Three Higgs-doublet model with S_3 symmetry

Ana C. B. Machado
UFABC
Rua Santa Adélia, 166. Bairro Bangu. Santo André - SP - Brasil . CEP 09.210-170

Outline

- Motivation And Proposal
  - About S3
- The model (Machado-Pleitez arXiv: 1205.0995)
- The phenomenology (Cardenas-Machado-Pleitez-Rodriguez- work in progress)
- Final remarks

Motivation

Glashow and Weinberg "The suppression of FCNC is natural if it depends only the symmetry and the representation content of the model"

PRD 15, 1958 (1977).

Motivation

Glashow and Weinberg "The supression of FCNC is natural if it depends only the symmetry and the representation content of the model"

PRD 15, 1958 (1977).

In a multi-Higgs models we have Flavor conservation if the fermion masses are generated by a single source.

The proposal

- We assume that the scalar sector also has three families (there is no limit on the SM scalar sector).
- And we, also, assume that the symmetry governing the scalar sector is the S3 symmetry.

The proposal

- Usually the discrete symmetries are used to give more predictability in flavor problem, for example reproducing ansäteze.
- About S3 symmetry (arXiv:1003.3552v2)

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_{\mathbf{2}} \otimes \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}_{\mathbf{2}} = (x_1y_1 + x_2y_2)_{\mathbf{1}} + (x_1y_2 - x_2y_1)_{\mathbf{1'}} + \begin{pmatrix} x_1y_2 + x_2y_1 \\ x_1y_1 - x_2y_2 \end{pmatrix}_{\mathbf{2}},$$
$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}_{\mathbf{2}} \otimes (y')_{\mathbf{1'}} = \begin{pmatrix} -x_2y' \\ x_1y' \end{pmatrix}_{\mathbf{2}}, \tag{41}$$
$$(x')_{\mathbf{1'}} \otimes (y')_{\mathbf{1'}} = (x'y')_{\mathbf{1}}.$$

The proposal

- Or, all permutation of S3 symmetry are represented on the reducible triplet (x1,x2,x3) as:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
$$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

- We change the representation using the unitary transformation:

$$U_{\rm tribi} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix} \quad U^\dagger g U \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{pmatrix},$$
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{1}{2} \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{1}{2} \end{pmatrix}.$$

The proposal

- Or, all permutation of S3 symmetry are represented on the reducible triplet (x1,x2,x3) as:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

- We change the representation using the unitary transformation:

$$U_{\text{tribi}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix} \quad U^\dagger g U$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{pmatrix},$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{1}{2} \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{1}{2} \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{1}{2} \end{pmatrix}.$$

The multiplication rule is the same

3 = 2+1

3 x 3 = (2+1)(2+1)

The model

- However, we have two possible representations for the singlet and the doublet:

A: $\mathbf{3} = \mathbf{2} + \mathbf{1} \equiv D + S,$

$$S = \frac{1}{\sqrt{3}}(H_1 + H_2 + H_3) \sim \mathbf{1},$$

$$D \equiv (D_1, D_2) = \left[\frac{1}{\sqrt{6}}(2H_1 - H_2 - H_3), \frac{1}{\sqrt{2}}(H_2 - H_3)\right] \sim \mathbf{2}.$$

And B:

$$S = H_1 \sim \mathbf{1}, \quad D = (H_2, H_3) \sim \mathbf{2}.$$

- All the fermions are singlets of S3 (Minimum extension of the SM).

The model

SU(3) X SU(2) X U(1) X S3

- The most general scalar potential invariant under the symmetry is given by:

$$\begin{aligned} V(D,S) &= \mu_s^2 S^\dagger S + \mu_d^2 [D^\dagger \otimes D]_1 + \lambda_1 ([D^\dagger \otimes D]_1)^2 + \lambda_2 [(D^\dagger \otimes D)_{1'} (D^\dagger \otimes D)_{1'}]_1 \\ &+ \lambda_3 [(D^\dagger \otimes D)_2 (D^\dagger \otimes D)_2] + \lambda_4 (S^\dagger S)^2 + \lambda_5 [D^\dagger \otimes D]_1 S^\dagger S + \lambda_6 S^\dagger [D^\dagger \otimes D]_1 S \\ &+ \{\lambda_7 [(S^\dagger \otimes D)_2 (D^\dagger \otimes S)_2]_1 + \lambda_8 [(S^\dagger \otimes D)_2 (D^\dagger \otimes D)_2]_1 + H.c.\} \qquad (1) \end{aligned}$$

The Yukawa Sector

$$-\mathcal{L}_{yukawa} = \bar{L}_{iL} (G^l_{ij} l_{jR} S + G^\nu_{ij} \nu_{jR} \tilde{S}) + \bar{Q}_{iL} (G^u_{ij} u_{jR} \tilde{S} + G^d_{ij} d_{jR} S) + H.c.,$$

Model A

The constrain equations:

$$18t_1 = 6\mu_d^2(2v_1 - v_2 - v_3) + 6\mu_s^2 V + 2(4\bar{\lambda} + \lambda_4 + 2\bar{\lambda}' - 2\sqrt{2}\lambda_8)v_1^3$$
$$-(4\bar{\lambda} + 6\lambda_2 - 2\lambda_4 - \bar{\lambda}' - \sqrt{2}\lambda_8)(v_2^3 + v_3^3) - 3(2\lambda_2 - 2\lambda_4 + \bar{\lambda}' + 2\sqrt{2}\lambda_8)(v_2^2 v_3 + v_2 v_3^2)$$
$$-3(4\bar{\lambda} - 2\lambda_4 - \bar{\lambda}' - \sqrt{2}\lambda_8)v_1^2(v_2 + v_3) + 6(2\bar{\lambda} - 2\lambda_2 + \lambda_4 + 2\sqrt{2}\lambda_8)v_1(v_2^2 + v_3^2)$$
$$+6(4\lambda_2 + 2\lambda_4 - \bar{\lambda}' - 2\sqrt{2}\lambda_8)v_1 v_2 v_3$$

$$18t_2 = -6\mu_d^2(v_1 - 2v_2 + v_3) + 6\mu_s^2 V + 2(4\bar{\lambda} - 3\lambda_2 + \lambda_4 + 2\bar{\lambda}' - 4\sqrt{2}\lambda_8)v_2^3$$
$$-(4\bar{\lambda} - 2\lambda_4 - \bar{\lambda}' - \sqrt{2}\lambda_8)(v_1^3 + v_3^3) - 3(4\bar{\lambda} + 2\lambda_4 + \bar{\lambda}' + \sqrt{2}\lambda_8)v_2^2 v_3$$
$$-3(2\lambda_2 - 2\lambda_4 + \bar{\lambda}' + 2\sqrt{2}\lambda_8)v_2^2 v_1 - 3(2\lambda_2 - 2\lambda_4 + \bar{\lambda}' + 2\sqrt{2}\lambda_8)v_1 v_3^2$$
$$+6(2\bar{\lambda} + \lambda_2 + \lambda_4 + \sqrt{2}\lambda_8)v_2 v_3^2 + 3(4\lambda_2 + 2\lambda_4 - \bar{\lambda}' - 2\sqrt{2}\lambda_8)v_1^2 v_3$$
$$-3(2\lambda_2 - 2\lambda_4 + \bar{\lambda}' + 2\sqrt{2}\lambda_8)v_1 v_3^2 - 6(2\lambda_2 - 2\lambda_4 - \bar{\lambda}' + 2\sqrt{2}\lambda_8)v_1 v_2 v_3$$

Model A

if v1 = v2 = v3.

