$A^0 \to \gamma\gamma$ decay on 2HDM-I, II and III-type

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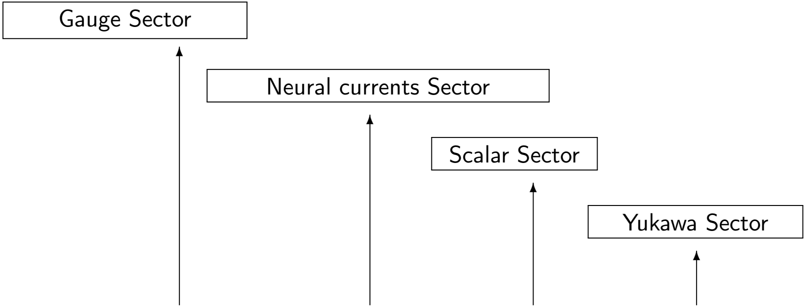
Table of Contents

Part I: Standard Model

The Standard Model (SM) is a good description for interactions at $\sim 10^{-16}$ cm.



$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{GS} + \mathcal{L}_{SM}^{NC} + \mathcal{L}_{SM}^{SS} + \mathcal{L}_{SM}^{YS}$$

Lagrangian Sectors

The sectors for the SM are given by ((1a)- (1d)):

$$\mathcal{L}_{ME}^{GS} = -\sum_{a=1}^{3} \frac{1}{4} W^{a}{}_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \tag{1a}$$

$$\mathcal{L}_{ME}^{NC} = g_{ME} \bar{\psi} \gamma^{\mu} \left(g_V^f - g_A^f \gamma^5 \right) \psi Z_{\mu} \tag{1b}$$

$$\mathcal{L}_{ME}^{SS} = \left(D_{\mu} \Phi \right)^{\dagger} D^{\mu} \Phi - V(\Phi^{\dagger} \Phi) \tag{1c}$$

$$\mathcal{L}_{ME}^{Y} \sim Y \bar{\psi}_{\bar{f}} \, \Phi \, \psi_f \tag{1d}$$

Gauge Sector

The gauge sector has terms as: $B_{\mu\nu} = D_{\mu} B_{\nu} - D_{\nu} B_{\mu}$. This sector involves vectorial fields.

Neutral Currents Sector

The Neutral Currents Sector contains the vector and the vector-axial couplings which are proportional to the charges.

Scalar Sector

We recall the Scalar Sector is composed for kinetic and interaction parts. Φ is the doublet.

Yukawa Sector

On the Yukawa Sector, we have a term Y, it is proportional to the fermion mass.

Part II: Symmetry breaking (SB) Scheme

Next (fig. 1) we show a schematic form for the SB.

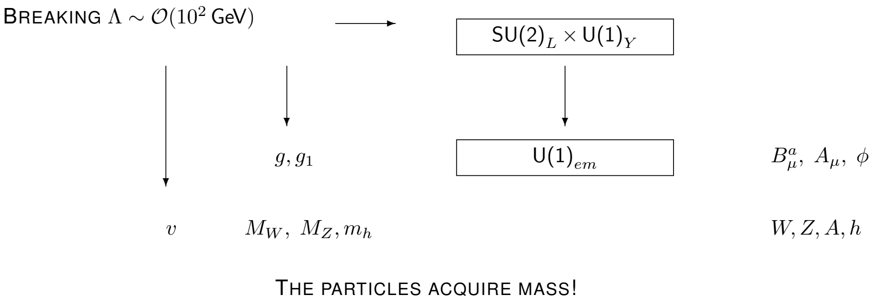


Figure 1: Symmetry breaking (SB) Scheme in the SM. We neglect the QCD terms. In $h\, f\, \bar{f}$ vertex, the coupling $g_{hf\bar{f}} \propto m_f$. This is the way to understand the mass for the matter fields.

The doublet and the Higgs Boson in SM

Before we mentioned the Higgs field, now, in this section, we discuss the doublet, boson and the field

Normalization factor

Pseudo-Goldstone boson charged

$$\boldsymbol{\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\omega^{+} \\ h + v + i\eta \end{pmatrix}}$$

Higgs Boson

Pseudo-Goldstone boson neutral

Vacuum expectation value

Part III: Beyond Standard Model (BSM)

We can extend the SM, it means a phenomenological rich models. New particles imply new interactions; namely, New Physics (NP).

