LHC phenomenology of the type II seesaw: Observability of neutral scalars in the nondegenerate case

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Type II seesaw introduces a $SU(2)_L$ triplet Δ with hypercharge 2 in addition to SM Higgs doublet Φ

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}, \tag{1}$$

The Yukawa coupling between the scalar triplet and lepton doublets is responsible for neutrino masses:

$$\mathcal{L}_{\rm Yuk} = -Y_{ij}\overline{L^C_{Li}}\left(i\tau^2\right)\Delta L_{Lj} + {\rm h.c.}, \tag{2}$$

The most general potential is given by (1105.1925)

$$\begin{aligned} V(\Phi,\Delta) &= -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_1(\Phi^\dagger\Phi)^2 \\ &+ \lambda_2\left(\mathrm{Tr}(\Delta^\dagger\Delta)\right)^2 + \lambda_3\mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) \\ &+ \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi + \left(\mu\Phi^T i\tau^2\Delta^\dagger\Phi + \mathrm{h.c.}\right), \end{aligned} \tag{3}$$

After SSB, we can separate out the vev's,

$$\phi^0 = \frac{1}{\sqrt{2}}(v + \phi + i\chi), \ \delta^0 = \frac{1}{\sqrt{2}}(v_\Delta + \delta + i\xi), \tag{4}$$

the scalars mix as follows:

$$\begin{pmatrix} \phi^\pm \\ \delta^\pm \end{pmatrix} = R(\theta_+) \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \begin{pmatrix} \chi \\ \xi \end{pmatrix} = R(\alpha) \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}, \begin{pmatrix} \phi \\ \delta \end{pmatrix} = R(\theta_0) \begin{pmatrix} h \\ H^0 \end{pmatrix}$$

Here $R(\omega)$ is the standard rotation matrix in the plane, and the mixing angles are given by

$$\tan\theta_+ = \frac{\sqrt{2}v_\Delta}{v}, \tan\alpha = \frac{2v_\Delta}{v}, \tan 2\theta_0 = \frac{v_\Delta}{v} \frac{2v^2(\lambda_4 + \lambda_5) - 4M_\Delta^2}{2v^2\lambda_1 - M_\Delta^2 - v_\Delta^2(\lambda_2 + \lambda_3)}$$

In the limit $v_\Delta \ll v$, scalars have the masses approximately

$$M^2_{H^{\pm\pm}} \approx M^2_\Delta - \frac{1}{2}\lambda_5 v^2 \quad , \quad M^2_{H^\pm} \approx M^2_\Delta - \frac{1}{4}\lambda_5 v^2, \tag{5}$$

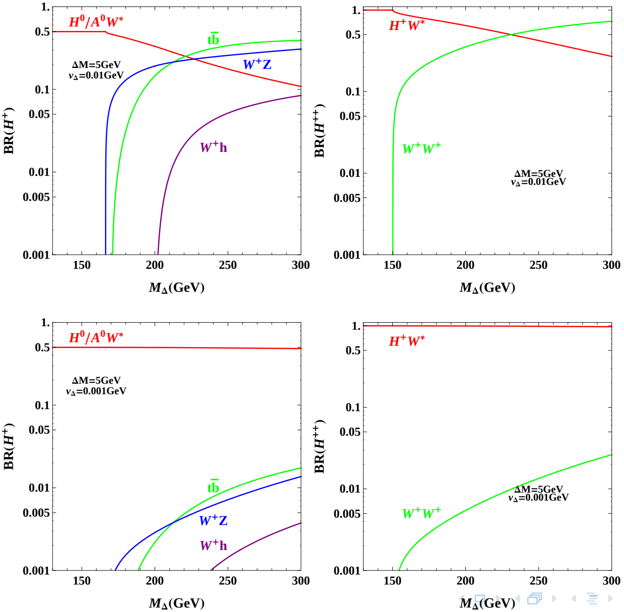
$$M^2_{H^0} \approx M^2_{A^0} \approx M^2_\Delta \quad , \quad M^2_h \approx 2\lambda_1 v^2 \tag{6}$$