- The mass matrix:

$$M_n^2 = \begin{pmatrix} a_n & -b_n & -b_n \\ -b_n & a_n & -b_n \\ -b_n & -b_n & a_n \end{pmatrix} \quad a_n, b_n > 0 \ (\text{or } a_n, b_n < 0 \ )$$

$$U_{TBM}^T M_n^2 U_{TBM} = \mathrm{diag}(a_n - 2b_n, a_n + b_n, a_n + b_n)$$

$$U_{TBM} = \begin{pmatrix} \frac{1}{\sqrt{3}} & -\sqrt{\frac{2}{3}} & 0 \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Model A

if v1 = v2 = v3.

- The mass matrix:

$$M_n^2 = \begin{pmatrix} a_n & -b_n & -b_n \\ -b_n & a_n & -b_n \\ -b_n & -b_n & a_n \end{pmatrix} \quad a_n, b_n > 0 \ (\text{or } a_n, b_n < 0\ )$$

$$U_{TBM}^T M_n^2 U_{TBM} = \text{diag}(a_n - 2b_n, a_n + b_n, a_n + b_n)$$

$$a_h = (2/3)\mu_d^2 + (2\lambda_4 + \bar{\lambda}')v^2 \quad 6b_h = 2\mu_d^2 - 3(4\lambda_4 - \bar{\lambda}')v^2$$

CP even $m_{h_1}^2 = \frac{2}{3}\lambda_4 v_{SM}^2, \qquad m_{h_2}^2 = m_{h_3}^2 \equiv m_h^2 = \mu_d^2 + \frac{1}{2}\bar{\lambda}' v_{SM}^2,$

$$a_a = (2/3)\mu_d^2 + \bar{\lambda}'v^2 \text{ and } 6b_a = 2\mu_d^2 + 3\bar{\lambda}'v^2$$

CP odd $m_{a_1}^2 = 0, \qquad m_{a_2}^2 = m_{a_3}^2 \equiv m_a^2 = \mu_d^2 + \frac{1}{6}\bar{\lambda}' v_{SM}^2$

$$6a_c = 2\mu_d^2 + 3\lambda_5 v^2 \text{ and } 12b_c = 2\mu_d^2 + 3\lambda_5 v^2$$

Cherged $m_{c_1}^2 = 0, \qquad m_{c_2}^2 = m_{c_3}^2 \equiv m_c^2 = \frac{1}{2}\mu_d^2 + \frac{\lambda_5}{12} v_{SM}^2.$

Model A

if v1 = v2 = v3.

- The mass matrix:

$$M_n^2 = \begin{pmatrix} a_n & -b_n & -b_n \\ -b_n & a_n & -b_n \\ -b_n & -b_n & a_n \end{pmatrix} \quad a_n, b_n > 0 \ (\text{or } a_n, b_n < 0\ )$$

$$U_{TBM}^T M_n^2 U_{TBM} = \text{diag}(a_n - 2b_n, a_n + b_n, a_n + b_n)$$

$$a_h = (2/3)\mu_d^2 + (2\lambda_4 + \bar{\lambda}')v^2 \quad 6b_h = 2\mu_d^2 - 3(4\lambda_4 - \bar{\lambda}')v^2$$

SM Higgs

$$m_{h_1}^2 = \frac{2}{3}\lambda_4 v_{SM}^2, \qquad m_{h_2}^2 = m_{h_3}^2 \equiv m_h^2 = \mu_d^2 + \frac{1}{2}\bar{\lambda}' v_{SM}^2,$$

$$a_a = (2/3)\mu_d^2 + \bar{\lambda}' v^2 \text{ and } 6b_a = 2\mu_d^2 + 3\bar{\lambda}' v^2$$

$$m_{a_1}^2 = 0, \qquad m_{a_2}^2 = m_{a_3}^2 \equiv m_a^2 = \mu_d^2 + \frac{1}{6}\bar{\lambda}' v_{SM}^2$$

Goldstones

$$6a_c = 2\mu_d^2 + 3\lambda_5 v^2 \text{ and } 12b_c = 2\mu_d^2 + 3\lambda_5 v^2$$

$$m_{c_1}^2 = 0, \qquad m_{c_2}^2 = m_{c_3}^2 \equiv m_c^2 = \frac{1}{2}\mu_d^2 + \frac{\lambda_5}{12} v_{SM}^2.$$

Model A

if v1 = v2 = v3.

- The mass matrix:

$$M_n^2 = \begin{pmatrix} a_n & -b_n & -b_n \\ -b_n & a_n & -b_n \\ -b_n & -b_n & a_n \end{pmatrix} \quad a_n, b_n > 0 \ (\text{or } a_n, b_n < 0\ )$$

$$U_{TBM}^T M_n^2 U_{TBM} = \text{diag}(a_n - 2b_n, a_n + b_n, a_n + b_n)$$

$$a_h = (2/3)\mu_d^2 + (2\lambda_4 + \bar{\lambda}')v^2 \quad 6b_h = 2\mu_d^2 - 3(4\lambda_4 - \bar{\lambda}')v^2$$

$$m_{h_1}^2 = \frac{2}{3}\lambda_4 v_{SM}^2, \qquad m_{h_2}^2 = m_{h_3}^2 \equiv m_h^2 = \mu_d^2 + \frac{1}{2}\bar{\lambda}' v_{SM}^2,$$

$$a_a = (2/3)\mu_d^2 + \bar{\lambda}' v^2 \text{ and } 6b_a = 2\mu_d^2 + 3\bar{\lambda}' v^2$$

$$m_{a_1}^2 = 0, \qquad m_{a_2}^2 = m_{a_3}^2 \equiv m_a^2 = \mu_d^2 + \frac{1}{6}\bar{\lambda}' v_{SM}^2$$

This parameter may be > 0 or < 0, and since it is not protected by any symmetry.

$$6a_c = 2\mu_d^2 + 3\lambda_5 v^2 \text{ and } 12b_c = 2\mu_d^2 + 3\lambda_5 v^2$$

$$m_{c_1}^2 = 0, \qquad m_{c_2}^2 = m_{c_3}^2 \equiv m_c^2 = \frac{1}{2}\mu_d^2 + \frac{\lambda_5}{12} v_{SM}^2.$$

Model A

if v1 = v2 = v3.