Some schemes for the NP

There are differents for the NP; i.e.:

- Extended Gauge Groups.
- Extra Dimensions
- Model with extended scalar sector
- GUT
- String

and other more... If we extended the scalar sector, adding one more Higgs doublet, we get: 2HDM

Motivation

Introducing a new doublet, we can:

- Explain the matter-antimatter asymmetry
- Explain the CP violation
- Even, imposing a Z_2 symmetry on the Lagrangian; this is either: $\Phi_1 \longleftrightarrow \Phi_1, \Phi_2 \longleftrightarrow -\Phi_2$ or $\Phi_1 \longleftrightarrow -\Phi_1, \Phi_2 \longleftrightarrow \Phi_2$, or new constraints, we could neglect FCNC and/or CP-violation

2HDM and some other types

Now, we get, one doublet could be coupled to the fermions in this way:

- 2HDM-I. All quarks couple to just one of the Higgs doublets (normally, Φ_2).
- 2HDM-II. u_R quarks couple to Φ_2 and d_R quarks couple to Φ_1.

- En 2HDM-III Each doublet couples to u and d type. Besides one can consider parameters, as χ_{ij} which may induce FCNC through scalar bosons.

2HDM properties

2HDM has a rich phenomenology:

Three degrees of freedom neutral (h, H and A^0) and two charged Higgsses $(H^{\pm})$

It could be a good signal for the New Physics

2HDM Lagrangian

The general potential is given by,

$$\begin{aligned} V(\Phi_1\Phi_2) \quad = \quad & \lambda_1\left(\Phi_1^\dagger\Phi_1 - v_1^2\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2 - v_2^2\right)^2 + \lambda_3\left[\left(\Phi_1^\dagger\Phi_1 - v_1^2\right) + \left(\Phi_2^\dagger\Phi_2 - v_2^2\right)\right]^2 \\ & + \lambda_4\left[\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) - \left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)\right] + \lambda_5\left[Re\left(\Phi_1^\dagger\Phi_2\right) - v_1 v_2\right]^2 + \lambda_6\left[Im\left(\Phi_1^\dagger\Phi_2\right)\right]^2 \end{aligned}$$

where λ_i are reals.

The Yukawa sector for the 2HDM-III is given by,

$$\mathcal{L}_{YS}^{THDM-III} = Y_1^u \overline{Q}_L^0 \tilde{\Phi}_1 u_R^0 + Y_2^u \overline{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \overline{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \overline{Q}_L^0 \Phi_2 d_R^0 + h.c.$$

where,

$$Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \qquad \overline{Q}_L^0 = \left(\overline{u}_L, \overline{d}_L\right), \qquad \Phi_1 = \begin{pmatrix} \phi_1^{\pm} \\ \phi_1 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^{\pm} \\ \phi_2 \end{pmatrix},$$

$$\tilde{\Phi}_j = i\sigma_2 \Phi_j^* = \begin{pmatrix} {\phi_j}^* \\ -\phi_i^{\mp} \end{pmatrix} \quad \text{y} \quad \phi_i = \frac{1}{\sqrt{2}}(v_i + \phi_i^0 + i\chi_i)$$

and Y_i are the Yukawa couplings. Then we obtained,

$$\mathcal{L}_{YS}^{THDM-III} = \mathcal{L}_{YS_{neutral\ \ sector}}^{THDM} + \mathcal{L}_{YS_{charged\ \ sector}}^{THDM}$$

$$\begin{aligned} \mathcal{L}_{YS}^{THDM} = {} & Y_1^u \overline{u}_L \phi_1^{0*} u_R + Y_2^u \overline{u}_L \phi_2^{0*} u_R + Y_1^d \overline{d}_L \phi_1^0 d_R + Y_2^d \overline{d}_L \phi_2^0 d_R \\ & + Y_1^u \overline{d}_L (-\phi_2^-) u_R + Y_2^u \overline{d}_L (-\phi_1^-) u_R + Y_1^d \overline{u}_L \phi_1^+ d_R + Y_2^d \overline{u}_L \phi_2^+ d_R + h.c. \end{aligned}$$