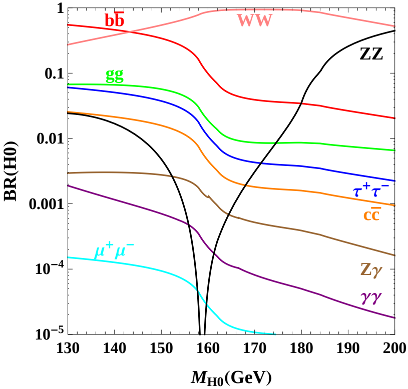
The triplet scalars are equidistant in masses squared to good approximation:

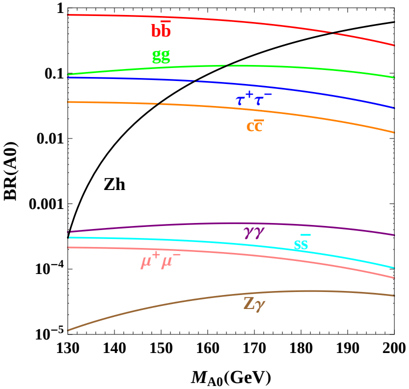
$$M^2_{H^{\pm\pm}} - M^2_{H^\pm} \approx M^2_{H^\pm} - M^2_{H^0/A^0} \approx -\frac{1}{4}\lambda_5 v^2, \tag{7}$$

Define the mass splitting as $\Delta M = M_{H^\pm} - M_{H^0}$, and EWPT require $|\Delta M| < 40~\mathrm{GeV}$ (1209.1303). Two scenarios for nondegenerate case:

$$\begin{aligned} \text{positive scenario } (\lambda_5 > 0) &: M_{H^{\pm\pm}} < M_{H^\pm} < M_{H^0/A^0}, \\ \text{negative scenario } (\lambda_5 < 0) &: M_{H^{\pm\pm}} > M_{H^\pm} > M_{H^0/A^0}. \end{aligned} \tag{8}$$

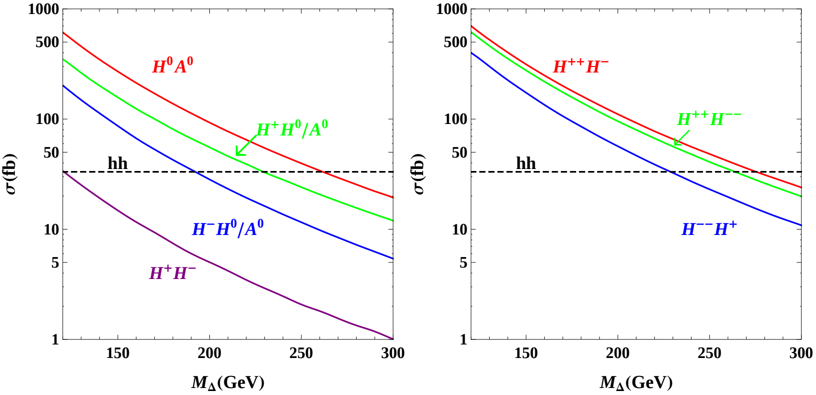

H^0/A^0W^*
$t\bar{b}$
W^+Z
W^+h
ΔM=5GeV
v_Δ=0.01GeV
$BR(H^+)$
M_Δ(GeV)
H^+W^*
W^+W^+
$BR(H^{++})$
ΔM=5GeV
v_Δ=0.001GeV
1.
0.5
0.1
0.05
0.01
0.005
0.001
150
200
250
300





at benchmark point:

$$v_\Delta = 0.001 \text{ GeV}, \ \Delta M = 5 \text{ GeV}, \ \lambda_2 = \lambda_3 = 0.1, \ \lambda_4 = 0.25. \quad (9)$$



Production cross sections for a pair of scalars at LHC14 versus M_Δ for a degenerate spectrum. The black dashed line is for the SM *hh* production.