The constrain equations becomes:

$$t_1 = t_2 = t_3 = v(\mu_s^2 + 3\lambda_4 v^2),$$

$$\mu_s^2 = -3\lambda_4 v^2 < 0, \ \lambda_4 > 0.$$

We have to check if this choice is a minimum:
to do so first random values are assigns for the lambdas

```
L1 = RandomReal[{-10, 10}, 100];
L2 = RandomReal[{-10, 10}, 100];
L3 = RandomReal[{-10, 10}, 100];
L4 = RandomReal[{-10, 10}, 100];
L5 = RandomReal[{-10, 10}, 100];
L6 = RandomReal[{-10, 10}, 100];
L7 = RandomReal[{-10, 10}, 100];
L8 = RandomReal[{-10, 10}, 100];
mud2 = RandomReal[{-40, 200}, 100];
```

therefore, the potential now is a function of
V(mus^2,v1,v2,v3)

Model A

if v1 = v2 = v3.

Second, we asked for the program to find the minimum of the function

$\{-3.52665\times10^{7}, \{v1\to45.715, v2\to45.715, v3\to45.715\}\}$

$\{-1.83696784932612\times10^{408}, \{v1\to1.34603\times10^{102}, v2\to5.9412\times10^{101}, v3\to5.9412\times10^{101}\}\}$

$\{-1.38087\times10^{7}, \{v1\to28.6058, v2\to28.6058, v3\to28.6058\}\}$

$\{-1.53611\times10^{7}, \{v1\to30.1709, v2\to30.1709, v3\to30.1709\}\}$

$\{-2.78463\times10^{7}, \{v1\to40.622, v2\to40.622, v3\to40.622\}\}$

$\{-2.29306195651464\times10^{415}, \{v1\to7.01408\times10^{103}, v2\to-3.39999\times10^{103}, v3\to-3.39999\times10^{103}\}\}$

$\{-6.09259771381128\times10^{393}, \{v1\to-4.5239\times10^{83}, v2\to1.55581\times10^{98}, v3\to-1.55581\times10^{98}\}\}$

$\{-6.96637\times10^{205}, \{v1\to4.22274\times10^{51}, v2\to1.72579\times10^{51}, v3\to1.72579\times10^{51}\}\}$

$\{-1.02118556587719\times10^{420}, \{v1\to4.62458\times10^{104}, v2\to4.62458\times10^{104}, v3\to4.62458\times10^{104}\}\}$

$\{-1.44181\times10^{8}, \{v1\to6.32409, v2\to135.579, v3\to135.579\}\}$

Model A

if v1 = v2 = v3.

Second, we asked for the program to find the minimum of the function

$\{-3.52665\times10^{7}, \{v1\to45.715, v2\to45.715, v3\to45.715\}\}$

$\{-1.836967849326120\times10^{408}, \{v1\to1.34603\times10^{102}, v2\to5.9412\times10^{101}, v3\to5.9412\times10^{101}\}\}$

$\{-1.38087\times10^{7}, \{v1\to28.6058, v2\to28.6058, v3\to28.6058\}\}$

$\{-1.53611\times10^{7}, \{v1\to30.1709, v2\to30.1709, v3\to30.1709\}\}$

$\{-2.78463\times10^{7}, \{v1\to40.622, v2\to40.622, v3\to40.622\}\}$

$\{-2.29306195651464\times10^{415}, \{v1\to7.01408\times10^{103}, v2\to-3.39999\times10^{103}, v3\to-3.39999\times10^{103}\}\}$

$\{-6.092597713811284\times10^{393}, \{v1\to-4.5239\times10^{83}, v2\to1.55581\times10^{98}, v3\to-1.55581\times10^{98}\}\}$

$\{-6.96637\times10^{205}, \{v1\to4.22274\times10^{51}, v2\to1.72579\times10^{51}, v3\to1.72579\times10^{51}\}\}$

$\{-1.021185565877198\times10^{420}, \{v1\to4.62458\times10^{104}, v2\to4.62458\times10^{104}, v3\to4.62458\times10^{104}\}\}$

$\{-1.44181\times10^{8}, \{v1\to6.32409, v2\to135.579, v3\to135.579\}\}$

implies restrictions to the values of lambdas or mud2

Almost all cases meet to v1 = v2 = v3.
This result is a global minimum, we do not know if it's the only choice, probably not.

Model A

- After diagonalize the mass matrix we obtain the following mass eigenstates:

$$S \equiv h_1 = \begin{pmatrix} h_1^+ \\ \frac{1}{\sqrt{2}}(3v + h_1^0 + ia_1^0) \end{pmatrix}, \; D \equiv -(h_2, h_3), \; h_k = \begin{pmatrix} h_k^+ \\ \frac{1}{\sqrt{2}}(h_k^0 + ia_k^0) \end{pmatrix}$$

$$\begin{aligned} V(h_i) &= 3\lambda_4 v^2 h_1^\dagger h_1 + \mu_d^2(h_2^\dagger h_2 + h_3^\dagger h_3) + \lambda_1(h_2^\dagger h_2 + h_3^\dagger h_3)^2 + \lambda_2(h_2^\dagger h_3 - h_3^\dagger h_2)^2 \\ &+ \lambda_3[(h_2^\dagger h_3 + h_3^\dagger h_2)^2 + (h_2^\dagger h_2 - h_3^\dagger h_3)^2] + \lambda_4(h_1^\dagger h_1)^2 + \lambda_5 h_1^\dagger h_1(h_2^\dagger h_2 + h_3^\dagger h_3) \\ &+ (\lambda_6 + \lambda_7)h_1^\dagger(h_2^\dagger h_2 + h_3^\dagger h_3)h_1 + [\lambda_8 h_1^\dagger h_2(h_2^\dagger h_3 + h_3^\dagger h_2) \\ &+ h_1^\dagger h_3(h_2^\dagger h_2 + h_1^\dagger h_1) + H.c.]. \end{aligned}$$

Model A

- After diagonalize the mass matrix we obtain the following mass eigenstates:

Goldstones

$$S \equiv h_1 = \begin{pmatrix} h_1^+ \\ \frac{1}{\sqrt{2}}(3v + h_1^0 + ia_1^0) \end{pmatrix}, \; D \equiv -(h_2, h_3), \; h_k = \begin{pmatrix} h_k^+ \\ \frac{1}{\sqrt{2}}(h_k^0 + ia_k^0) \end{pmatrix}$$

SM Higgs

$$\begin{aligned} V(h_i) &= 3\lambda_4 v^2 h_1^\dagger h_1 + \mu_d^2(h_2^\dagger h_2 + h_3^\dagger h_3) + \lambda_1(h_2^\dagger h_2 + h_3^\dagger h_3)^2 + \lambda_2(h_2^\dagger h_3 - h_3^\dagger h_2)^2 \\ &+ \lambda_3[(h_2^\dagger h_3 + h_3^\dagger h_2)^2 + (h_2^\dagger h_2 - h_3^\dagger h_3)^2] + \lambda_4(h_1^\dagger h_1)^2 + \lambda_5 h_1^\dagger h_1(h_2^\dagger h_2 + h_3^\dagger h_3) \\ &+ (\lambda_6 + \lambda_7)h_1^\dagger(h_2^\dagger h_2 + h_3^\dagger h_3)h_1 + [\lambda_8 h_1^\dagger h_2(h_2^\dagger h_3 + h_3^\dagger h_2) \\ &+ h_1^\dagger h_3(h_2^\dagger h_2 + h_1^\dagger h_1) + H.c.]. \end{aligned}$$

Model A

- After diagonalize the mass matrix we obtain the following mass eigenstates:

Goldstones

$$S \equiv h_1 = \begin{pmatrix} h_1^+ \\ \frac{1}{\sqrt{2}}(3v + h_1^0 + i a_1^0) \end{pmatrix}, \quad D \equiv -(h_2, h_3), \quad h_k = \begin{pmatrix} h_k^+ \\ \frac{1}{\sqrt{2}}(h_k^0 + i a_k^0) \end{pmatrix}$$

SM Higgs

$$\begin{aligned} V(h_i) &= 3\lambda_4 v^2 h_1^\dagger h_1 + \mu_d^2(h_2^\dagger h_2 + h_3^\dagger h_3) + \lambda_1(h_2^\dagger h_2 + h_3^\dagger h_3)^2 + \lambda_2(h_2^\dagger h_3 - h_3^\dagger h_2)^2 \\ &+ \lambda_3[(h_2^\dagger h_3 + h_3^\dagger h_2)^2 + (h_2^\dagger h_2 - h_3^\dagger h_3)^2] + \lambda_4(h_1^\dagger h_1)^2 + \lambda_5 h_1^\dagger h_1(h_2^\dagger h_2 + h_3^\dagger h_3) \\ &+ (\lambda_6 + \lambda_7) h_1^\dagger(h_2^\dagger h_2 + h_3^\dagger h_3)h_1 + [\lambda_8 h_1^\dagger h_2(h_2^\dagger h_3 + h_3^\dagger h_2) \\ &+ h_1^\dagger h_3(h_2^\dagger h_2 + h_1^\dagger h_1) + H.c.]. \end{aligned}$$

- It is possible to note that there are still a residual Z2 symmetry, it is the exchange of the doublets h2 and h3 still allowed.

Model A

- Soft terms break the Z2 symmetry to avoid the mass degeneracy:

$$\mu_{nm}^2 H_n^\dagger H_m,\ n,m = 2,3$$

$$M_n^2 = \begin{pmatrix} a_n & -b_n & -b_n \\ -b_n & a_n + \mu_{22}^2 & -b_n + \mu_{23}^2 \\ -b_n & -b_n + \mu_{23}^2 & a + \mu_{33}^2 \end{pmatrix}$$

$$\mu_{22}^2 = \mu_{33}^2 = -\mu_{23}^2 \equiv \mu^2.$$

$$\mu_{22}^2 = \mu_{33}^2 = \nu^2\ ;\ \ \mu_{23}^2 = \mu^2$$

$$(2a_n - b_n, a_n + b_n, a_n + b_n + \mu^2)$$

"this mass matrix is god for neutrinos but not for Higgs scalars sector all eigenvalues are different from zero: there are no Goldstone bosons"

Model A

- It is possible to explain, for example, three bosons with mass equal125 GeV and the charged with 308 GeV.

```
V = 246 / Sqrt[2];
Mh1 = Sqrt[(2 / 3) * L4 * V^2];
Mh2[mud2_] := Sqrt[mud2 + (1 / 2) * L * V^2];
Mc2[mud2_] := Sqrt[(1 / 2) mud2 + (1 / 12) * L5 * V^2];

NSolve[Mh1 == 125, L4]

{{L4 → 0.774589}}

NSolve[Mh2[- 20] == 125, L]

{{L → 1.03411}}

NSolve[Mh2[20] == 125, L]

{{L → 1.03146}}

NSolve[Mh2[- 40] == 125, L]

{{L → 1.03543}}

NSolve[Mh2[- 140] == 125, L]

{{L → 1.04204}}

NSolve[Mc2[- 20] == 308, L5]

{{L5 → 37.626}}

NSolve[Mc2[20] == 308, L5]

{{L5 → 37.6181}}

NSolve[Mc2[- 140] == 308, L5]

{{L5 → 37.6498}}

NSolve[Mc2[40] == 308, L5]

{{L5 → 37.6141}}
```

Model A

- It is possible to explain, for example, three bosons with mass equal125 GeV and the chargeds with 308 GeV.

```
V = 246 / Sqrt[2];
Mh1 = Sqrt[(2 / 3) * L4 * V^2];
Mh2[mud2_] := Sqrt[mud2 + (1 / 2) * L * V^2];
Mc2[mud2_] := Sqrt[(1 / 2) mud2 + (1 / 12) * L5 * V^2];

NSolve[Mh1 == 125, L4]

{{L4 → 0.774589}}

NSolve[Mh2[- 20] == 125, L]

{{L → 1.03411}}

NSolve[Mh2[20] == 125, L]

{{L → 1.03146}}

NSolve[Mh2[- 40] == 125, L]

{{L → 1.03543}}

NSolve[Mh2[- 140] == 125, L]

{{L → 1.04204}}
```

```
L1 = -1;
L2 = -1;
L3 = -1;
L4 = 0.7746;
L5 = 37.6;
L6 = -6.6;
L7 = -15;
L8 = 0;
mud2 = -20;
FindMinimum[VA[-23 438, v1, v2, v3], {v1, 53}, {v2, 53}, {v3, 53}]

{-1.77298 × 10^8, {v1 → 100.429, v2 → 100.429, v3 → 100.429}}
```

```
NSolve[Mc2[- 20] == 308, L5]

{{L5 → 37.626}}

NSolve[Mc2[20] == 308, L5]

{{L5 → 37.6181}}

NSolve[Mc2[- 140] == 308, L5]

{{L5 → 37.6498}}

NSolve[Mc2[40] == 308, L5]

{{L5 → 37.6141}}
```