After to do algebra. . . We obtain the general Lagrangian for the 2HDM III-type:

$$
\begin{aligned}
\mathcal{L}^{\textbf{2HDM-III}}_{f_i f_j A^0} \;=\; \frac{ig}{2M_W}\Bigg\{ & \bar{d}_i\Big[m_{d_i}\ X\ \delta_{ij} - f(X)\frac{\sqrt{m_{d_i} m_{d_j}}}{\sqrt{2}}\widetilde{\chi}^{d}_{ij}\Big]\gamma^5\ d_j \\
& + \bar{u}_i\Big[m_{u_i}\ Y\ \delta_{ij} - f(Y)\frac{\sqrt{m_{u_i} m_{u_j}}}{\sqrt{2}}\widetilde{\chi}^{u}_{ij}\Big]\gamma^5\ u_j \\
& + \bar{l}_i\Big[m_{l_i}\ Z\ \delta_{ij} - f(Z)\frac{\sqrt{m_{u_i} m_{u_j}}}{\sqrt{2}}\widetilde{\chi}^{l}_{ij}\Big]\gamma^5\ l_j \Bigg\}\ A^0
\end{aligned}
$$

$f(X), f(Y)$ and $f(Z)$ are functions of the associated parameters to the model. The $\widetilde{\chi}^{*}_{ij}$ are the rotated matrix elements.

Part IV: Phenomenology

$\bar{u}\ u\ A^0$ interaction

Consider

$$\mathcal{L} \quad = \quad \bar{u}_i \Big(S^u_{ij\ A} + i\gamma^5 P^u_{ij\ A} \Big) u_j A^0 + h.c.$$

we can obtain similar equations for d-type quarks and leptons. with

$$S^u_{ijA} = i \frac{\sqrt{m_i m_j}}{2\sqrt{2} v \cos\beta} \left(\chi_{ij} - \chi^\dagger_{ij} \right)$$

and

$$P^u_{ijA} = \frac{1}{2v} M^U_{ij} \tan\beta - \frac{\sqrt{m_i m_j}}{2\sqrt{2} v \cos\beta} \left(\chi_{ij} + \chi^\dagger_{ij} \right)$$

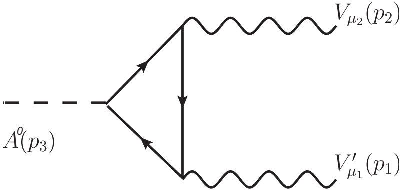
the χ_{ij} are **dimensionless unknown coefficients** related to the neutral escalar interactions that flavor change. Now, we take the diagonal couplings;

$$\mathcal{L}^f_{A^0} = \frac{g m^f_i}{2 m_W} \overline{f}_i \left(g^f_{S_i} + i\gamma^5 g^f_{P_i} \right) f_i A^0$$

considering, Yukawa matrix are hermitians $g^f_{S_i} = 0$, we found, $g^u_{P_i} = \cot\beta - \frac{1}{\sin\beta}\left(\chi_{ii}\right)$.

$A \to \gamma\gamma$ decay (PRD 90 095019)

At tree-level does not exist, but at loop-level does,



$$\mathcal{M} = \frac{ig\, r_f N_C\, k_{V_1ff}\, k_{V_2ff} \mathcal{A}^{\mu_1\mu_2}_{\mathbf{VV'}} \epsilon^*{}_{\mu_1} \epsilon^*{}_{\mu_2}}{16 m_W \pi^2 \left(1 - 2\left(r_1 + r_2\right) + \left(r_1 - r_2\right)^2\right)^2}$$

where $r_i = \frac{M^2_{V_i}}{m^2_A}$

Let us to analize the tensorial structures:

$$\mathcal{A}^{\mu_1\mu_2}_{VV'} = g^f_S \left(\mathcal{A}_1 g^{\mu_1\mu_2} + \mathcal{A}_2 p_2^{\mu_1} p_1^{\mu_2}\right) + g^f_P\, \mathcal{A}_3 \epsilon^{\alpha\beta\mu_1\mu_2} p_{1_\alpha} p_{2_\beta}$$

$\mathcal{A}_i$ are the form factors.

