrictions on the physical Higgs masses

\[ 0 \leq (m_H^2 - m_A^2)(\tan^2 \beta + \cot^2 \beta) + 2m_h^2 \leq \frac{32\pi v^2}{3}. \]

Degeneracy of \( m_A - m_H \) for progressively increasing \( \tan \beta \)
Restrictions on the physical Higgs masses contd..

Degeneracy of $m_A - m_H$ for progressively increasing $\tan \beta$ contd..

![Graph showing the degeneracy of $m_A - m_H$ for $\tan \beta = 10.0$ and $\tan \beta = 100.0$.]
Restrictions on the physical Higgs masses contd..

Electroweak T-parameter

\[ T = \frac{1}{16} \sin 2\theta_{ew} M_W \]

with

\[ F(x;y) = \frac{x + y^2}{x^2 y^2} x^6 y^6 \]

The new physics contribution to the T-parameter is

\[ T = 0.05 \pm 0.12 \] [Ref: M.Baak and R.Kogler, arXiv:1306.0571[hep-ph]]
Restrictions on the physical Higgs masses contd..

Electroweak T-parameter

\[ T = \frac{1}{16\pi \sin^2 \theta_W M_W^2} \left[ F(m_{\xi}^2, m_{\tilde{\eta}}^2) + F(m_{\xi}^2, m_{\tilde{\chi}_1^0}^2) - F(m_{\tilde{\eta}}^2, m_{\tilde{\chi}_1^0}^2) \right], \]

with

\[ F(x, y) = \begin{cases} \frac{x+y}{2} & x \neq y \\ \frac{xy}{x-y} \ln \left( \frac{x}{y} \right) & x = y \end{cases} \]

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Restrictions on the physical Higgs masses contd..

**Electroweak T-parameter**

\[
T = \frac{1}{16\pi \sin^2 \theta_W M_Z^2} \left[ F(m^2_\xi, m^2_H) + F(m^2_\xi, m^2_A) - F(m^2_H, m^2_A) \right],
\]

with

\[
F(x, y) = \begin{cases} 
\frac{x+y}{2} & x \neq y \\
0 & x = y
\end{cases}
\]

The new physics contribution to the T-parameter is \(T = 0.05 \pm 0.12\) [Ref: M.Baak and R.Kogler, arXiv:1306.0571[hep-ph]]

**Constraints coming from electroweak T-parameter**

![Graph showing constraints on Higgs masses](image-url)
The allowed mass range plot for the physical Higgs bosons

The mass ranges for $m_H$ and $m_\xi$ has been obtained by superimposing the conditions coming from the stability conditions, the perturbative unitarity conditions, the $T$-parameter constraints and the Veltman Conditions. The plots for the four types of 2HDMs are shown below.
The allowed mass range plot for the physical Higgs bosons contd...

Allowed region for Type-I model, tan$\beta$=5.0

Allowed range for Type-II model, tan$\beta$=5.0

Allowed region for Lepton Specific model, tan$\beta$=5.0

Allowed region for Flipped model, tan$\beta$=5.0
Results and Conclusion

The region of intersection gives the allowed mass range of $m_{H}$ and $m_{A}$ for various types of 2HDMS. The range of $m_{H}$ lies between 420GeV to 620GeV. The range of $m_{A}$ lies between 500GeV to 680GeV. The above mass ranges vary between a few GeV for the various 2HDMs. Direct searches have shown that $m_{A} > 100$ GeV and our results agree with this lower bound. [Ref. Beringer et al. (PDG), Phys.Rev.D86(2012) 010001]

The degeneracy in the masses of the physical Higgs bosons for large enough $\tan\beta$ is evident from our plots.
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The range of $m_\xi$ lies between 500GeV to 680GeV.

The above mass ranges vary between a few GeV for the various 2HDMs.

Direct searches have shown that $m_\xi > 100\text{GeV}$ and our results agree with this lower bound. [Ref. Beringer et al. (PDG), Phys.Rev.D86(2012) 010001]
The region of intersection gives the allowed mass range of $m_H$ and $m_\xi$ for various types of 2HDMs.

- The range of $m_H$ lies between 420GeV to 620GeV
- The range of $m_\xi$ lies between 500GeV to 680GeV
- The above mass ranges vary between a few GeV for the various 2HDMs.

Direct searches have shown that $m_\xi > 100\,\text{GeV}$ and our results agree with this lower bound. [Ref. Beringer et al. (PDG), Phys.Rev.D86(2012) 010001]

The degeneracy in the masses of the physical Higgs bosons for large enough $\tan\beta$ is evident from our plots.
Thank you!