125 GeV Higgs Boson and Type-II Seesaw

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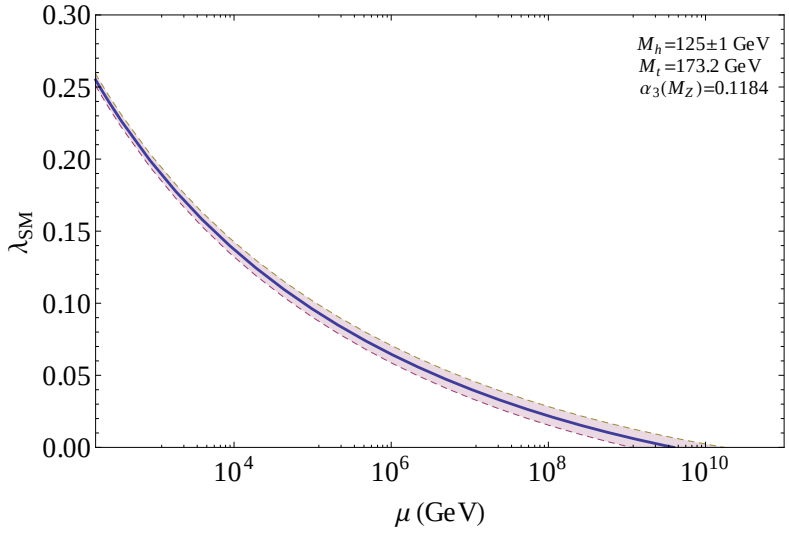
Motivation

- The **125 GeV** resonance detected at LHC implies that the vacuum destabilizes at some scale. Can a simple extension of the SM solve this electroweak vacuum stability problem ?
- Experiments reveal the fact that neutrinos have mass and mixing. Standard Model(SM) predicts massless neutrinos.
- Can a Beyond Standard Model(BSM) model which provides mechanism to generate neutrinos with sufficiently small mass solve the stability problem simultaneously.
- Is the model phenomenologically viable in concern with the recent LHC result?

RG Running of SM Higgs Quartic Coupling

- $V_{\text{eff}}(\Phi) = -m_\Phi^2(\Phi^\dagger\Phi) + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2$.

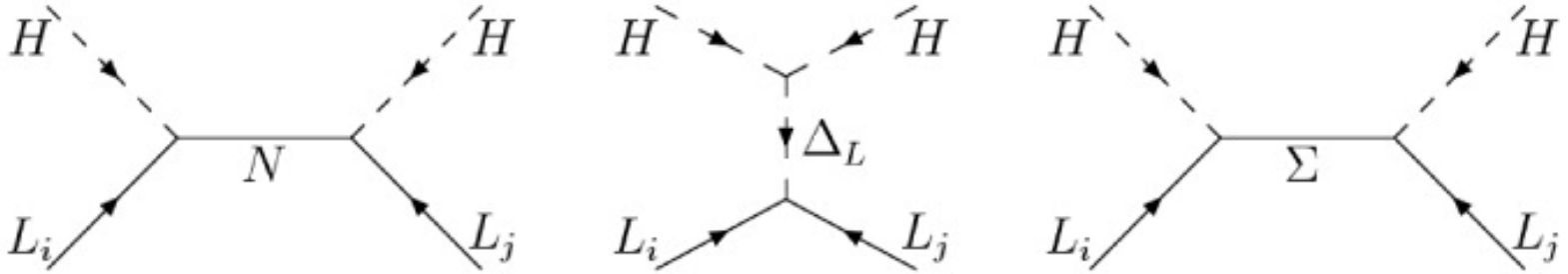


- For a 125 GeV Higgs boson, new physics should be introduced below $10^9 - 10^{10}$ GeV to make the electroweak vacuum stable. (There is a considerable width in the unstability scale due to the large Top mass uncertainty).
- We choose the simplest extension to SM with a massive neutrino - The Seesaw Model.

Seesaw Models

- The simplest way to obtain non-zero neutrino masses is by breaking the global (B - L) symmetry of the SM.
- One Classic solution ⇒ **SEESAW MECHANISM**
- This is a realization of the **effective dimension-5 Weinberg operator** using only renormalizable interactions.
- The effective Weinberg operator is ⇒ $y_{ij}(L_i^T\Phi)(L_j^T\Phi)/M$, M → heavy physics mass scale.

There are three types of Seesaw :



We choose Type-II Seesaw.