$$
\begin{aligned}
\mathcal{A}_1 \quad = \quad & g^f_{v_1} g^f_{v_2} m_A^2 \big(r_1^2 - 2\big(r_2+1\big)r_1 + \big(r_2-1\big)^2\big) \times \\
& \Bigg(\Bigg\{ \frac{m_A^2}{2}\Big(4r_f + 2r_1\big(r_1\big(4r_f - r_2 - 3\big) - 4\big(r_2+2\big)r_f + r_1^2 + r_2 + 3\big) - 1\Big) C_0(V_1,V_2) \\
& +2r_1(1-r_1+r_2)\Delta B_0(A,V_1) + 2r_1^2 - 2\big(r_2+2\big)r_1 + 1 \Bigg\} + \Bigg\{ 1 \leftrightarrow 2 \Bigg\}\Bigg) \\
& +g^f_{a_1} g^f_{a_2} m_A^2 \big(r_1^2 - 2\big(r_2+1\big)r_1 + \big(r_2-1\big)^2\big) \times \\
& \Bigg(\Bigg\{ \frac{m_A^2}{2}\Big(2r_1^2\big(-4r_f - r_2 - 1\big) + 2r_1\big(8r_f + r_2\big(4r_f - 1\big) - 1\big) - 4r_f + 2r_1^3 + 1\Big) C_0(V_1,V_2) \\
& +2(2r_2r_1 - r_1^2 - r_2^2 + 2r_1 + 2r_2 - 1)B_0^R + 2(r_2^2 - r_1r_2 - 2r_2 - r_1 + 1)\Delta B_0(A,V_1) \\
& +2r_1^2 - 2\big(r_2+2\big)r_1 + 1 \Bigg\} + \Bigg\{ 1 \leftrightarrow 2 \Bigg\}\Bigg),
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{A}_2 \quad = \quad & g^f_{v_1} g^f_{v_2} \Bigg(\Bigg\{ m_A^2 \big(r_1 + r_2 - 1\big) C_0(V_1, V_2) \times \\
& \Big(2r_1^2 \big(4r_f - r_2 - 3\big) - 2r_1 \big(8r_f + r_2(4r_f - 5) - 3\big) + 4r_f + 2r_1^3 - 1 \Big) \\
& + 4 \Big(r_1^3 + 4r_2 r_1^2 - 2r_1^2 - 5r_2^2 r_1 + 4r_2 r_1 - \big(r_1^2 - (r_2 + 2) r_1 + 2r_2 + 1\big) r_1 + r_1 \Big) B_0^R(A) \\
& + 4(-r_1^3 - 4r_2 r_1^2 + 2r_1^2 + 5r_2^2 r_1 - 4r_2 r_1 - r_1) \Delta B_0(A, V_1) \\
& + 4r_1 \big(r_1^2 - \big(r_2 + 3\big) r_1 - r_2 + 3\big) - 2 \Bigg\} + \Bigg\{ 1 \leftrightarrow 2 \Bigg\} \Bigg) \\
& + \big(r_1 + r_2 - 1\big) g^f_{a_1} g^f_{a_2} \times \\
& \Bigg(\Big\{ m_A^2 \Big(4r_f + 2r_1 \big(r_1 \big(4r_f - r_2 - 1\big) - 4\big(r_2 + 2\big) r_f + r_1^2 + 3r_2 - 1 \big) + 1 \Big) C_0(V_1, V_2) \\
& + 4 \Big(r_1^2 - 2r_1 - r_2^2 + 2r_2 \Big) B_0^R + 4\big((r_2 - 1)^2 + (r_2 + 1) r_1 - 2r_1^2\big) \Delta B_0(A, V_1) \\
& + 4r_1^2 - 4\big(r_2 + 2\big) r_1 + 2 \Big\} + \Big\{ 1 \leftrightarrow 2 \Big\} \Bigg),
\end{aligned}
$$

and

$$
\begin{aligned}
\mathcal{A}_3 \quad = \quad & -m_A^2 g_{v_1}^f g_{v_2}^f \Bigg(\Big\{ 2r_1^4 - 8\big(r_2+1\big)r_1^3 + 2\big(3r_2^2+4r_2+6\big)r_1^2 + 4\big(r_2-2\big)r_1 + 1 \Big\} + \\
& \Big\{ 1 \leftrightarrow 2 \Big\} \Bigg) C_0(V_1,V_2) - g_{a_1}^f g_{a_2}^f \big(r_1^2 - 2(r_2+1)r_1 + (r_2-1)^2 \big) \times \\
& \Bigg(\Big\{ m_A^2 \big(2r_1^2 - 2r_2 r_1 - 1\big) C_0(V_1,V_2) - 4\,(r_1 - r_2 + 1)\,\Delta B_0(A,V_1) \Big\} + \Big\{ 1 \leftrightarrow 2 \Big\} \Bigg).
\end{aligned}
$$

where
$B_0(i) = B_0(m_i^2, m_f^2, m_f^2)$, $\Delta B_0(i,j) = B_0(i) - B_0(j)$, $C_0(i,j) = C0(m_A^2, m_i^2, m_j^2, m_f^2, m_f^2, m_f^2)$. We use the normalization JHEP 11 151 (2012). Pittau, where we describe: $B_0^R = B_0(m_A^2, m_f^2 + \mu_R^2, m_f^2 + \mu_R^2) - B_0(0, \mu_R^2, \mu_R^2)$, with μ_R normalization scale. We show the Bose's symmetry.