Reference cross section,independent on the cascade decay parameters:

$$X_0 = \sigma(pp \to Z^* \to H^0 A^0) \tag{10}$$

$H^\pm \psi^0$ is the first mechanism with cascade decays, which involves four process:

$$\begin{aligned} H^\pm H^0 \to H^0 H^0 W^* \quad &, \quad H^\pm H^0 \to A^0 H^0 W^* \\ H^\pm A^0 \to H^0 A^0 W^* \quad &, \quad H^\pm A^0 \to A^0 A^0 W^* \end{aligned} \tag{11}$$

Three kinds of final state with neutral Higgs-pair: H^0H^0, A^0H^0, and A^0A^0, where H^0H^0 and A^0A^0 pair production can only raise from cascade decays of $H^\pm$ in the negative scenario.

Using the fact that

$$\sigma(pp \to W^* \to H^\pm H^0) \simeq \sigma(pp \to W^* \to H^\pm A^0) \quad (12)$$
$$\mathrm{BR}(H^\pm \to H^0 W^*) \simeq \mathrm{BR}(H^\pm \to A^0 W^*) \quad (13)$$

we can calculate the production cross section of these three final states:

$$H^0A^0 : X_1 = 2[\sigma(pp \to H^\pm H^0)] \times \mathrm{BR}(H^\pm \to A^0 W^*) \quad (14)$$
$$H^0H^0 : Y_1 = [\sigma(pp \to H^\pm H^0)] \times \mathrm{BR}(H^\pm \to H^0 W^*) \quad (15)$$
$$A^0A^0 : Z_1 = [\sigma(pp \to H^\pm A^0)] \times \mathrm{BR}(H^\pm \to A^0 W^*) \quad (16)$$

A more general relation:

$$X_i = 2Y_i = 2Z_i, \ (i = 1, 2, 3, 4) \quad (17)$$

The second mechanism is H^+H^-.

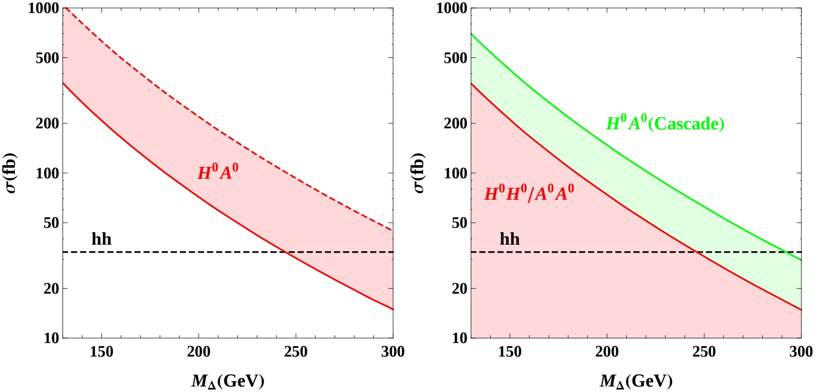
$$X_2 = 2\sigma(pp \to H^+H^-) \times \mathrm{BR}(H^\pm \to H^0W^*)\mathrm{BR}(H^\pm \to A^0W^*) \quad (18)$$

The third mechanism is $H^\pm H^{\mp\mp}$.

$$\begin{aligned} X_3 &= 2[\sigma(pp \to H^\pm H^{\mp\mp})] \times \mathrm{BR}(H^{\pm\pm} \to H^\pm W^*) \quad (19) \\ &\quad \mathrm{BR}(H^\pm \to H^0W^*)\mathrm{BR}(H^\pm \to A^0W^*) \end{aligned}$$

The forth mechanism is $H^{++}H^{--}$.

