On Naturalness in type II seesaw models and the heavy Higgs masses.

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AIM

The type II seesaw Model (dubbed HTM) is an extension of the Standard Model which provides a consistent explanation of neutrino mass generation :

- This extension is severely constrained by unitarity, boundedness from below.
- HTM is consistent with experimental tests related to diphoton exces observed by LHC.
- Naturalness of the Higgs mass leads to the hierarchy problem in the Standard model.
- Main objective: study the problem of naturalness and see its impact on the space parameters, and its effects on the masses of heavy Higgs bosons.

Introduction

We aim to investigate the naturalness problem in the context of Type II Seesaw model, dubbed HTM, with emphasis on its effect of the HTM parameter space . More precisely, we will study how to soften the divergencies and how to gain some insight on the allowed masses of the heavy scalars in the Higgs sector.
Our study use the most general renormalisable Higgs potential of HTM and is essentially based on dimensional regularisation approach which complies with unitarity and Lorentz invariance. Phenomenologically analysis takes into account the full set of theoretical constraints, including unitarity and the consistent conditions of boundedness from below.

Type II Seesaw Model

Seesaw mechanism is implemented in the Standard Model via addition of a scalar field Δ with hypercahrge $Y = 2$. The potential of this model is

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{\text{Yukawa}}$$

where :

$$\begin{aligned} V(H,\Delta) = & -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) \\ & + [\mu (H^T i\sigma^2 \Delta^\dagger H) + \text{h.c.}] + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) \\ & + \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \end{aligned}$$

Triplet Δ and doublet Higgs H are represented by:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \text{ and } H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

After the spontaneous electroweak symmetry breaking, the Higgs doublet and triplet fields acquire their vacuum expectation values v_d and v_t respectively,

$$\langle \Delta \rangle = \begin{pmatrix} 0 & 0 \\ \frac{v_t}{\sqrt{2}} & 0 \end{pmatrix} \text{ and } H = \begin{pmatrix} 0 \\ \frac{v_d}{\sqrt{2}} \end{pmatrix}$$

Extended Higgs sector: two CP_{even} neutral scalars (h^0, H^0), one neutral pseudo-scalar A^0 and a pair of simply and doubly charged Higgs bosons $H^\pm$ and $H^{\pm\pm}$.

Higgs Bosons Masses

The masse of these Higgs bosons are given by,

$$\begin{aligned} m_{h^0} &= \frac{1}{2}(A + C - \sqrt{(A-C)^2 + 4B^2}) \\ m_{H^0} &= \frac{1}{2}(A + C + \sqrt{(A-C)^2 + 4B^2}) \\ m_{H^{\pm\pm}}^2 &= \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2v_t} \\ m_{H^\pm}^2 &= \frac{(v_d^2 + 2v_t^2)\,[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t} \\ m_{A^0}^2 &= \frac{\mu(v_d^2 + 4v_t^2)}{\sqrt{2}v_t} \end{aligned}$$

The coefficients A, B and C are the entries of the CP_{even} mass matrix defined by,

$$\begin{aligned} A &= \frac{\lambda}{2}v_d^2 \\ B &= v_d(-\sqrt{2}\mu + (\lambda_1 + \lambda_4)v_t), \\ C &= \frac{\sqrt{2}\mu\, v_d^2 + 4(\lambda_2 + \lambda_3)v_t^3}{2v_t} \end{aligned}$$

Theoretical Constraints

The HTM Higgs potential parameters have to obey several constraints originating from theoretical requirements.
BFB:

$$\begin{aligned} & \lambda \geq 0\,,\ \lambda_2 + \lambda_3 \geq 0\,,\ \lambda_1 + \lambda_4 \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0 \\ & \lambda_1 + \sqrt{\lambda(\lambda_2 + \lambda_3)} \geq 0\,,\ \lambda_2 + \frac{\lambda_3}{2} \geq 0 \\ & \lambda_3\sqrt{\lambda} \leq |\lambda_4| \sqrt{\lambda_2 + \lambda_3} \\ & \quad \text{or } \ 2\lambda_1 + \lambda_4 + \sqrt{(\lambda - \lambda_4^2)(2\frac{\lambda_2}{\lambda_3} + 1)} \geq 0 \end{aligned}$$

Unitarity:

$$\begin{aligned} & |\lambda_1 + \lambda_4| \leq 8\pi\,,\ |\lambda_1| \leq 8\pi\,,\ |\lambda| \leq 16\pi \\ & |2\lambda_1 + 3\lambda_4| \leq 16\pi\,,\ |\lambda_2 + \lambda_3| \leq 4\pi\,,\ |\lambda_2| \leq 4\pi \\ & |\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}\ | \\ & \qquad \leq 32\pi \\ & |3\lambda + 16\lambda_2 + 12\lambda_3 \pm \\ & \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}\ | \leq 32\pi \\ & |2\lambda_1 - \lambda_4| \leq 16\pi\,,\ |2\lambda_2 - \lambda_3| \leq 8\pi \end{aligned}$$

Main Results

The mVC induce a drastic reduction of the space parameter. As a byproduct important effect for the upper bound on the simply and doubly charged Higgs masses: $161 \leq m_{H^\pm} \leq 288$ GeV, $90 \leq m_{H^{\pm\pm}} \leq 351$ GeV.

