LHC phenomenology of type II seesaw: nondegenerate case

Z. L. Han, R. Ding and Y. Liao

School of Physics, Nankai University

Based on 1502.05242 and 1506.08996
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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:

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

The most general potential is given by (1105.1925)

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

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

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

$$M^2_{H^0} \approx M^2_{A^0} \approx M^2_\Delta \quad , \quad M^2_h \approx 2\lambda_1 v^2 \tag{5}$$

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

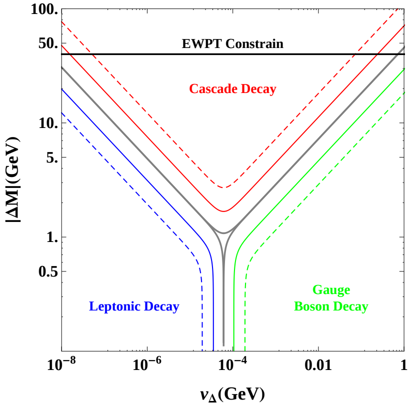
$$M^2_{H^{\pm\pm}} - M^2_{H^\pm} \approx M^2_{H^\pm} - M^2_{H^0/A^0} \approx -\frac{1}{4}\lambda_5 v^2, \tag{6}$$

Two scenarios for nondegenerate case:

$$\begin{aligned} \text{positive scenario } (\lambda_5 > 0) &: M_{H^{\pm\pm}} < M_{H^\pm} < M_{H^0/A^0}, \\ \text{negative scenario } (\lambda_5 < 0) &: M_{H^{\pm\pm}} > M_{H^\pm} > M_{H^0/A^0}. \end{aligned} \tag{7}$$

Define the mass splitting as $\Delta M = M_{H^{\pm\pm}} - M_{H^\pm}$, and EWPT require $|\Delta M| < 40\ \mathrm{GeV}$ (1209.1303).

Generic Decay Phase (1108.4416)



The dashed, thin solid, and thick solid lines correspond to a branching ratio of 99%, 90%, and 50%, respectively.

Decay Properties of Triplet Scalar

Degenerate scenario (0805.3536):

$$H^{\pm\pm} \to l^\pm l^\pm, W^\pm W^\pm \quad , \quad H^\pm \to l^\pm \nu, W^\pm h, W^\pm Z, t\bar{b} \quad (8)$$
$$H^0 \to \nu\nu, b\bar{b}, hh, ZZ, t\bar{t} \quad , \quad A^0 \to \nu\nu, b\bar{b}, Zh, t\bar{t} \quad (9)$$

Positive scenario (1105.2209,1502.05242):

$$H^{\pm\pm} \to l^\pm l^\pm, W^\pm W^\pm \quad , \quad H^\pm \to H^{\pm\pm} W^{\mp *} \quad (10)$$
$$H^0 \to H^\pm W^{\mp *} \quad , \quad A^0 \to H^\pm W^{\mp *} \quad (11)$$

Negative scenario (1110.4625,1502.05242):

$$H^{\pm\pm} \to H^\pm W^{\pm *} \quad , \quad H^\pm \to H^0 W^{\pm *}, A^0 W^{\pm *} \quad (12)$$
$$H^0 \to \nu\nu, b\bar{b}, hh, ZZ, t\bar{t} \quad , \quad A^0 \to \nu\nu, b\bar{b}, Zh, t\bar{t} \quad (13)$$

In positive scenario, four-lepton signal is still the most promising:

$$pp \to H^{++}H^{--} \to l^+l^+ + l^-l^- \tag{14}$$

which is extensively studied (0706.0441,0808.2468).
$*$ To probe mass deference, we consider the five-lepton signal coming from $H^{\pm\pm}H^{\mp}$ associated production:

$$pp \to H^{\pm\pm}H^{\mp} \to H^{\pm\pm} + H^{\mp\mp}W^{\pm *} \to \ell^{\pm}\ell^{\pm} + \ell^{\mp}\ell^{\mp} + \ell^{\pm}\not{E}_T \tag{15}$$