$$\begin{aligned} X_4 &= 2\sigma(pp \to H^{++}H^{--}) \times \mathrm{BR}(H^{\pm\pm} \to H^\pm W^*)^2 \\ &\quad \times \mathrm{BR}(H^\pm \to H^0W^*)\mathrm{BR}(H^\pm \to A^0W^*) \quad (20) \end{aligned}$$



$$\sigma(H^0A^0) = X = \sum X_i, i = 0...4;\ \sigma(H^0H^0) = Y = \sum Y_i, i = 1...4;$$
$$\sigma(A^0A^0) = Z = \sum Z_i, i = 1...4.$$

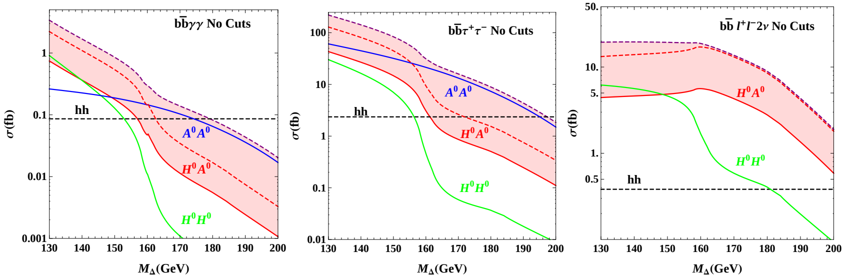
Signal rate

For instance, the cross section of $b\bar{b}\gamma\gamma$ is

$$\begin{aligned} S_0(b\bar{b}\gamma\gamma) &= X_0 \times [\text{BR}(H^0 \to b\bar{b})\text{BR}(A^0 \to \gamma\gamma) \\ &\quad + \text{BR}(H^0 \to \gamma\gamma)\text{BR}(A^0 \to b\bar{b})] \qquad (21) \end{aligned}$$

$$\begin{aligned} S(b\bar{b}\gamma\gamma) &= X \times [\text{BR}(H^0 \to b\bar{b})\text{BR}(A^0 \to \gamma\gamma) \\ &\quad + \text{BR}(H^0 \to \gamma\gamma)\text{BR}(A^0 \to b\bar{b})] \\ &+ 2Y \times \text{BR}(H^0 \to b\bar{b})\text{BR}(H^0 \to \gamma\gamma) \\ &+ 2Z \times \text{BR}(A^0 \to b\bar{b})\text{BR}(A^0 \to \gamma\gamma) \qquad (22) \end{aligned}$$

S_0 corresponds to degenerate scenario, and S corresponds to negative scenario. The cascade enhance factor E_h is therefor S/S_0.


bb̄γγ No Cuts
σ(fb)
1
0.1
0.01
0.001
hh
A0A0
H0A0
H0H0
130 140 150 160 170 180 190 200
MΔ(GeV)
bb̄τ+τ− No Cuts
100
10
1
0.1
0.01
hh
A0A0
H0A0
H0H0
130 140 150 160 170 180 190 200
MΔ(GeV)
bb̄ l+l−2ν No Cuts
50.
10.
5.
1.
0.5
hh
H0A0
H0H0
130 140 150 160 170 180 190 200
MΔ(GeV)

The signature is:

$$pp \to \varphi^0\varphi^0 + X \to b\bar{b}\gamma\gamma + X \quad (23)$$

where $\varphi^0 = H^0, A^0$. The main SM backgrounds we taking into account are:

$$b\bar{b}\gamma\gamma : pp \to b\bar{b}\gamma\gamma \quad (24)$$

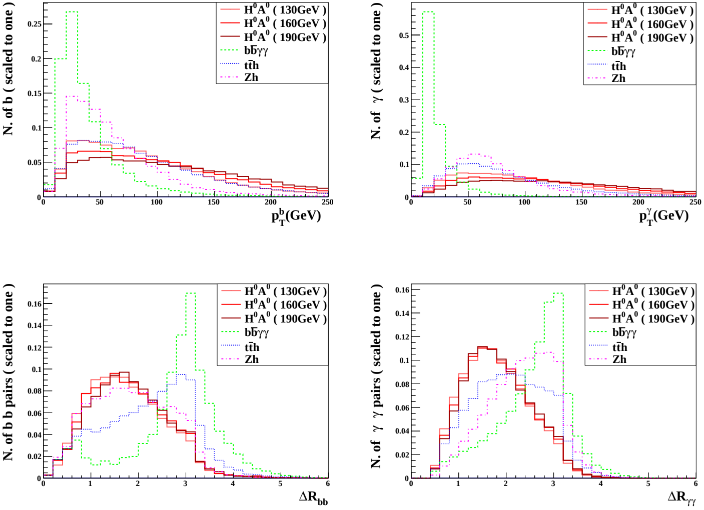
$$t\bar{t}h : pp \to t\bar{t}h \to b\ell^+\nu\,\bar{b}\ell^-\nu\,\gamma\gamma(\ell^\pm \text{ missed}) \quad (25)$$

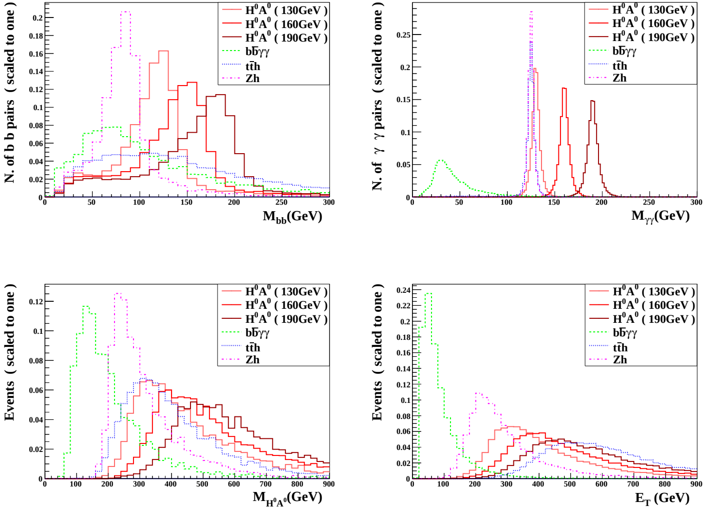
$$Zh : pp \to Zh \to b\bar{b}\gamma\gamma \quad (26)$$

Fake $b\bar{b}\gamma\gamma$ signals:

$$pp \to b\bar{b}jj \to b\bar{b}\gamma\gamma, pp \to b\bar{b}j\gamma \to b\bar{b}\gamma\gamma, \ldots \quad (27)$$

$\varepsilon_b = 0.7$,$\varepsilon_{c\to b} = 0.1$,$\varepsilon_{j\to b} = 0.01$, $\varepsilon_{j\to\gamma} = 1.2\times 10^{-4}$.


N. of b (scaled to one)
p_T^b(GeV)
N. of γ (scaled to one)
p_T^γ(GeV)
N. of b b pairs (scaled to one)
ΔR_{bb}
N. of γ γ pairs (scaled to one)
$\Delta R_{\gamma\gamma}$
H^0A^0 (130GeV)
H^0A^0 (160GeV)
H^0A^0 (190GeV)
$b\bar{b}\gamma\gamma$
$t\bar{t}h$
Zh


N. of b b pairs (scaled to one)
M_bb(GeV)
N. of γ γ pairs (scaled to one)
M_γγ(GeV)
Events (scaled to one)
M_H0A0(GeV)
Events (scaled to one)
E_T (GeV)
H0A0 (130GeV)
H0A0 (160GeV)
H0A0 (190GeV)
bb̄γγ
tt̄h
Zh

Basic cuts:

$$p_T^b > 30\ \text{GeV},\ p_T^\gamma > 30\ \text{GeV},\ |\eta_{b/\gamma}| < 2.4 \tag{28}$$
$$\Delta R_{bb} > 0.4,\ \Delta R_{\gamma\gamma} > 0.4,\ \Delta R_{b\gamma} > 0.4$$