Type-II Seesaw

[Magg, Wetterich '80; Cheng, Li '80; Lazarides, Shafi, Wetterich '80; Schechter, Valle '80; Mohapatra, Senjanovic '81]

- Add a scalar $\Delta(1,3,2)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$.

$$\Delta = \frac{\sigma^i}{\sqrt{2}}\Delta_i = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \to \begin{pmatrix} 0 & 0 \\ \frac{v_\Delta}{\sqrt{2}} & 0 \end{pmatrix},$$

$\Delta_1 = (\delta^{++} + \delta^0)/\sqrt{2},\ \Delta_2 = i(\delta^{++} - \delta^0)/\sqrt{2},\ \Delta_3 = \delta^+.$

- The Lagrangian for this model:

$$\begin{aligned} \mathcal{L} &= \mathcal{L}^{\rm SM}_{\rm kinetic} + \mathcal{L}^{\rm SM}_Y - \mathcal{V}(\Phi,\Delta) + {\rm Tr}\left[(D_\mu\Delta)^\dagger (D^\mu\Delta)\right] \\ &\quad - \left[\frac{1}{\sqrt{2}}(Y_\Delta)_{ij} L_i^{\rm T} C i\sigma_2 \Delta L_j + {\rm H.c.}\right] \\ D_\mu\Delta &= \partial_\mu\Delta + i\frac{g}{2}[\sigma^a W^a_\mu, \Delta] + i\frac{g'}{2}B_\mu\Delta \qquad (a = 1,2,3) \end{aligned}$$

C $\to$ Dirac charge conjugation matrix.

- The Scalar Potential :

$$\begin{aligned}\mathcal{V}(\Phi,\Delta) &= -m_\Phi^2(\Phi^\dagger\Phi)+\frac{\lambda}{2}(\Phi^\dagger\Phi)^2+M_\Delta^2\mathrm{Tr}(\Delta^\dagger\Delta)+\frac{\lambda_1}{2}\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2\\ &+\frac{\lambda_2}{2}\left(\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2-\mathrm{Tr}\left[(\Delta^\dagger\Delta)^2\right]\right)+\lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta)\\ &+\lambda_5\Phi^\dagger[\Delta^\dagger,\Delta]\Phi+\left(\frac{\Lambda_6}{\sqrt{2}}\Phi^\mathsf{T}i\sigma_2\Delta^\dagger\Phi+\mathrm{H.c.}\right)\end{aligned}$$

- From EWPT constraints, $\frac{v_\Delta}{v}<0.02$
- For $\mu<M_\Delta$, The low-energy effective scalar potential for the SM Higgs doublet:

$$\begin{aligned}V_{\mathrm{eff}}(\Phi) &= -m_\Phi^2(\Phi^\dagger\Phi)+\frac{1}{2}(\lambda-\lambda_6^2)(\Phi^\dagger\Phi)^2,\\ &\lambda\to\lambda_{\mathrm{SM}}=\lambda-\lambda_6^2\,,\\ \text{where}\qquad &\lambda_6=\frac{\Lambda_6}{M_\Delta}=\frac{2v_\Delta M_\Delta}{v^2}\left(1+\frac{v^2}{2M_\Delta}(\lambda_4-\lambda_5)\right)\end{aligned}$$

- For lowscale Seesaw, $\lambda_6^2\ll\lambda$ is always true.
- We choose, $v_\Delta=1$ GeV, for $M_\Delta\simeq\mathcal{O}(\text{EW scale})$
- For High scale Seesaw, we choose $v_\Delta=0.05$ eV to avoid λ_6 effect.
- Seven physical massive eigenstates $\to H^{\pm\pm},\ H^\pm,\ h,\ H^0,\ A^0$.

- The physical mass eigenvalues are,

$$
\begin{aligned}
m_{H^{\pm\pm}}^2 &= M_\Delta^2 + \frac{1}{2}(\lambda_4+\lambda_5)v^2 + \frac{1}{2}(\lambda_1+\lambda_2)v_\Delta^2, \\
m_{H^{\pm}}^2 &= \left(M_\Delta^2 + \frac{1}{2}\lambda_4 v^2 + \frac{1}{2}\lambda_1 v_\Delta^2\right)\left(1+\frac{2v_\Delta^2}{v^2}\right), \\
m_{A^0}^2 &= \left(M_\Delta^2 + \frac{1}{2}(\lambda_4-\lambda_5)v^2 + \frac{1}{2}\lambda_1 v_\Delta^2\right)\left(1+\frac{4v_\Delta^2}{v^2}\right), \\
m_h^2 &= \frac{1}{2}\left(A+C-\sqrt{(A-C)^2+4B^2}\right), \\
m_{H^0}^2 &= \frac{1}{2}\left(A+C+\sqrt{(A-C)^2+4B^2}\right),
\end{aligned}
$$

with,

$$
\begin{aligned}
A &= \lambda v^2,\ B = -\frac{2v_\Delta}{v}\left(M_\Delta^2 + \frac{1}{2}\lambda_1 v_\Delta^2\right), \\
C &= M_\Delta^2 + \frac{1}{2}(\lambda_4-\lambda_5)v^2 + \frac{3}{2}\lambda_1 v_\Delta^2.
\end{aligned}
$$