$M_{H^{\pm\pm}} = 400\ \mathrm{GeV}$, $M_{H^{\pm}} = 430\ \mathrm{GeV}$,$M_{\psi^0} = 458\ \mathrm{GeV}$ at 14 TeV LHC with $\mathcal{L}_{int} = 300\ \mathrm{fb}^{-1}$. The five-lepton signal can also originate from $H^{\pm}H^0$, $H^{\pm}A^0$ and H^0A^0 associated production (1105.2209). The main SM background is

$$ZZW^{\pm} \to \ell^+\ell^- + \ell^+\ell^- + \ell^{\pm}\not{E}_T. \tag{16}$$

Cuts applied by ATLAS (1412.0237):

$$p_T^\mu > 20\mathrm{GeV}, p_T^e > 25\mathrm{GeV}, \Delta R_{\ell\ell} > 0.4 \tag{17}$$

$$M_{\ell^\pm\ell^\pm} > 15\mathrm{GeV} \tag{18}$$

$$70 < M_{e^\pm e^\pm} < 110\mathrm{GeV}\ (Z\,\mathrm{veto}) \tag{19}$$

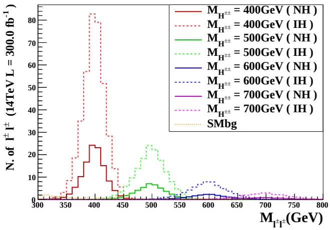
We also veto events with $M_{\ell^\pm\ell^\pm} < 300\mathrm{GeV}$.

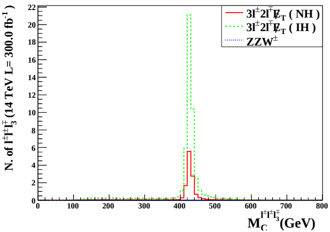
	Pre-selection	Post-selection	$S/\sqrt{S+B}$	S/B
NH	40.5	27.2	4.73	4.63
IH	154	104	9.92	17.7
$ZZW^\pm$	9.00	5.87	—	—

Reconstruct $M_{H^\pm}$ with cluster mass:

$$M_C^{\ell^\pm\ell^\pm\ell_3^\mp} = \sqrt{\left(\sqrt{p^2_{T,\ell^\pm\ell^\pm\ell_3^\mp} + M^2_{\ell^\pm\ell^\pm\ell_3^\mp}} + \not{E}_T\right)^2 - \left(\vec{p}_{T,\ell^\pm\ell^\pm\ell_3^\mp} + \vec{\not{E}}_T\right)^2}$$

Reconstruct Scalar Masses





* Six-lepton signal from $H^\pm H^0/A^0$:

$$H^\pm\psi^0 \to H^{\pm\pm}W^{\mp *}W^{\pm *}W^{\pm *}H^{\mp\mp} \to \ell^\pm\ell^\pm jj + \ell^\pm\ell^\pm \not{E}_T \ell^\mp\ell^\mp \quad (20)$$

$$H^\pm\psi^0 \to H^{\pm\pm}W^{\mp *}W^{\mp *}W^{\mp *}H^{\pm\pm} \to \ell^\pm\ell^\pm jj + \ell^\mp\ell^\mp \not{E}_T \ell^\pm\ell^\pm \quad (21)$$

where $\psi^0 = H^0/A^0$. According to our simulation, it is challenging at LHC.

In negative scenario, $H^{\pm\pm}$ is the heaviest. We consider:

$$pp \to H^{\pm\pm}H^{\mp} \to W^{\pm *}W^{\pm *}\psi^0 + \psi^0 W^{\mp *} \to \ell^{\pm}\ell^{\pm}\not{E}_T b\bar{b} + b\bar{b}(jj).$$

with $M_{H^{\pm\pm}} = 185\ \mathrm{GeV}, M_{H^{\pm}} = 160\ \mathrm{GeV}, M_{H^0,A^0} = 130\ \mathrm{GeV}$.
It could reach 4σ significance at 14TeV LHC with $300\mathrm{fb}^{-1}$.
⋆ For $H^{\pm}$, a promising channel would be:

$$\text{SG:} \quad H^{\pm}\psi^0 \to W^{\pm *}\psi^0\psi^0 \to \ell^{\pm}\not{E}_T + b\bar{b}b\bar{b} \quad (22)$$

$$\text{BG:} \quad t\bar{t} \to W^{+}bW^{-}\bar{b} \to \ell^{\pm}\not{E}_T + b\bar{b}jj, \quad (23)$$

$$t\bar{t}b\bar{b} \to \ell^{\pm}\not{E}_T + b\bar{b}b\bar{b} + (jj/\ell^{\mp}), \quad (24)$$

$$W^{\pm}b\bar{b}b\bar{b} \to \ell^{\pm}\not{E}_T + b\bar{b}b\bar{b} \quad (25)$$

b-tagging efficiency is assumed to be 0.7, and the misidentification rate of a *c*- and light-jet as a *b*-jet is taken to be 0.1 and 0.01 respectively.