Reproduce the neutral Higgs boson from b and γ:

$$\Delta R_{bb} < 2.5, \qquad |M_{bb} - M_\Delta| < 15\ \text{GeV} \tag{29}$$
$$\Delta R_{\gamma\gamma} < 2.5, \qquad |M_{\gamma\gamma} - M_\Delta| < 10\ \text{GeV}$$

Additional cuts:

$$M_{H^0A^0} > 2M_\Delta + 90\ \text{GeV},\ E_T > 2M_\Delta - 60\ \text{GeV} \tag{30}$$

H^0A^0(130GeV)	$b\bar{b}\gamma\gamma$	$t\bar{t}h$	Zh	$\mathcal{S}(S,B)$
8.01×10^{-1}	5.92×10^{3}	1.18	2.99×10^{-1}	5.75×10^{-1}
6.99×10^{-2}	7.07	1.50×10^{-2}	9.61×10^{-4}	1.44
5.28×10^{-2}	1.03×10^{-1}	1.08×10^{-2}	7.32×10^{-4}	8.01
4.21×10^{-2}	2.04×10^{-2}	4.69×10^{-3}	3.23×10^{-4}	1.20×10^{1}
3.31×10^{-2}	6.58×10^{-3}	4.68×10^{-3}	2.27×10^{-4}	1.28×10^{1}
1.51×10^{-1}	$--$	$--$	$--$	4.10×10^{1}
H^0A^0(160GeV)	$b\bar{b}\gamma\gamma$	$t\bar{t}h$	Zh	$\mathcal{S}(S,B)$
5.10×10^{-2}	5.92×10^{3}	1.18	2.99×10^{-1}	3.63×10^{-2}
4.11×10^{-3}	5.06	1.34×10^{-2}	2.36×10^{-4}	9.99×10^{-2}
3.27×10^{-3}	3.42×10^{-2}	1.57×10^{-5}	0.00	9.53×10^{-1}
2.57×10^{-3}	1.12×10^{-2}	1.18×10^{-5}	0.00	1.28
1.73×10^{-3}	3.95×10^{-3}	1.03×10^{-5}	0.00	1.41
1.10×10^{-2}	$--$	$--$	–	7.29

Table: Cross sections (in fb) at LHC 14 TeV for the $b\bar{b}\gamma\gamma$ with $L_{int} = 3000\text{fb}^{-1}$.

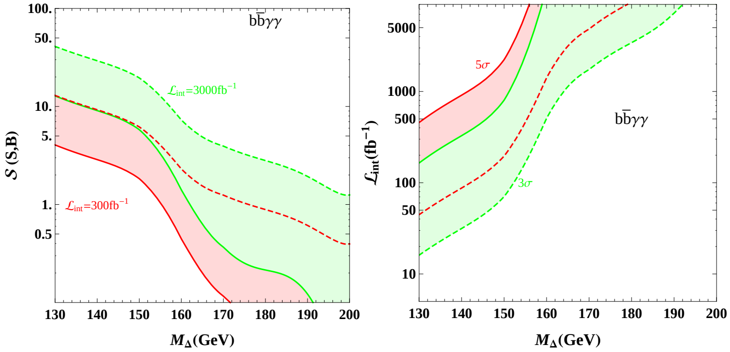


Figure: The solid line corresponds to the signal from S_0 alone, and the dashed line corresponds to the total signal S.

Conclusion

- Scalar interaction λ_i has great impact on the decays of H^0/A^0. $H^0 \to W^+W^-$ can be dominant when $M_{H^0} < 2M_h$.
- Cascade decays of $H^{\pm\pm}$ and $H^{\pm}$ contribute to the production of φ^0. The enhance factor can reach about 3.
- Production of $\varphi^0\varphi^0$ for $M_{\varphi^0} < 200~\mathrm{GeV}$ is much larger than hh.
- Signatures as $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}W^+W^-$ are in the reach of LHC.