Consider $k_{\gamma ff} = e|Q_f|$, $g_v^f = 1$, $g_a^f = 0$; then,

$$\Gamma(A^0 \to \gamma\gamma) = m_A r_f \kappa_{\gamma\gamma} \left(I_f^2 {g_P^f}^2 + 2{g_S^f}^2 \left(I_f(4r_f - 1) + 2\right)^2 \right),$$

where, $I_f = C_0(0,0)m_A^2$ y $\kappa_{\gamma\gamma} = \frac{(N_C^f)^2}{128\pi^5}\left(\frac{gm_f}{2m_W}\right)^2\left(e|Q_f|\right)^4$

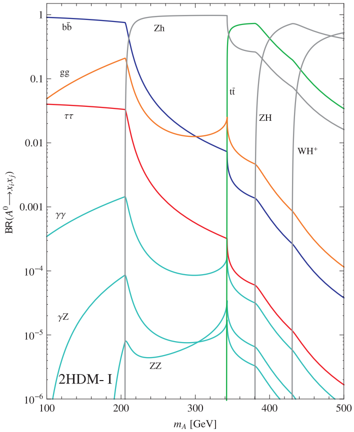
Couplings on I, II, III-type

The **pseudoscalar couplings** to fermions are given by,

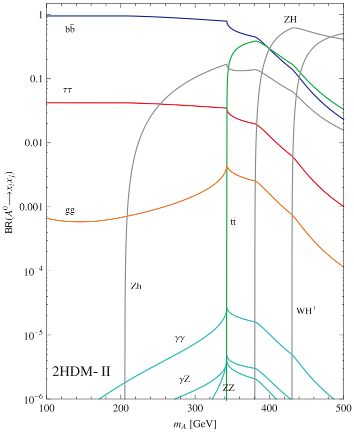
	Type I	Type II	Type III
g_P^u	$\cot\beta$	$\cot\beta$	$\cot\beta - \frac{1}{\sin\beta}(\chi_{ii}^u)$
g_P^d	$-\cot\beta$	$\tan\beta$	$\tan\beta - \frac{1}{\cos\beta}(\chi_{ii}^d)$
g_P^l	$-\cot\beta$	$\tan\beta$	$\tan\beta - \frac{1}{\cos\beta}(\chi_{ii}^l)$

then we obtained...

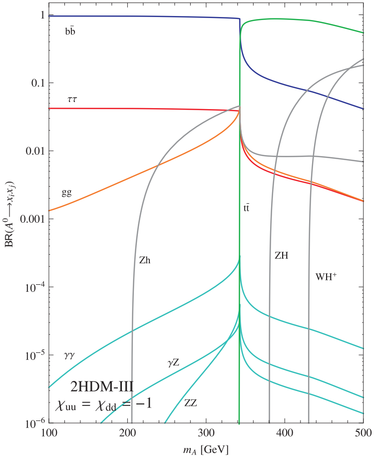
Results $\tan\beta = 5,\ m_H = 300$ GeV and $m_{H^\pm} = 350$ GeV