Basic cuts:

$$\begin{aligned} p_T^\ell &> 10\ \mathrm{GeV},\ |\eta_\ell| < 2.5, \\ p_T^j &> 20\ \mathrm{GeV},\ |\eta_j| < 2.5, \\ \Delta R_{j\ell} &> 0.4,\ \Delta R_{jj} > 0.4. \end{aligned} \tag{26}$$

To suppress the BG, we require $4b$ jets in our signal.
Selection cuts:

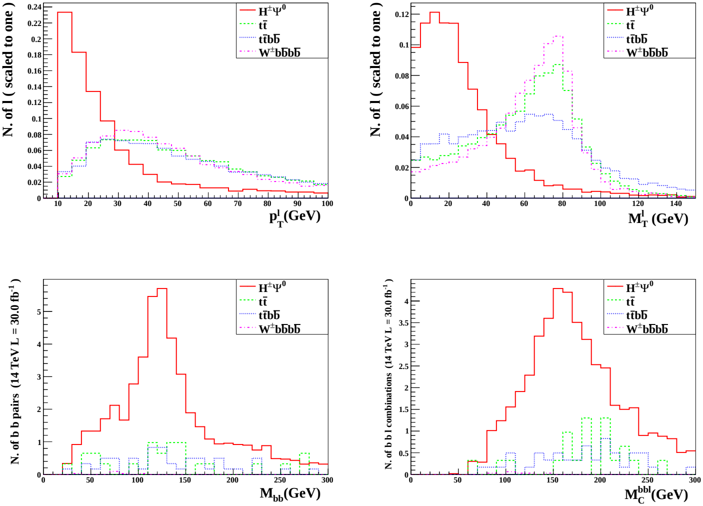
$$\not{E}_T < 30\ \mathrm{GeV},\ p_T^\ell < 30\ \mathrm{GeV}, \tag{27}$$

$$M_T^\ell < 30\ \mathrm{GeV}, \Delta R_{b\ell} < 2.0. \tag{28}$$

Reconstruct $M_{H^\pm}$ with cluster mass:

$$M_C^{bb\ell} = \sqrt{\left(\sqrt{p_{T,bb\ell}^2 + M_{bb\ell}^2} + \not{E}_T\right)^2 - \left(\vec{p}_{T,bb\ell} + \vec{\not{E}}_T\right)^2} \tag{29}$$

Negative scenario



$H^{\pm}\psi^0$	$t\bar{t}$	$t\bar{t}b\bar{b}$	$W^{\pm}b\bar{b}b\bar{b}$	$S/\sqrt{S+B}$	S/B
567	2039202	162410	1295	0.373	0.000256
22.2	317	218	3.45	0.940	0.0412
18.4	69.6	53.7	0.488	1.54	0.148
10.6	5.53	3.80	0.0916	2.37	1.13
9.00	1.63	1.98	0.0305	2.53	2.47
8.94	1.30	1.32	0.0305	2.63	3.37

at 14TeV LHC with $30\mathrm{fb}^{-1}$. A 5σ discovery needs $109\mathrm{fb}^{-1}$.
$\star$ For the lightest H^0, A^0, there are also promising signals as (1506.08996):

$$H^0A^0 \to b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-, b\bar{b}W^+W^- \qquad (30)$$

Conclusion

In positive scenario:

- Four-lepton signal is the most promising signature to detect $H^{\pm\pm}$
- Five-lepton signal is crucial to determine the spectrum of triplet scalars.
- Six-lepton signal is not promising.

In negative scenario:

- $H^{\pm\pm}$ is hard to detect in this scenario.
- $H^{\pm}H^0/A^0 \to l^{\pm}\not{E}_T + 4b$ is promising for light scalars. Both $M_{H^{\pm}}$ and M_{H^0/A^0} can be reconstructed.
- H^0A^0 has same signals as SM Higgs pair production hh.