Revisiting the high-scale validity of Type-II seesaw model with novel LHC signature

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Model

Type-II seesaw model contains an $SU(2)_L$ triplet scalar field Δ with hypercharge $Y = 2$ in addition to the SM fields.

$$\Delta = \frac{\sigma^i}{\sqrt{2}}\Delta_i = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}, \tag{1}$$

The complete Lagrangian of this scenario is given by:

$$\mathcal{L} = \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{Kinetic}} - V(\Phi, \Delta), \tag{2}$$

$$\mathcal{L}_{\text{kinetic}} = (D_\mu\Phi)^\dagger (D^\mu\Phi) + \mathrm{Tr}\left[(D_\mu\Delta)^\dagger (D^\mu\Delta)\right], \tag{3}$$

$$\mathcal{L}_{\text{Yukawa}} = \mathcal{L}^{\text{SM}}_{\text{Yukawa}} - (Y_\Delta)_{ij} L_i^T C i\sigma_2 \Delta L_j + \text{h.c.} \tag{4}$$

The most general scalar potential[1] is given as :

$$V(\Phi, \Delta) = -m_\Phi^2(\Phi^\dagger\Phi) + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + M_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left(\mu\Phi^T i\sigma_2\Delta^\dagger\Phi + \text{h.c.}\right) + \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4\Phi^\dagger\Delta\Delta^\dagger\Phi. \tag{5}$$

[1] A. Arhrib et al,PhysRevD.84.095005

Model

The SM ρ-parameter is given by:

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{1+\frac{2v_t^2}{v_d^2}}{1+\frac{4v_t^2}{v_d^2}}. \quad (6)$$

One gets an upper bound on $\frac{v_t}{v_d} < 0.02$ or $v_t < 5$ GeV. After EWSB, the scalar fields expanded around respective vevs, can be parameterized as

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\chi_d^+ \\ v_d + h_d + i\eta_d \end{pmatrix} \qquad \Delta = \frac{1}{\sqrt{2}}\begin{pmatrix} \delta^+ & \sqrt{2}\delta^{++} \\ v_t + h_t + i\eta_t & -\delta^+ \end{pmatrix}. \quad (7)$$

As a consequence, the scalar spectrum contains seven physical Higgs bosons: two doubly charged $H^{\pm\pm}$, two singly charged $H^{\pm}$, two CP-even neural (h, H) and a CP-odd (A) Higgs particles.
The corresponding mixing angles are given as

$$\tan\beta' = \frac{\sqrt{2}v_t}{v_d}, \quad \tan\beta = \frac{2v_t}{v_d} \equiv \sqrt{2}\tan\beta' \quad (8a)$$

$$\text{and} \quad \tan 2\alpha = \frac{2\mathcal{B}}{\mathcal{A}-\mathcal{C}}, \quad (8b)$$

$$\text{where,} \quad \mathcal{A} = \frac{\lambda}{2}v_d^2, \qquad \mathcal{B} = v_d[-\sqrt{2}\mu + (\lambda_1+\lambda_4)v_t], \quad \mathcal{C} = \frac{\sqrt{2}\mu v_d^2 + 4(\lambda_2+\lambda_3)v_t^3}{2v_t}. \quad (8c)$$

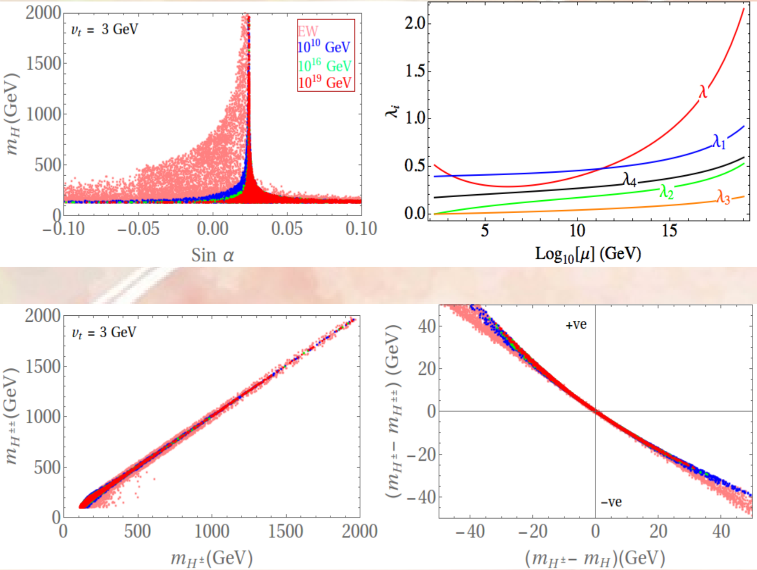
Theoretical And Experimental Constraints