- $m_{H^0} > m_h$ **is always satisfied.**

Dynamical Constraints

[Arhrib, Benbrik, Chabab, Moultaka, Rahili 11]

- Electroweak Vacuum Stability:

$$\lambda \geq 0, \quad \lambda_1 \geq 0, \quad 2\lambda_1 + \lambda_2 \geq 0,$$
$$\lambda_4 + \lambda_5 + \sqrt{\lambda\lambda_1} \geq 0, \quad \lambda_4 + \lambda_5 + \sqrt{\lambda\left(\lambda_1 + \frac{\lambda_2}{2}\right)} \geq 0,$$
$$\lambda_4 - \lambda_5 + \sqrt{\lambda\lambda_1} \geq 0, \quad \lambda_4 - \lambda_5 + \sqrt{\lambda\left(\lambda_1 + \frac{\lambda_2}{2}\right)} \geq 0.$$

- Unitarity:

$$\lambda \leq \frac{8}{3}\pi, \quad \lambda_1 - \lambda_2 \leq 8\pi, \quad 4\lambda_1 + \lambda_2 \leq 8\pi, \quad 2\lambda_1 + 3\lambda_2 \leq 16\pi,$$
$$|\lambda_5| \leq \frac{1}{2}\min\left[\sqrt{(\lambda \pm 8\pi)(\lambda_1 - \lambda_2 \pm 8\pi)}\right],$$
$$|\lambda_4| \leq \frac{1}{\sqrt{2}}\sqrt{\left(\lambda - \frac{8}{3}\pi\right)(4\lambda_1 + \lambda_2 - 8\pi)}.$$

Running Coupling Constants

[Schmidt 07; Chao, Zhang 07]

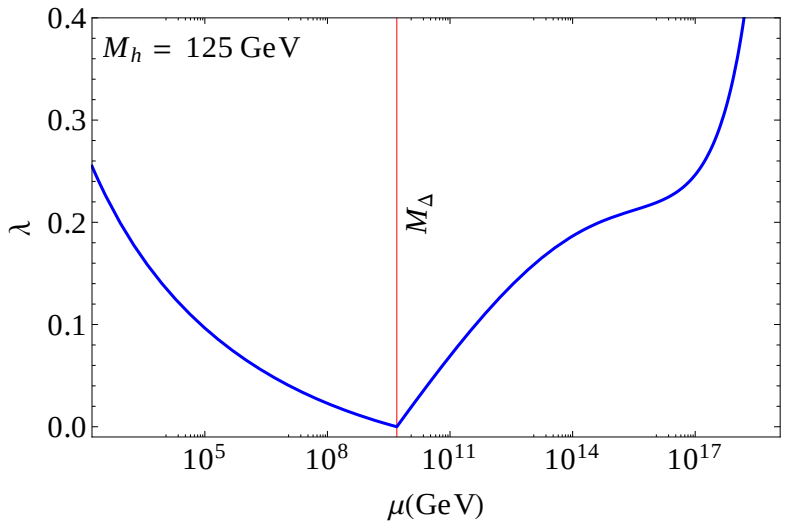
With Type-II Seesaw :

$$\beta_\lambda \to \beta_\lambda^{SM} + 6\lambda_4^2 + 4\lambda_5^2,$$

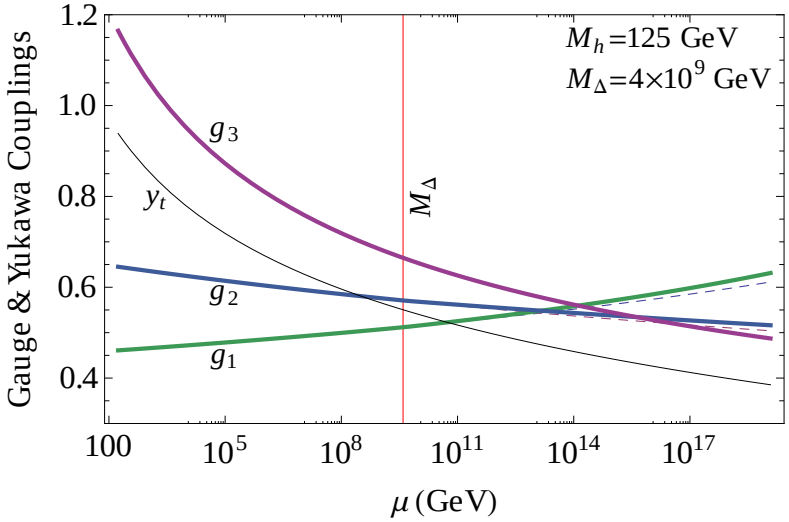
The new physics contribution introduces at the Seesaw scale M_Δ.
For $\mu > M_\Delta$ the gauge coupling beta function changes at one loop level.