Model A

- It is possible to explain, for example, three bosons with mass equal125 GeV.

```
V = 246 / Sqrt[2];
Mh1 = Sqrt[(2 / 3) * L4 * V^2];
Mh2[mud2_] := Sqrt[mud2 + (1 / 2) * L * V^2];
Mc2[mud2_] := Sqrt[(1 / 2) mud2 + (1 / 12) * L5 * V^2];

NSolve[Mh1 == 125, L4]

{{L4 → 0.774589}}

NSolve[Mh2[- 20] == 125, L]

{{L → 1.03411}}

NSolve[Mh2[20] == 125, L]

{{L → 1.03146}}

NSolve[Mh2[- 40] == 125, L]

{{L → 1.03543}}

NSolve[Mh2[- 140] == 125, L]

{{L → 1.04204}}
```

```
L1 = -1;
L2 = -1;
L3 = -1;
L4 = 0.7746;
L5 = 37.6;
L6 = -6.6;
L7 = -15;
L8 = 0;
mud2 = -20;
FindMinimum[VA[-23 438, v1, v2, v3], {v1, 53}, {v2, 53}, {v3, 53}]

{-1.77298×10^8, {v1 → 100.429, v2 → 100.429, v3 → 100.429}}
```

$\mu_s^2 = -\lambda_4 v_{SM}^2$ **= - 0.7746* (246/Sqrt[2])^2**

```
NSolve[Mc2[- 20] == 308, L5]

{{L5 → 37.626}}

NSolve[Mc2[20] == 308, L5]

{{L5 → 37.6181}}

NSolve[Mc2[- 140] == 308, L5]

{{L5 → 37.6498}}

NSolve[Mc2[40] == 308, L5]

{{L5 → 37.6141}}
```

Model A

- It is possible to explain, for example, three bosons with mass equal 125 GeV.

```
V = 246 / Sqrt[2];
Mh1 = Sqrt[(2 / 3) * L4 * V^2];
Mh2[mud2_] := Sqrt[mud2 + (1 / 2) * L * V^2];
Mc2[mud2_] := Sqrt[(1 / 2) mud2 + (1 / 12) * L5 * V^2];

NSolve[Mh1 == 125, L4]

{{L4 → 0.774589}}

NSolve[Mh2[- 20] == 125, L]

{{L → 1.03411}}

NSolve[Mh2[20] == 125, L]

{{L → 1.03146}}

NSolve[Mh2[- 40] == 125, L]

{{L → 1.03543}}

NSolve[Mh2[- 140] == 125, L]

{{L → 1.04204}}
```

```
L1 = -1;
L2 = -1;
L3 = -1;
L4 = 0.7746;
L5 = 37.6;
L6 = -6.6;
L7 = -15;
L8 = 0;
mud2 = -20;
FindMinimum[VA[-23 438, v1, v2, v3], {v1, 53}, {v2, 53}, {v3, 53}]

{-1.77298 × 10^8, {v1 → 100.429, v2 → 100.429, v3 → 100.429}}
```

```
NSolve[Mc2[- 20] == 308, L5]

{{L5 → 37.626}}

NSolve[Mc2[20] == 308, L5]

{{L5 → 37.6181}}

NSolve[Mc2[- 140] == 308, L5]

{{L5 → 37.6498}}

NSolve[Mc2[40] == 308, L5]

{{L5 → 37.6141}}
```

v1= v2 = v3 = v_sm/Sqrt[3] = 246/Sqrt[6] = 100.429

Model A: phenomenology

$$
\begin{aligned}
-\mathcal{L}_l &= \bar{\nu}_{iL}\frac{\hat{M}_i^l}{v_{SM}}(V_{PMNS})_{ij} l_{jR} h_1^+ + \bar{l}_{iL}\frac{\hat{M}_i^l}{v_{SM}} l_{jR}\left[1+\frac{h_1^0+ia_1^0}{\sqrt{2}}\right] \\
&+ \bar{l}_{iL}\frac{\hat{M}_i^\nu}{v_{SM}}(V_{PMNS})_{ij}\nu_{jR} h_1^- + \bar{\nu}_{iL}\frac{\hat{M}_i^\nu}{v_{SM}}\nu_{iR}\left[1+\frac{h_1^0+ia_1^0+}{\sqrt{2}}\right] + H.c.,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{gauge} &= (\mathcal{D}_\mu S)^\dagger(\mathcal{D}^\mu S) + (\mathcal{D}_\mu D)^\dagger(\mathcal{D}^\mu D) \\
&= (\mathcal{D}_\mu H_1)^\dagger(\mathcal{D}^\mu H_1) + (\mathcal{D}_\mu H_2)^\dagger(\mathcal{D}^\mu H_2) + (\mathcal{D}_\mu H_3)^\dagger(\mathcal{D}^\mu H_3)
\end{aligned}
$$

Interactions with h20 and the charged ones:

$$
\begin{aligned}
&(\lambda_6+\lambda_7)h_1^- h_2^+, \quad -\lambda_8 h_2^- h_2^+, \quad \lambda_8 h_3^- h_3^+, \\
&-(\lambda_6+\lambda_7)(h_1^0 h_2^0 + a_1^0 a_2^0), \quad i(\lambda_6+\lambda_7)(-h_1^0 a_2^0 + h_2^0 a_1^0), \\
&-\lambda_8 h_2^0 h_2^0, \quad -\lambda_8 a_2^0 a_2^0, \lambda_8 h_3^0 h_3^0, \quad \lambda_8 a_3^0 a_3^0.
\end{aligned}
$$

