Probing Higgs in Type III Seesaw at the Large Hadron Collider

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Plan

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2. Seesaw Mechanism
3. Type III Seesaw
4. Triplet fermions and Decay modes
5. Phenomenology at the LHC
    - 2b + 3l
    - 2b + SSD
6. Conclusion

Neutrino Mass Dirac & Majorana

If neutrinos are of only Dirac type

$\Rightarrow$ Possible mass term is $y_\nu L H \nu$

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Is there other way to get small neutrino mass?

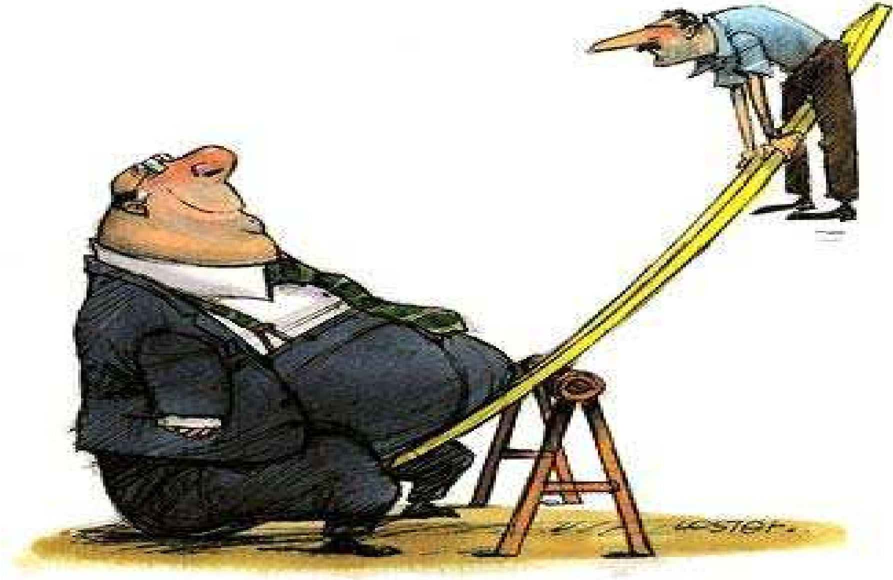
If neutrinos are Majorana !

Majorana Neutrino

1. $\nu^c = \nu$, self-conjugate under the charge conjugation.
2. We can have a mass term

$$-\mathcal{L} = \frac{1}{2} m_L \overline{(\psi_L)^c} \psi_L + \frac{1}{2} m_R \overline{(\psi_R)^c} \psi_R + h.c$$

3. This kind of mass can be naturally generated by Seesaw Mechanism.



Seesaw Mechanism

- Seesaw mechanism is one where the smallness of neutrino mass is explained by a large scale.
- There are different versions of this seesaw mechanism but have a basic structure:

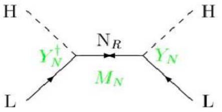
$$M_\nu \simeq \frac{<v>^2}{M_{\mathrm{seesaw}}} \simeq \frac{\mathrm{MeV}^2}{\mathrm{TeV}} \approx \mathrm{eV}$$

- Introduces two scales: very high scale and a moderate scale to get the very small scale.

The 3 basic seesaw models

→ i.e. tree level ways to generate the dim 5 operator

Right-handed singlet:
(type-I seesaw)

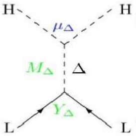


↓

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida; Glashow; Mohapatra, Senjanovic

Scalar triplet:
(type-II seesaw)

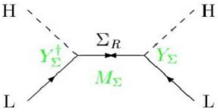


↓

$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet:
(type-III seesaw)



↓

$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy; T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Type III Seesaw Mechanism

- $SU(2)_L$ triplet fermions with $Y = 0$, $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$. The matrix form of the triplet;

  $$\mathbf{\Sigma} = \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

  where Σ^+ is the antiparticle state of Σ^-: $\Sigma^+ \equiv (\Sigma^-)^c$.
- Then the gauge invariant Yukawa terms are

  $$\mathcal{L} = \left[y_i H \varepsilon \bar{\mathbf{\Sigma}} P_L l_i + h.c.\right] + \frac{1}{4}\mathrm{Tr}\left[\bar{\mathbf{\Sigma}}\mathbf{\Sigma}\right]$$

  where l_i is the lepton doublet and H is the Higgs doublet: $l = (\nu_i, e_i)_L$ and $H = (H^+, H^0)$.

Neutrino mass and mixing

- The neutrinos get a seesaw mass
  $$m_{\nu,ij} \sim y_i y_j v^2/M$$
  which becomes $\mathcal{O} \sim 0.1$ eV for $y_i \sim 10^{-6}$ and $M \sim 1$ TeV.
- The neutrino Dirac mass, $y_i v$, induces mixing between l and Σ.
- The mixing angles for the neutral and charged part are
  $$\theta_{\nu_i} \approx \frac{y_i v}{M} \quad \text{and} \quad \theta_{l_i} \approx \sqrt{2}\frac{y_i v}{M}$$
  respectively.