$$b_i^{\rm SM} = \left(-\tfrac{41}{10}, \tfrac{19}{6}, 7\right) \Rightarrow b_i = \left(-\tfrac{47}{10}, \tfrac{5}{2}, 7\right)$$

With Type-II Seesaw :



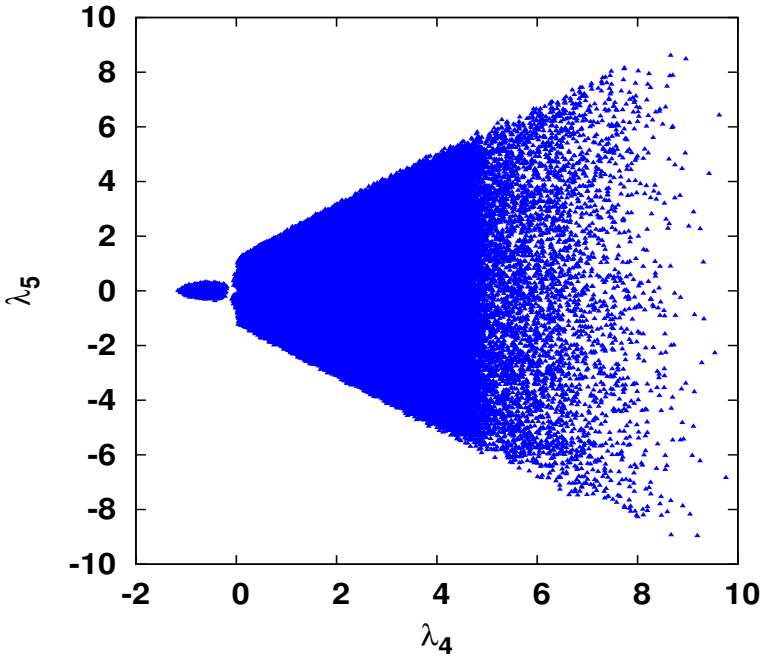
Top Yukawa and Gauge Coupling Running:



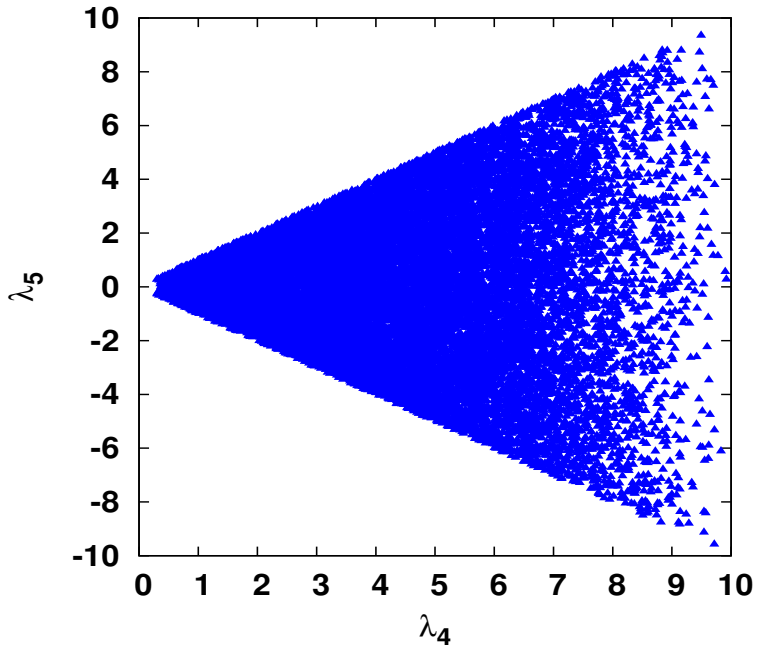
Scanning Allowed Parameter Space

- For both high and low Seesaw scale there exists sufficient parameter space which satisfy all the dynamical constraints.