Model A: phenomenology

$$-\mathcal{L}_l = \bar{\nu}_{iL}\frac{\hat{M}_i^l}{v_{SM}}(V_{PMNS})_{ij}l_{jR}h_1^+ + \bar{l}_{iL}\frac{\hat{M}_i^l}{v_{SM}}l_{jR}\left[1+\frac{h_1^0+ia_1^0}{\sqrt{2}}\right]$$
$$+ \bar{l}_{iL}\frac{\hat{M}_i^\nu}{v_{SM}}(V_{PMNS})_{ij}\nu_{jR}h_1^- + \bar{\nu}_{iL}\frac{\hat{M}_i^\nu}{v_{SM}}\nu_{iR}\left[1+\frac{h_1^0+ia_1^0+}{\sqrt{2}}\right] + H.c.,$$

$$\mathcal{L}_{gauge} = (\mathcal{D}_\mu S)^\dagger(\mathcal{D}^\mu S) + (\mathcal{D}_\mu D)^\dagger(\mathcal{D}^\mu D)$$
$$= (\mathcal{D}_\mu H_1)^\dagger(\mathcal{D}^\mu H_1) + (\mathcal{D}_\mu H_2)^\dagger(\mathcal{D}^\mu H_2) + (\mathcal{D}_\mu H_3)^\dagger(\mathcal{D}^\mu H_3)$$

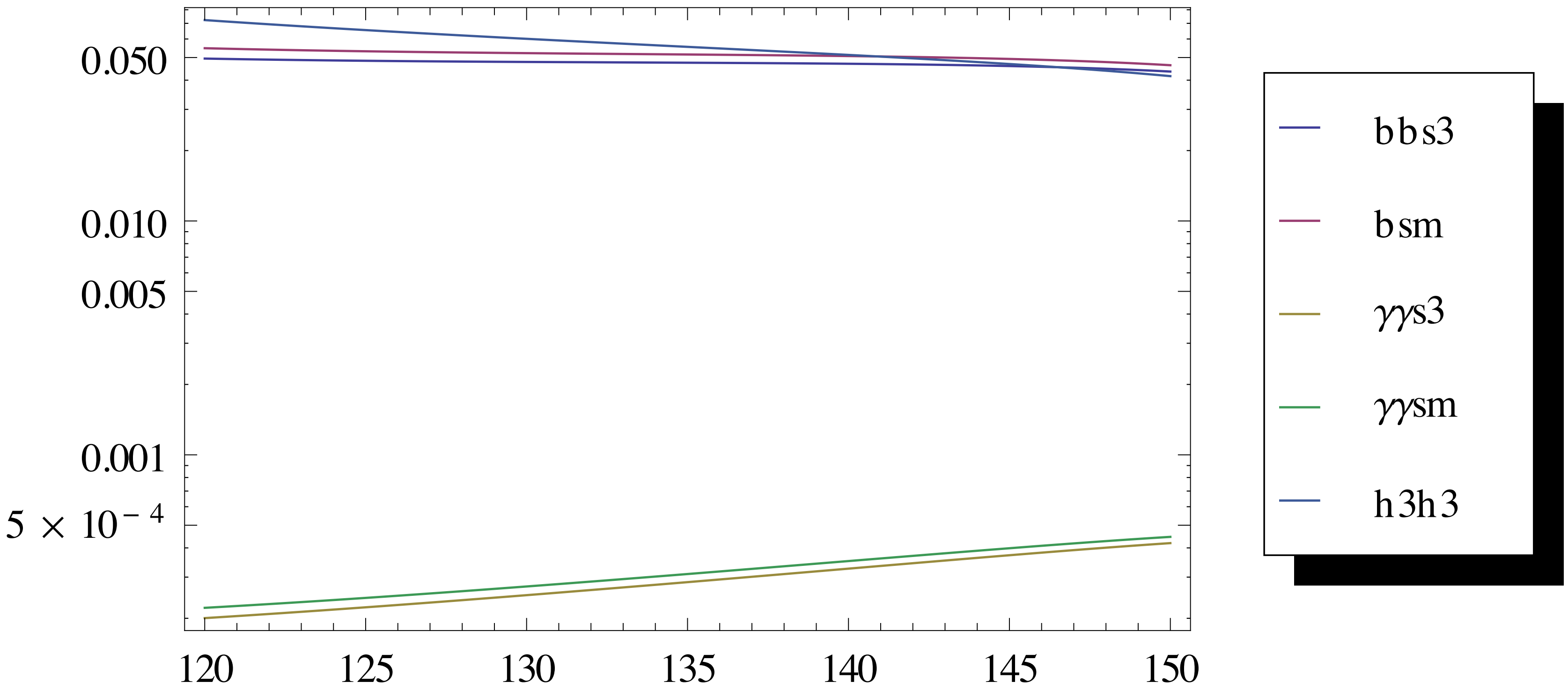
Interactions with h20 and the charged ones:

$$(\lambda_6+\lambda_7)h_1^-h_2^+, \quad -\lambda_8 h_2^-h_2^+, \quad \lambda_8 h_3^-h_3^+,$$
$$-(\lambda_6+\lambda_7)(h_1^0h_2^0+a_1^0a_2^0), \quad i(\lambda_6+\lambda_7)(-h_1^0a_2^0+h_2^0a_1^0),$$
$$-\lambda_8 h_2^0h_2^0, \quad -\lambda_8 a_2^0a_2^0, \lambda_8 h_3^0h_3^0, \quad \lambda_8 a_3^0a_3^0.$$