- **Vacuum Stability**
- **Perturbative Unitarity**
- **Constraints from electroweak precision test**: T-parameter which imposes strict limit on the mass splitting between the doubly and singly charged scalars, $\Delta M \equiv\mid m_{H^{\pm\pm}} - m_{H^{\pm}} \mid$ which should be $\lesssim 50$ GeV[2].
- **Experimental bounds on scalar masses** : The direct search on the singly charged scalar at the LEP II puts a limit on $m_{H^{\pm}} \geq 78$ GeV. For $v_t < 10^{-4}$ GeV (corresponds to large Yukawa couplings) the direct search of the doubly charged Higgs boson at 13 TeV LHC run puts the current lower bound at 95% CL to be $m_{H^{\pm\pm}} > 700 - 800$ GeV[3].
- **Constraints from Higgs signal strength**: Our choice of benchmark points remain within the 2σ limit of the current experimental bound $(0.85^{+0.22}_{-0.20})$ of the Higgs to diphoton signal strength.

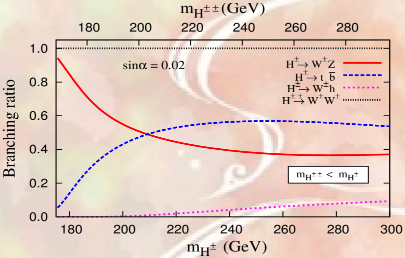
[2] E. J. Chun et al.,JHEP11(2012)106

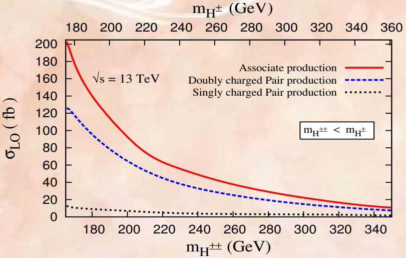
[3] ATLAS collaboration

High Scale Stability



Collider Analysis





Mass Scenario	$\sin\alpha$	$m_{H^{\pm\pm}}$ (GeV)	$m_{H^\pm}$ (GeV)	$m_H = m_A$ (GeV)	$\mu_{\gamma\gamma}$
Positive					
BP1	0.0220	165.48	173.25	180.70	0.79
BP2	0.0280	175.99	177.47	178.93	0.82
Negative					
BP1	0.0277	179.60	176.30	173.01	0.79
BP2	0.0300	184.17	180.11	175.95	0.81

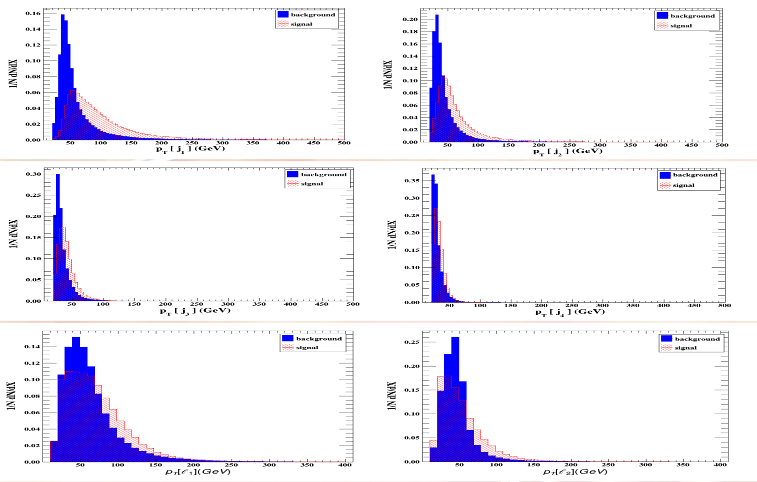
We consider the following two signal topologies:

$$(i) \quad 3\ell^\pm + \not{E}_T;$$

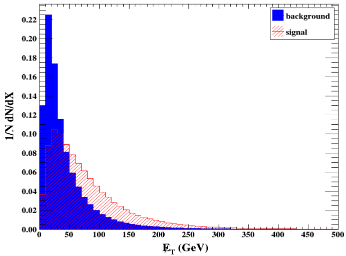
$$(ii) \quad (\ell^+\ell^+) + 4j + \not{E}_T,$$