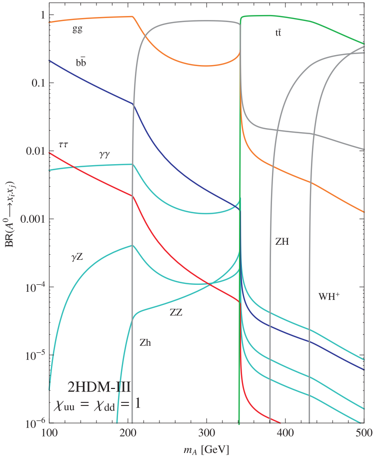


2HDM-I



2HDM-II



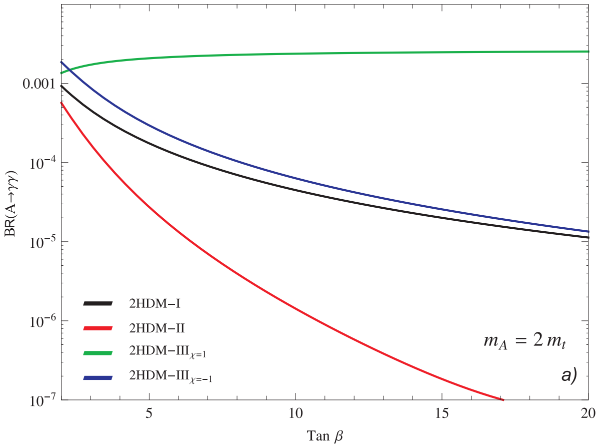


2HDM-III ($\chi_{uu/dd} = -1$)

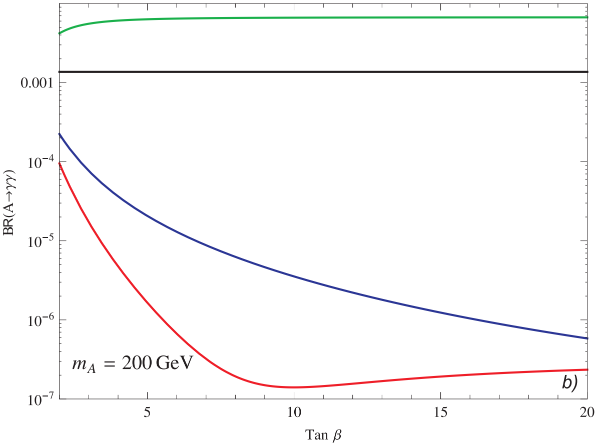
2HDM-III ($\chi_{uu/dd} = 1$)

I, II, III-type comparison

We show the Br vs $\tan\beta$, considering $m_A = 2m_t$ and 200 GeV



Model Comparison



LHC Constraints

We compare, considering: obseved signal Higgs-like (CMS and ATLAS). The signal intensity can be described by;

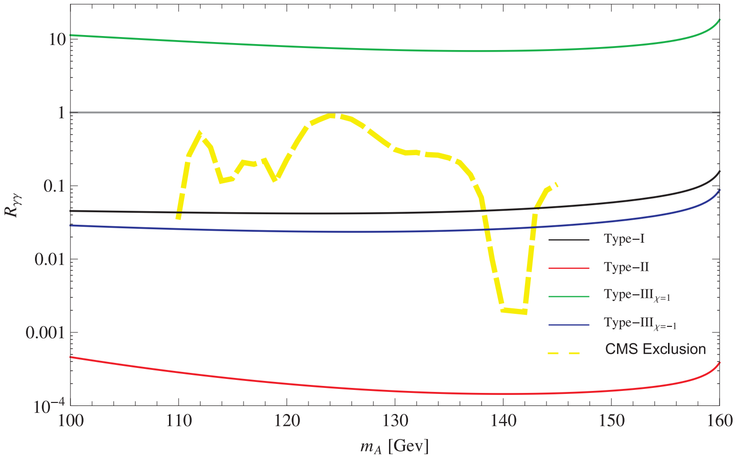
$$R_{XX} = \frac{\Gamma(A^0 \to gg)}{\Gamma(\phi_{ME} \to gg)} \frac{Br(A^0 \to XX)}{Br(\phi_{ME} \to XX)}$$

where $X = \gamma$.

Warning: we know about the pseudoscalar.

Heavy Higgs Bosons Contraints

Constraints about m_A (estimation)



Whenever the predictions from the models fall above these lines, such scenarios would be excluded.

Part V: Conclusions

We evaluated the fermion contribution on $A^0 \to \gamma\gamma$ decay, including the **scalar y pseudoscalar vertex**. We found **regions** where *branching ratios* for the loop modes could be interesting.

We use the **LHC constraints** on Heavy Higgs bosons to **constrain parameters** for 2HDM-I-II and III in $A^0 \to \gamma\gamma$ decay; we obtained:

- 2HDM-I excluded range $138\,\text{GeV} < m_A < 144\,\text{GeV}$.
- 2HDM-II looks aceptable for all of range that we explore.
- 2HDM-III with $\chi = 1$ excluded for mass range $100\,\text{GeV} < m_A < 160\,\text{GeV}$.
- 2HDM-III with $\chi = -1$ excluded for mass range $138\,\text{GeV} < m_A < 144\,\text{GeV}$.