$M_\Delta = 200$ GeV



$M_\Delta = 10^9$ GeV

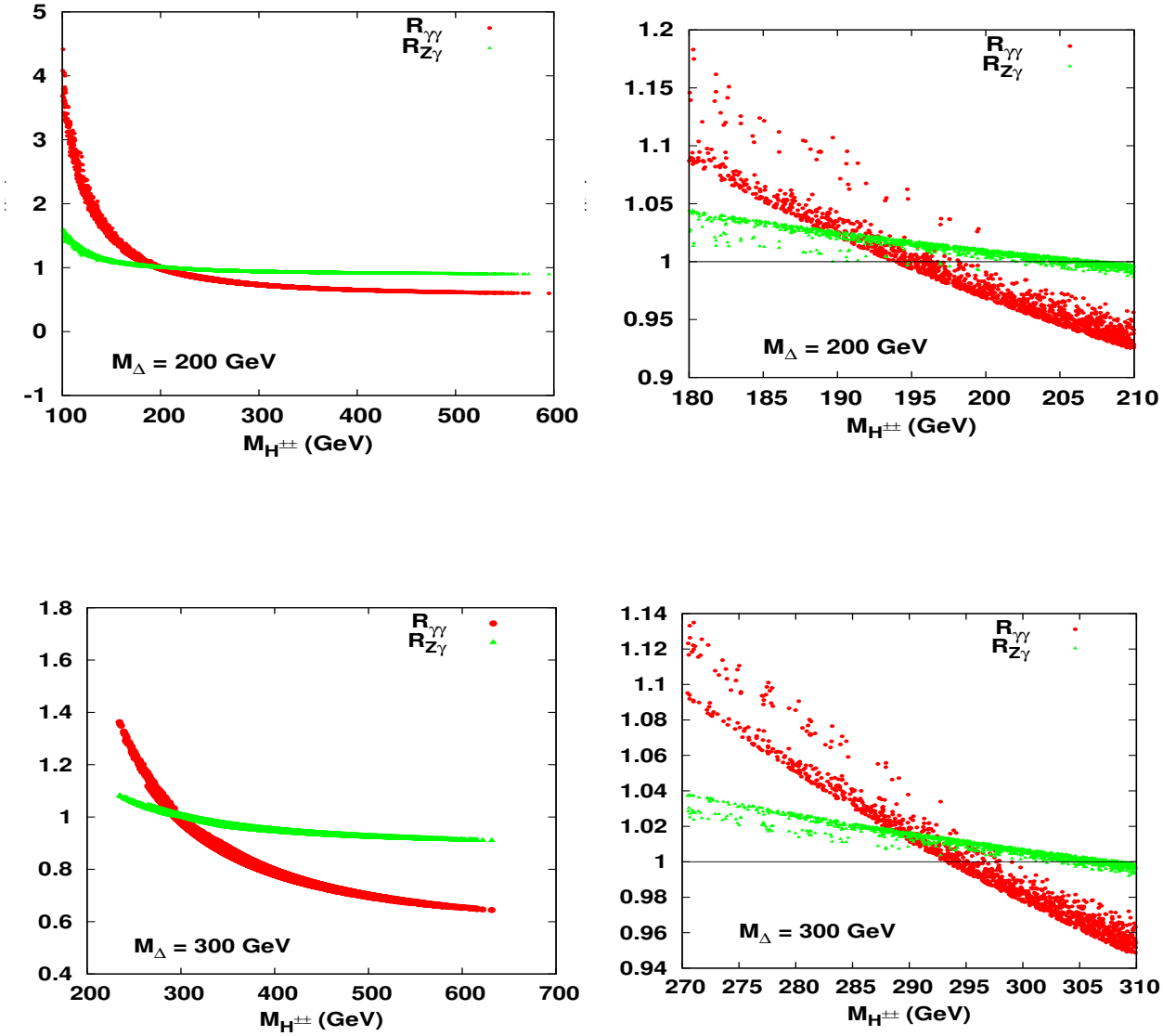


- No allowed points near $(\lambda_4, \lambda_5) = (0, 0)$.

Experimental Limits on $M_{H^{\pm\pm}}$ and $M_{H^{\pm}}$

- $\Gamma(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \propto \mid y_{ij} \mid^2 \sim \mid \frac{M_\nu^{ij}}{v_\Delta} \mid^2$
- $\Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm}) \propto g^2 v_\Delta^2$
- Large triplet VEV $\Longrightarrow$ large BR for WW
- Direct search limits: $M_{H^{\pm\pm}} > 300 - 400$ GeV (LHC) (assuming dominant $\ell^{\pm}\ell^{\pm}$ decay mode)
- Valid for $v_\Delta < 10^{-4}$ GeV (large Yukawa coupling)
- For $v_\Delta > 10^{-4}$ GeV (small Yukawa), BR to $\ell^{\pm}\ell^{\pm}$ drops significantly and the mass limit lowered to about 100 GeV. [Melfo,Nemevsek, Nesti, Senjanovic, Zhang, (11)]
- LEP limit on $M_{H^{\pm}} > 90$ GeV
- Constraints from LFV require $v_\Delta M_{H^{\pm\pm}} \geq 150$eV GeV [Melfo,Nemevsek, Nesti, Senjanovic, Zhang, (11)]
- Constraints from S, T, U parameters require $\Delta M \equiv \mid M_{H^{\pm\pm}} - M_{H^{\pm}} \mid \lesssim 40$ GeV [Chun,Lee,Sharma (12)]