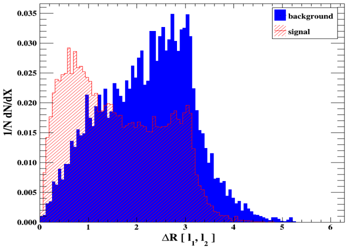
$2\ell^{\pm} + 4j + \not{E}_T$

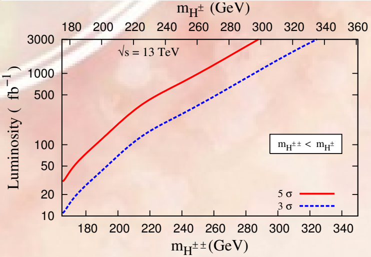
$$
\begin{aligned}
pp \to H^{++}H^{--} &\to (W^+W^+) + (W^-W^-) \to (\ell^+\ell^+) + 4j + \not{E}_T \\
pp \to H^{++}H^{-} &\to (W^+W^+) + (W^-Z) \to (\ell^+\ell^+) + 4j + \not{E}_T \ . \qquad (9
\end{aligned}
$$

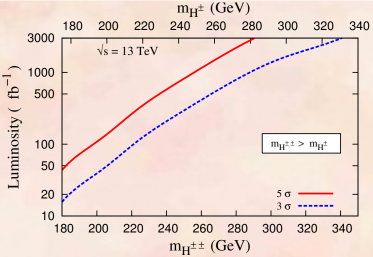


$2\ell^{\pm} + 4j + \not{E}_T$









Conclusion

- We have found that the additional scalar fields can certainly surmount the instability problem and provide us with an absolutely stable vacuum even up to the Planck scale.
- Depending on the mass hierarchy, two possible scenarios (positive and negative) exist which however, at the end, yielded similar signal significance. In the allowed parameter space, with appreciable production cross section, the masses of the charged scalar can presumably be chosen around 200 GeV.
- For $(2\ell^{\pm} + 4j + \not{E}_T)$ channel we have found that even a 5σ discovery reach is possible with the present LHC data with only around 40 fb^{-1} luminosity at 13 TeV LHC run.

Vacuum stability

$$\begin{aligned}
\lambda &\geq 0\,, && (10a)\\
\lambda_2+\lambda_3 &\geq 0\,, && (10b)\\
\lambda_2+\frac{\lambda_3}{2} &\geq 0, && (10c)\\
\lambda_1+\sqrt{\lambda(\lambda_2+\lambda_3)} &\geq 0\,, && (10d)\\
\lambda_1+\sqrt{\lambda\left(\lambda_2+\frac{\lambda_3}{2}\right)} &\geq 0, && (10e)\\
\lambda_1+\lambda_4+\sqrt{\lambda(\lambda_2+\lambda_3)} &\geq 0\,, && (10f)\\
\lambda_1+\lambda_4+\sqrt{\lambda\left(\lambda_2+\frac{\lambda_3}{2}\right)} &\geq 0. && (10g)
\end{aligned}$$

Perturbative unitarity

$$
\begin{aligned}
|\lambda_1 + \lambda_4| &\leq 16\pi\,, && (11a)\\
|\lambda_1| &\leq 16\pi\,, && (11b)\\
|2\lambda_1 + 3\lambda_4| &\leq 32\pi\,, && (11c)\\
|\lambda| &\leq 32\pi\,, && (11d)\\
|\lambda_2| &\leq 8\pi\,, && (11e)\\
|\lambda_2 + \lambda_3| &\leq 8\pi\,, && (11f)\\
|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}| &\leq 64\pi\,, && (11g)\\
|3\lambda + 16\lambda_2 + 12\lambda_3 \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}| &\leq 64\pi\,, && (11h)\\
|2\lambda_1 - \lambda_4| &\leq 16\pi\,, && (11i)\\
|2\lambda_2 - \lambda_3| &\leq 16\pi. && (11j)
\end{aligned}
$$

- **Constraints from electroweak precision test**: The strongest bound comes from the T-parameter which imposes strict limit on the mass splitting between the doubly and singly charged scalars, $\Delta M \equiv\mid m_{H^{\pm\pm}} - m_{H^{\pm}} \mid$ which should be $\lesssim 50$ GeV[4].

[4] E. J. Chun et al.,JHEP11(2012)106

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Here, we will present the one loop RGEs of all the relevant couplings (gauge, Yukawa and scalar quartic couplings) of the Type-II seesaw model[M. A. Schmidt et at, PhysRevD.76.073010]. For convenience, we introduce the shorthand notation $\mathcal{D} \equiv 16\pi^2 \frac{\mathrm{d}}{\mathrm{d}(\ln\mu)}$.

Gauge and top Yukawa couplings: The RGE for the gauge couplings,

$$\mathcal{D}g_1 = \frac{47}{10}{g_1}^3 , \tag{12a}$$

$$\mathcal{D}g_2 = -\frac{5}{2}g_2^3 , \tag{12b}$$

$$\mathcal{D}g_3 = -7g_3^3 . \tag{12c}$$

The RGE for the top Yukawa coupling,

$$\mathcal{D}y_t = y_t\left(\frac{9}{2}y_t^2 - \left(8g_3^2 + \frac{9}{4}g_2^2 + \frac{17}{20}{g_1}^2\right)\right) , \tag{12d}$$

where, $g_1 = \sqrt{\frac{5}{3}}g'$ with GUT renormalization.