Experimental Constraints

ρ parameter:
First, recall that the ρ parameter in HTM at the tree level is given by the formula,

$$\rho \simeq 1 - 2\frac{v_t^2}{v_d^2}$$

which indicates a deviation from unity. Consistency with the current limit on ρ from precision measurements requires that the limit $|\delta\rho| \leq 10^{-3}$ resulting in an upper limit on v_t about ≤ 5 GeV.
Masses of Higgs bosons :
Many experimental mass limits have been found for the Heavy Higgs bosons. From the LEP direct search results, the lower bounds on $m_{A^0,H^0} > 80-90$ GeV for models with more than one doublet in the case of the neutral scalars. For the singly charged Higgs mass we use the LEP II latest bounds, $m_{H^\pm} \geq 78$ GeV from direct search results, whereas the indirect limit is slightly higher $m_{H^\pm} \geq 125$ GeV.
In the case of the doubly charged Higgs masses, the most recent experimental lower limits reported by ATLAS and CMS are respectively $m_{H^{\pm\pm}} \geq 409$ GeV and $m_{H^{\pm\pm}} \geq 445$ GeV (assuming $Br(H^{\pm\pm}/tol^\pm l^\pm = 100\%)$). But one can find scenarios where the mass goes down to 90 - 100 GeV.

Veltman Conditions (mVC)

The Veltman condition implies that the quadratic divergencies of the two possible tadpoles T_{h^0} and T_{H^0} of the h^0 and H^0 CP-even neutral scalar fields vanish. The linear combination of the fermionic coupling constants $s_\alpha c_{f\bar{f}} + c_\alpha C_{f\bar{f}}$ is zero; further it turns out that the combination $s_\alpha T_{h^0} + c_\alpha T_{H^0}$ induces simplification and one ends up with the short expression:

$$T_t = 4\frac{m_W^2}{v_{sm}^2}(\frac{1}{c_w^2} + 1) + (2\lambda_1 + 8\lambda_2 + 6\lambda_3 + \lambda_4)$$

the orthogonal combination, $c_\alpha T_{h^0} - s_\alpha T_{H^0}$, leads to a simple result :

$$T_d = -2Tr(I_n)\Sigma_f \frac{m_f^2}{v_d^2} + 3(\lambda + 2\lambda_1 + \lambda_4) + 2\frac{m_W^2}{v_{sm}^2} \times (\frac{1}{c_w^2} + 2)$$

Results

- VC for HTM field leads to a drastic reduction of the parameter space to a relatively small allowed region (marked in brown in the figures)
- $\lambda_1 \in [-0.3, 2.3]$ corresponding to $m_{H^{\pm\pm}}$ varying from 90 to 351 GeV, for which λ_4 is limited to lie in a reduced interval between -2.6 and 1.18. There are translated to dramatically reduced ranges for the heavy Higgs masses.