Prediction for $h \to \gamma\gamma$ and $h \to Z\gamma$



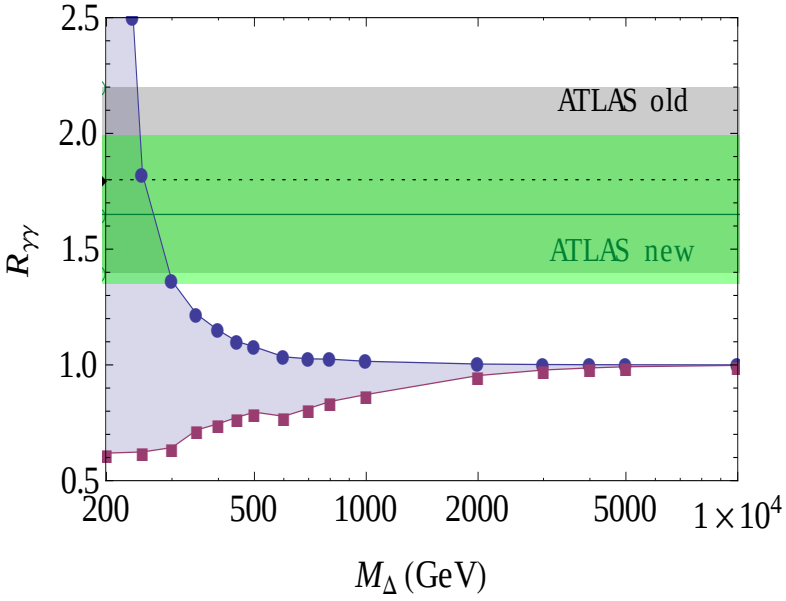
- The Couplings are :

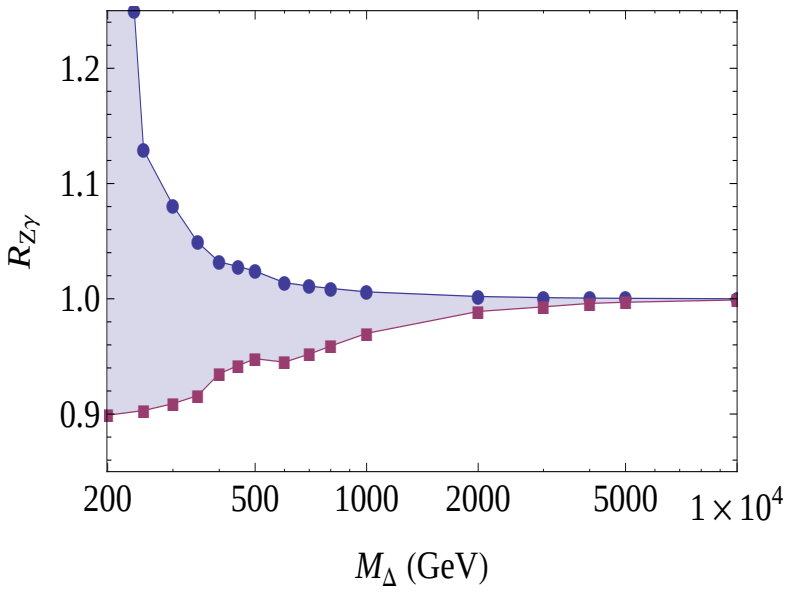
$$
\begin{aligned}
g_{ZH^+H^-} &= -\frac{s_W}{c_W}, \\
g_{ZH^{++}H^{--}} &= \frac{\cos 2\theta_W}{c_W}. \\
g_{hH^{++}H^{--}} &\simeq -(\lambda_4+\lambda_5)v\,, \quad g_{hH^+H^-} \simeq -\lambda_4 v.
\end{aligned}
$$

- $H^{\pm\pm}$ contribution dominate over the $H^{\pm}$ contribution for both $h \to \gamma\gamma$ and $h \to Z\gamma$ amplitude for most of the allowed parameter space.
- The partial decay width of $h \to \gamma\gamma$:

  $R_{\gamma\gamma} = \frac{\sigma_{model}(pp\to h\to\gamma\gamma)}{\sigma_{SM}(pp\to h\to\gamma\gamma)} = \frac{\sigma_{model}(pp\to h)}{\sigma_{SM}(pp\to h)}\frac{BR_{model}(h\to\gamma\gamma)}{BR_{SM}(h\to\gamma\gamma)}$
  Similarly , for $R_{Z\gamma}$.
- In the type-II Seesaw model, $R_{\gamma\gamma} > 1 \Rightarrow$ constructive interference happens for $(\lambda_4+\lambda_5) < 0$ which is allowed over a small range of the parameter space.
- Mostly correlated , small anti-correlation near $M_{H^{\pm\pm}} \simeq M_{\Delta}$
- For a sufficiently low Seesaw scale, the deviations from the SM prediction could be significant for $h \to \gamma\gamma$ channel.

With increase in Seesaw scale, the enhancement in the rates decreases substantially.