the unitary gauge

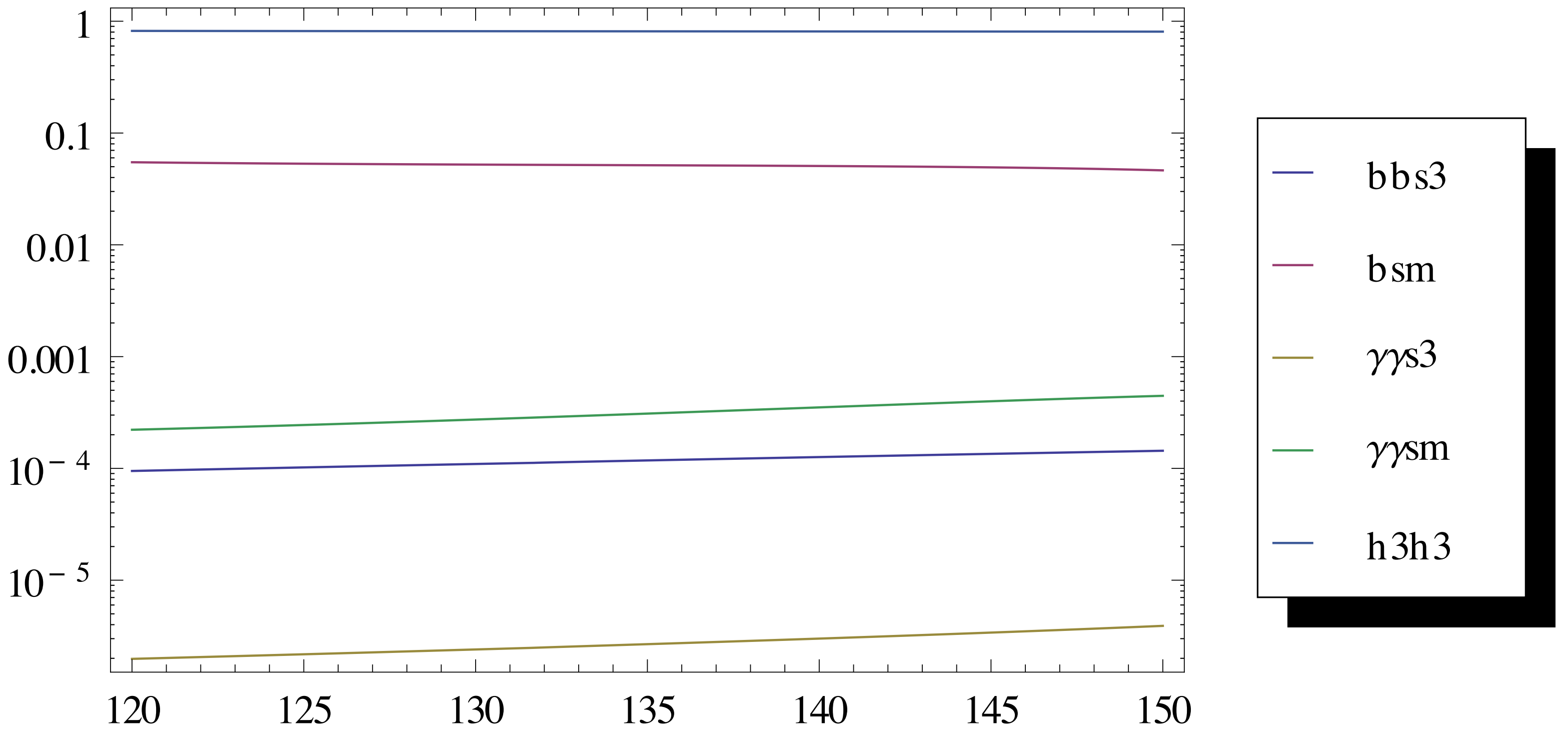
Model A: phenomenology

L5=0.001 and L6=L7=0.02 and mh2 = 350 Gev
main decays



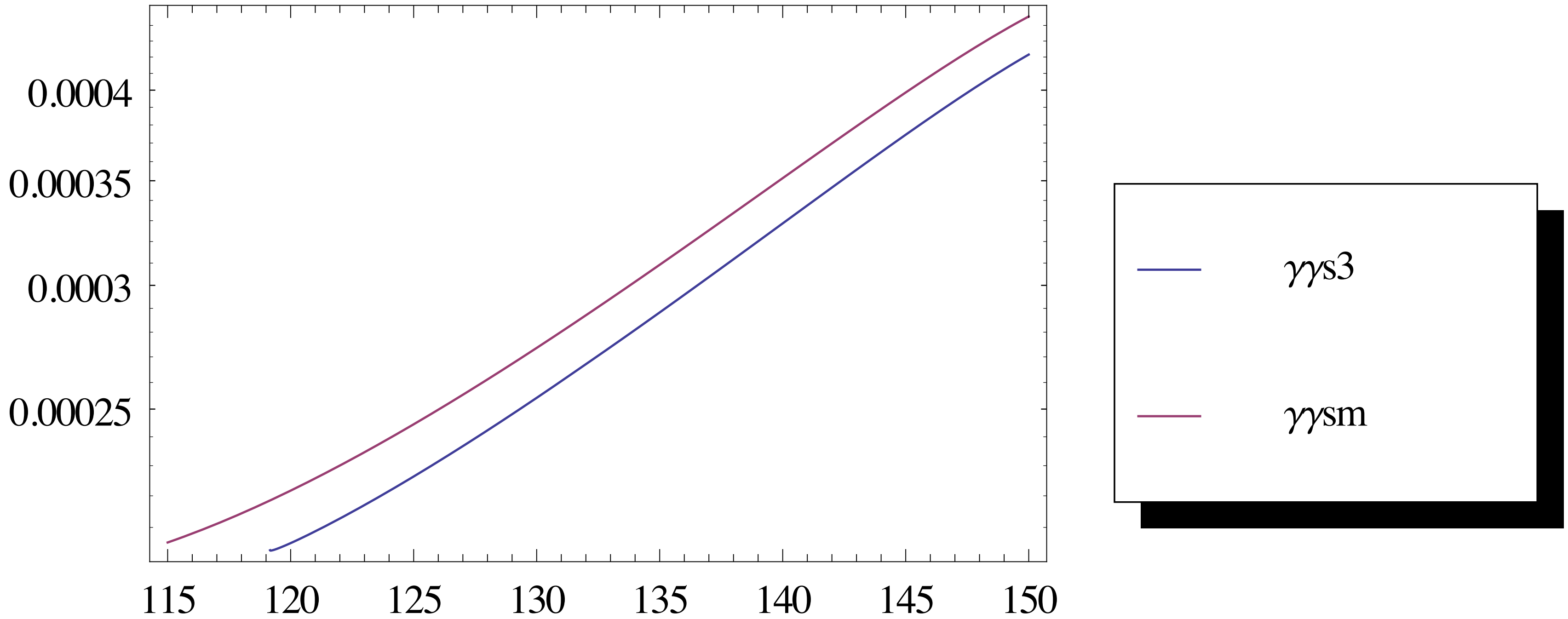
Model A

L5=L6=L7=1 and mh2 = 350 Gev maindecays



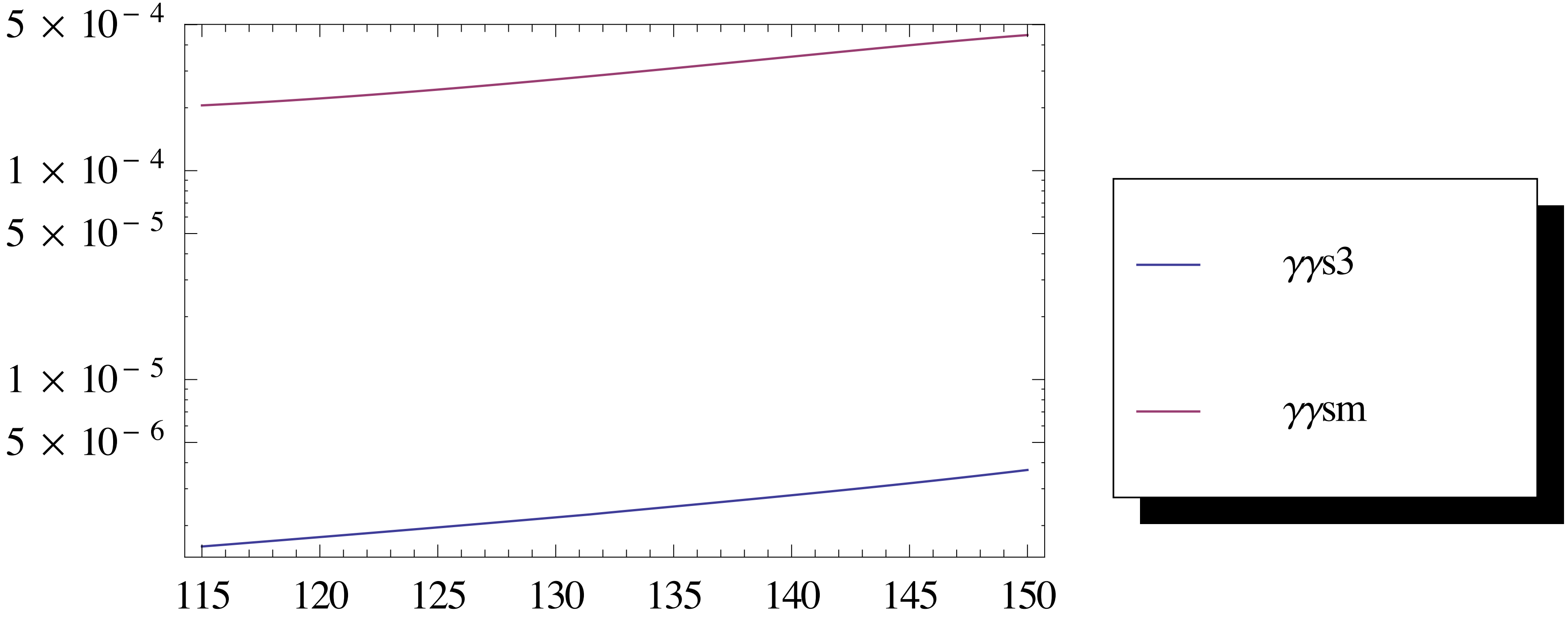
Model A

L5=0.001 and L6=L7=0.02 and mh2 = 350 Gev comparing with the standard Higgs



Model A

L5=L6=L7=1 and mh2 = 350 Gev
comparing with the standard Higgs



Model A

- So we can see that:
  - The decays depend on the value of the parameters lambda.
  - is possible to obtain a scalar potential that satisfies all the theoretical conditions of spontaneous symmetry breaking to give mass to the model spectrum.
  - We can obtain decay rates similar to SM for the S3 model.
  - We are analyzing the two-photon channel and it seems that it is possible to explain the results of the LHC...

Model B

$$S = H_1 \sim \mathbf{1}, \quad D = (H_2, H_3) \sim \mathbf{2}. \ (3)$$

$$v_1 \equiv v_{SM}, \ v_2 = v_3 = 0$$

The constrain equation implies:

$$\mu_s^2 = -\lambda_4 v_{SM}^2$$

```
L1 = 1;
L2 = 1;
L3 = 1;
L4 = 1;
L5 = 1;
L6 = 1;
L7 = 1;
L8 = 0;
mud2 = -10;
FindMinimum[VB[- 100, v1, v2, v3], {v1, 5}, {v2, 0}, {v3, 0}]

{-2500., {v1 → 10., v2 → 0., v3 → 0.}}
```

This is a Minimum Global, is easy to check that for any numerical values is possible to obtain this vacuum alignment

Model B

- The mass matrix is diagonal in this case, but the masses are the same as in case of the Model A

$$m_{h_1}^2 = \frac{2}{3}\lambda_4 v_{SM}^2, \qquad m_{h_2}^2 = m_{h_3}^2 \equiv m_h^2 = \mu_d^2 + \frac{1}{2}\bar{\lambda}' v_{SM}^2,$$

$$m_{a_1}^2 = 0, \qquad m_{a_2}^2 = m_{a_3}^2 \equiv m_a^2 = \mu_d^2 + \frac{1}{6}\bar{\lambda}' v_{SM}^2$$