Scalar quartic couplings: We express the RGEs of the scalar quartic coupling with a redefinition of the coupling to match with the potential notation of Ref. [?] which can be translated from our notation in the following way.

$$\Lambda_0 = \frac{\lambda}{2}\,, \tag{13a}$$

$$\Lambda_1 = 2\lambda_2 + 2\lambda_3\,, \tag{13b}$$

$$\Lambda_2 = -2\lambda_3\,, \tag{13c}$$

$$\Lambda_4 = \lambda_1 + \frac{\lambda_4}{2}\,, \tag{13d}$$

$$\Lambda_5 = -\frac{\lambda_4}{2}\,. \tag{13e}$$

The RGEs for the five quartic couplings that appear are then given by,

$$\mathcal{D}\Lambda_i = \beta_{\Lambda_i} + G_i\,, (i = 0, 1, 2, 4, 5)\,, \tag{14}$$

where, β_{Λ_i} and G_i are as follows:

$$\beta_{\Lambda_0} = 12\Lambda_0^2 + 6\Lambda_4^2 + 4\Lambda_5^2\,, \tag{15a}$$

$$\beta_{\Lambda_1} = 14\Lambda_1^2 + 4\Lambda_1\Lambda_2 + 2\Lambda_2^2 + 4\Lambda_4^2 + 4\Lambda_5^2\,, \tag{15b}$$

$$\beta_{\Lambda_2} = 3\Lambda_2^2 + 12\Lambda_1\Lambda_2 - 8\Lambda_5^2\,, \tag{15c}$$

$$\beta_{\Lambda_4} = \Lambda_4\left(8\Lambda_1 + 2\Lambda_2 + 6\Lambda_0 + 4\Lambda_4 + 8\Lambda_5^2\right)\,, \tag{15d}$$

$$\beta_{\Lambda_5} = \Lambda_5\left(2\Lambda_1 - 2\Lambda_2 + 2\Lambda_0 + 8\Lambda_4\right)\,, \tag{15e}$$

and,

$$
\begin{aligned}
G_0 &= \left(12y_t^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\right)\Lambda_0 + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2g_2^2 + g_2^4\right) - 12y_t^4\,, &\text{(16a)}\\
G_1 &= -\left(\frac{36}{5}g_1^2 + 24g_2^2\right)\Lambda_1 + \frac{108}{25}g_1^4 + 18g_2^4 + \frac{72}{5}g_1^2g_2^2\,, &\text{(16b)}\\
G_2 &= -\left(\frac{36}{5}g_1^2 + 24g_2^2\right)\Lambda_2 + 12g_2^4 - \frac{144}{5}g_1^2g_2^2\,, &\text{(16c)}\\
G_4 &= \left(6y_t^2 - \left(\frac{9}{2}g_1^2 + \frac{33}{2}g_2^2\right)\right)\Lambda_4 + \frac{27}{25}g_1^4 + 6g_2^4\,, &\text{(16d)}\\
G_5 &= \left(6y_t^2 - \left(\frac{9}{2}g_1^2 + \frac{33}{2}g_2^2\right)\right)\Lambda_5 - \frac{18}{5}g_1^2g_2^2\,. &\text{(16e)}
\end{aligned}
$$

Basic cuts

In our signal and background events, we select jets and leptons using the following basic kinematical acceptance cuts :

$$\Delta R_{jj} > 0.6, \quad \Delta R_{\ell\ell} > 0.4, \quad \Delta R_{j\ell} > 0.7\,, \tag{17a}$$

$$\Delta R_{bj} > 0.7, \quad \Delta R_{b\ell} > 0.2, \tag{17b}$$

$$p^{j}_{T_{\rm min}} > 20 \text{ GeV}, \quad |\eta_j| < 5, \tag{17c}$$

$$p^{\ell}_{T_{\rm min}} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5, \tag{17d}$$

b-jet abiding by the efficiency as proposed by the ATLAS collaboration [?]:

$$\epsilon_b = \begin{cases} 0 & p^b_T \leq 30 \text{ GeV} \\ 0.6 & 30 \text{ GeV} < p^b_T < 50 \text{ GeV} \\ 0.75 & 50 \text{ GeV} < p^b_T < 400 \text{ GeV} \\ 0.5 & p^b_T > 400 \text{ GeV}\ . \end{cases} \tag{18}$$

beamerbackground