M_Δ [GeV]	$(R_{\gamma\gamma})$max(min)	$(R_{\gamma\gamma})$max(min)
200	4.41 (0.62)	1.59 (0.90)
300	1.36 (0.64)	1.08 (0.91)
400	1.15 (0.75)	1.03 (0.93)
500	1.08 (0.80)	1.02 (0.95)
1000	1.02 (0.87)	1.01 (0.97)

Conclusion

- We have studied the effects of electroweak vacuum stability and unitarity conditions on the full parameter space of the minimal type-II Seesaw model in the light of the recent discovery of a SM Higgs-like particle at the LHC in the mass range $124 - 126$ GeV.

- There exists a large parameter space in the model, irrespective of the Seesaw scale.

- It yields a SM-like Higgs mass around 125 GeV while satisfying all the stability and unitarity conditions as well as neutrino oscillation data, collider bounds and other low-energy data.

- Predictions for the partial decay widths of the $h \to \gamma\gamma$ and $h \to Z\gamma$ with respect to their SM expectations showed that these two rates are mostly-correlated in the type-II Seesaw model.

- For more than 10% deviation of the $\gamma\gamma$ signal strength from its SM value, the corresponding upper bound on the type-II Seesaw scale is about 450 GeV which is completely within the reach of the LHC.


Thank you!

BACKUPS

Mixings

The mixing between the doublet and triplet scalar fields in the charged, CP-even and CP-odd scalar sectors are respectively given by,

$$\begin{pmatrix} G^{\pm} \\ H^{\pm} \end{pmatrix} = \begin{pmatrix} \cos\beta' & \sin\beta' \\ -\sin\beta' & \cos\beta' \end{pmatrix} \begin{pmatrix} \phi^{\pm} \\ \delta^{\pm} \end{pmatrix}, \tag{1}$$

$$\begin{pmatrix} h \\ H^{0} \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi \\ \delta \end{pmatrix}, \tag{2}$$

$$\begin{pmatrix} G^{0} \\ A^{0} \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi \\ \eta \end{pmatrix}, \tag{3}$$

where the mixing angles are given by

$$\tan\beta' = \frac{\sqrt{2}v_{\Delta}}{v}, \tan\beta = \frac{2v_{\Delta}}{v} \equiv \sqrt{2}\tan\beta',$$

$$\tan 2\alpha = \frac{2B}{A-C} = \frac{4v_{\Delta}}{v}\frac{M_{\Delta}^2 + \frac{1}{2}\lambda_1 v_{\Delta}^2}{M_{\Delta}^2 + \frac{1}{2}(\lambda_4 - \lambda_5 - 2\lambda)v^2 + \frac{3}{2}\lambda_1 v_{\Delta}^2}.$$

Collider constraints on v_Δ

- The strongest limits come from the ongoing LHC searches for doubly-charged Higgs bosons. They can be produced via :

$$q\bar{q} \to \gamma^*, Z^*, W^{\pm *}W^{\pm *} \to H^{++}H^{--},$$
$$q'\bar{q} \to W^* \to H^{\pm\pm}H^{\mp}, H^{\pm\pm}W^{\mp},$$

- The possible decay channels:
  (i) same-sign charged lepton pair ($\ell^\pm\ell^\pm$),
  (ii) pair of charged gauge bosons ($W^\pm W^\pm$),
  (iii) $W^\pm H^\pm$, and (iv) $H^\pm H^\pm$, if kinematically allowed.

- <u>$v_\Delta < 10^{-4}$ **GeV (large Yukawa couplings)**</u> :
  Degenerate triplet scalars $\Rightarrow H^{++} \to \ell^\pm\ell^\pm$.
  The 95% CL lower limit $\Rightarrow M_{H^{\pm\pm}} > 300$ - 400 GeV, depending on the final-state lepton-flavor.

- <u>$v_\Delta > 10^{-4}$ **GeV (small Yukawa)**</u>:
  BR($\ell^\pm\ell^\pm$) decreases significantly, and the other decay channels (ii), (iii) and (iv) become dominant and $H^{\pm\pm} \geq 100$ GeV.
  Provided the mass splitting between the singly- and doubly-charged scalars is large enough to allow for the cascade decays.

- The β-function of Higgs quartic-coupling in one loop order

$$\beta_\lambda^{(1)} = 12\lambda^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right) + 12y_t^2\lambda - 12y_t^4$$

where, $(g_i, i = 1, 2, 3) \rightarrow$ The Gauge couplings,
$y_t \rightarrow$ the Top Yukawa coupling.