$$m_{c_1}^2 = 0, \qquad m_{c_2}^2 = m_{c_3}^2 \equiv m_c^2 = \frac{1}{2}\mu_d^2 + \frac{\lambda_5}{12} v_{SM}^2.$$

- However the term below breaks S2 symmetry between v2 and v3 which meaning that this term should be forbidden, a aditional Z2 symmetry is able to do so, if D -> - D.

$$\lambda_8[(S^\dagger \otimes D)_2 (D^\dagger \otimes D)_2]_1 + H.c.$$

Model B

```
L1 = -1;
L2 = -1;
L3 = -1;
L4 = 0.7746;
L5 = 37.6;
L6 = -6.6;
L7 = -15;
L8 = 0;
mud2 = -20;
```

```
FindMinimum[VB[-23438, v1, v2, v3], {v1, 5}, {v2, 0}, {v3, 0}]
```

$\{-1.77298\times 10^{8}, \{v1 \to 173.949, v2 \to 0., v3 \to 0.\}\}$

Model B

- To avoid the mass degeneration we will adding quadratic terms, like we did in model A.

$$\mu_{nm}^2 H_n^\dagger H_m,\ n,m = 2,3$$

$$M_n^2 = \begin{pmatrix} m_{n_1}^2 & 0 & 0 \\ 0 & m_{n_2}^2 + \nu^2 & \mu^2 \\ 0 & \mu^2 & m_{n_2} + \nu^2 \end{pmatrix}$$

$$\mu_{22}^2 = \mu_{33}^2 = -\mu_{23}^2 \equiv \mu^2.$$

Do nothing

$$\mu_{22}^2 = \mu_{33}^2 = \nu^2 \ ; \ \mu_{23}^2 = \mu^2$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$S \equiv h_1 = \begin{pmatrix} h_1^+ \\ \frac{1}{\sqrt{2}}(3v + h_1^0 + ia_1^0) \end{pmatrix},$$

$$D_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(-h_2^+ + h_3^+) \\ \frac{1}{2}[-h_2^0 + h_3^0 + i(-a_2^0 + a_3^0)] \end{pmatrix}, D_2 = \begin{pmatrix} \frac{1}{\sqrt{2}}(h_2^+ + h_3^+) \\ \frac{1}{2}[h_2^0 + h_3^0 + i(a_2^0 + a_3^0)] \end{pmatrix}.$$

Final Thoughts

- We have a three higgs doublets model that have a simple scalar potential.
- This model remain closer to the standard model than a 3 - higgs model without s3 symmetry.
- h2 and h3 could be possible candidates to explain the photon counts in the LHC.
- Models A and B are similar or not?

Thank you