....Results

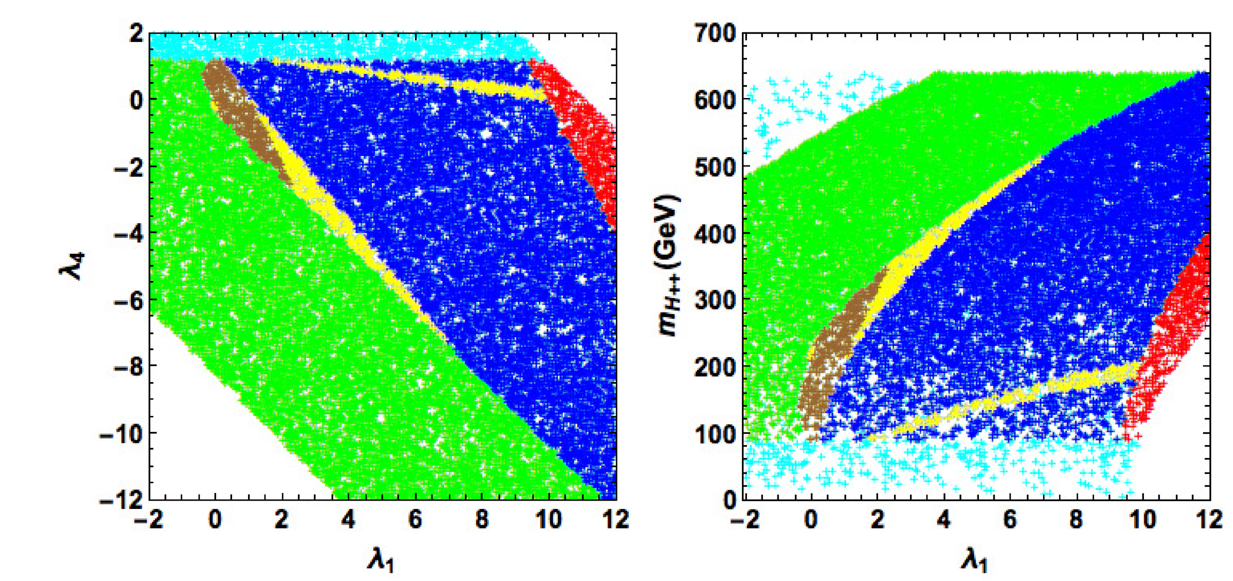

Figure: The allowed regions in (λ_1, λ_4) and $(\lambda_1, m_{H^{\pm\pm}})$ plans. (cyan) : Excluded by μ constraints, (red) : Excluded by μ+Unitarity constraints, (green) : Excluded by μ+Unitarity+BFB constraints, (blue) : Excluded by μ+Unitarity+BFB+$R_{\gamma\gamma}$ constraints, (yellow) : Excluded by μ+Unitarity+BFB $R_{\gamma\gamma}$& $T_d = 0 \wedge T_t = 0$ constraints. Only the brown area obeys ALL constraints. Our inputs are $\lambda = 0.52$, $-2 \leq \lambda_1 \leq 12$, $\lambda_2 = -\frac{1}{6}$, $\lambda_3 = \frac{3}{8}$, $-12 \leq \lambda_4 \leq 2$, $v_t = 1$ GeV and $\mu = 1$ GeV.

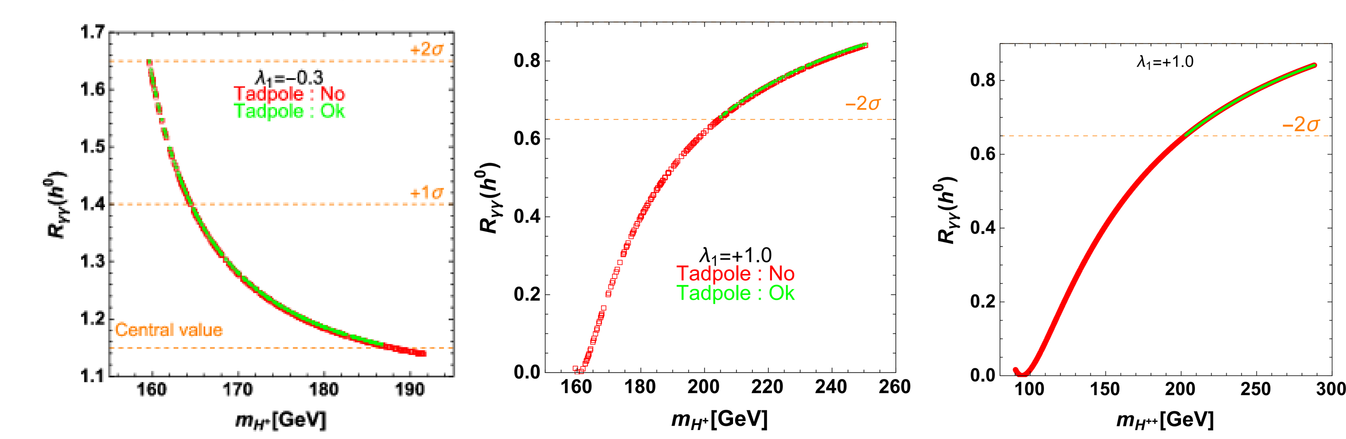

Figure: $R_{\gamma\gamma}(h^0)$ as a function of $m_{H^\pm}$ and $m_{H^{\pm\pm}}$ for two values of λ_1. with and without VC.

m_Φ	**Unitarity**	**Unitarity + BFB**	**Unitarity + BFB + $R_{\gamma\gamma}$**	**Unitarity + BFB + $R_{\gamma\gamma}$ + mVC**
H^0	$[206.8-207.3]$ GeV	$[206.8-207]$ GeV	$[206.8-207]$ GeV	206.8 GeV
A^0	206.8 GeV	206.8 GeV	206.8 GeV	206.8 GeV
$H^\pm$	$[160-474]$ GeV	$[160-474]$ GeV	$[160-392]$ GeV	$[161-288]$ GeV
$H^{\pm\pm}$	$[90-637]$ GeV	$[90-637]$ GeV	$[90-513]$ GeV	$[90-351]$ GeV

Figure: Higgs bosons masses allowed intervals in the Higgs triplet model.

Conclusion

The mVC modified by additional scalar charged states severely constrain the parameter region which affect on the masses of heavy Higgs bosons H^0, A^0, $H^\pm$ and $H^{\pm\pm}$.

References

M. Chabab et al., Phys. Rev. D 93 (2016) 115021

Acknowledgements

This work is partially supported by the Moroccan Ministry of Higher Education and Scientific Research under contract n° PPR/2015/6 and by the grant H2020 − MSCA − RISE/2014 − 645722.

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