- For the new scalar couplings in the type-II seesaw model, the one-loop RG equations are given by :

[M.A.Schmidt ';W.Chao and H.Zhang ']

Decay width $h \to \gamma\gamma$

[Nucl.Phys.**30**, 711 (1979),Shifman *et al.*]

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 G_F M_h^3}{128\sqrt{2}\pi^3} \Bigg| \sum_f N_c Q_f^2 g_{hf\bar{f}} A_{1/2}^h(\tau_f) + g_{hW^+W^-} A_1^h(\tau_W) + \tilde{g}_{hH^\pm H^\mp} A_0^h(\tau_{H^\pm}) + 4\tilde{g}_{hH^{\pm\pm}H^{\mp\mp}} A_0^h(\tau_{H^{\pm\pm}}) \Bigg|^2$$

$$\begin{aligned}
\tau_i &= M_h^2/4M_i^2 \ (i = f, W, H^\pm, H^{\pm\pm}) \\
A_0(\tau) &= -[\tau - f(\tau)]\tau^{-2}, \\
A_{1/2}(\tau) &= 2\left[\tau + (\tau - 1)f(\tau)\right]\tau^{-2}, \\
A_1(\tau) &= -\left[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)\right]\tau^{-2},
\end{aligned}$$

$$f(\tau) = \begin{cases} \left[\sin^{-1}\left(\sqrt{\tau}\right)\right]^2, & (\tau \le 1) \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}}\right) - i\pi\right]^2, & (\tau > 1). \end{cases}$$

$$\tilde{g}_{hH^{++}H^{--}} = -\frac{M_W}{gM_{H^{\pm\pm}}^2} g_{hH^{++}H^{--}}, \quad \tilde{g}_{hH^+H^-} = -\frac{M_W}{gM_{H^\pm}^2} g_{hH^+H^-},$$

Decay width $h \to Z\gamma$

In the limit $v_\Delta \ll v$,

$$g_{hH^{++}H^{--}} \simeq -(\lambda_4 + \lambda_5)v\,, \quad g_{hH^+H^-} \simeq -\lambda_4 v.$$

$$\begin{aligned}
\Gamma(h \to Z\gamma) &= \frac{\alpha G_F^2 M_W^2 M_h^3}{64\pi^4}\left(1 - \frac{M_Z^2}{M_h^2}\right)^3 \\
&\quad \Bigg| \frac{1}{c_W}\sum_f N_c Q_f (2I_3^f - 4Q_f s_W^2) g_{hf\bar{f}} A_{1/2}^{Z\gamma}(\tau_f, \lambda_f) \\
&\quad + c_W g_{hW^+W^-} A_1^{Z\gamma}(\tau_W, \lambda_W) \\
&\quad - 2s_W g_{ZH^\pm H^\mp} \tilde{g}_{hH^\pm H^\mp} A_0^{Z\gamma}(\tau_{H^\pm}, \lambda_{H^\pm}) \\
&\quad - 4s_W g_{ZH^{\pm\pm}H^{\mp\mp}} \tilde{g}_{hH^{\pm\pm},H^{\mp\mp}} A_0^{Z\gamma}(\tau_{H^{\pm\pm}}, \lambda_{H^{\pm\pm}}) \Bigg|^2 \\
g_{ZH^\pm H^\mp} &= -\frac{s_W}{c_W},\ g_{ZH^{\pm\pm}H^{\mp\mp}} = \frac{\cos 2\theta_W}{c_W}. \\
\tau_i &= 4M_i^2/M_h^2, \\
\lambda_i &= 4M_i^2/M_Z^2\ (i = W, f, H^\pm, H^{\pm\pm})
\end{aligned}$$

$$
\begin{aligned}
A_1^{Z\gamma}(x,y) &= 4(3-\tan^2\theta_W)I_2(x,y) + [(1+2x^{-1})\tan^2\theta_W \\
&\quad -(5+2x^{-1})]I_1(x,y), \\
A_{1/2}^{Z\gamma}(x,y) &= I_1(x,y) - I_2(x,y), \\
A_0^{Z\gamma}(x,y) &= I_1(x,y),
\end{aligned}
$$

$$
\begin{aligned}
I_1(x,y) &= \frac{xy}{2(x-y)} + \frac{x^2y^2}{2(x-y)^2}[f(x^{-1}) - f(y^{-1})] \\
&\quad + \frac{x^2y}{(x-y)^2}[g(x^{-1}) - g(y^{-1})], \\
I_2(x,y) &= -\frac{xy}{2(x-y)}[f(x^{-1}) - f(y^{-1})].
\end{aligned}
$$

$$
g(\tau) = \begin{cases} \sqrt{\tau^{-1}-1}\sin^{-1}\left(\sqrt{\tau}\right), & (\tau < 1) \\ s\frac{1}{2}\sqrt{1-\tau^{-1}}\left[\log\left(\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}}\right) - i\pi\right], & (\tau \geq 1)\,. \end{cases}
$$

New contributions from the charged Higgs bosons in the type-II seesaw model become negligible beyond a seesaw scale of $M_\Delta \sim 10$ TeV. upper bound on the seesaw scale. This in turn imposes an upper bound on the masses of the singly- and doubly-charged Higgs bosons in the model.