Gauge interaction

- Due to the l–Σ mixing, we get the mixed gauge interaction as follows;

$$
\begin{aligned}
\mathcal{L}_{mixed} \quad = \quad & -g\theta_{\nu_i} W_\mu^+ \left[\frac{1}{\sqrt{2}} \bar{\Sigma}^0 \gamma^\mu P_L e_i + \bar{\nu}_i \gamma^\mu R_R \Sigma^- \right] \\
& -g\theta_{\nu_i} W_\mu^- \left[\frac{1}{\sqrt{2}} \bar{e}_i \gamma^\mu P_L \Sigma^0 + \bar{\Sigma}^- \gamma^\mu P_R \nu_i \right] \\
& + \frac{g\theta_{\nu_i}}{2c_W} Z_\mu \left[\sqrt{2} \bar{\Sigma}^- \gamma_\mu P_L e_i + \sqrt{2} \bar{e}_i \gamma^\mu P_L \Sigma^- - \bar{\Sigma}^0 \gamma^\mu \gamma_5 \nu_i \right]
\end{aligned}
$$

Phenomenology

- Thus, we have the electroweak production of the triplets at the LHC,

$$pp \to \Sigma^{\pm}\Sigma^{0}, \quad \Sigma^{\pm}\Sigma^{\mp}$$

- The triplet decays as follows:

$$\begin{aligned} \Sigma^{\pm} &\to l^{\pm}h \\ &\to l^{\pm}Z^{0} \\ &\to \nu W^{\pm} \\ &\to \Sigma^{0}\pi^{\pm} \end{aligned} \qquad \begin{aligned} \Sigma^{0} &\to \nu h \\ &\to \nu Z^{0} \\ &\to l^{\pm}W^{\mp} \end{aligned}$$

- We can see the final states with multi-leptons could be interesting.[1]

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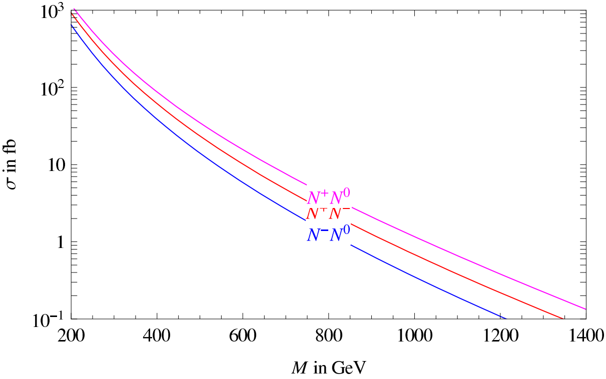
[1] Aguila08

Cross-section of the triplet fermions @ 14 TeV LHC



Cross-section is very low for higher triplet mass[2].

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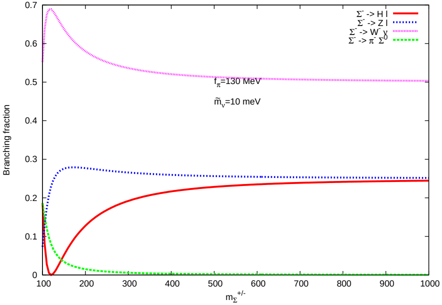
[2] Hambye et al. 08, Aguila et al. 08

Decay branching of the triplet fermions



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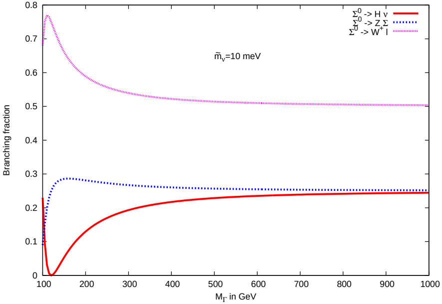
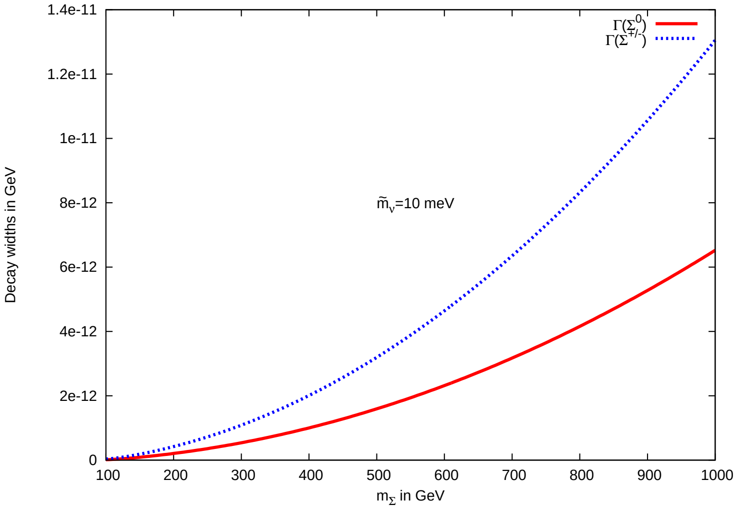
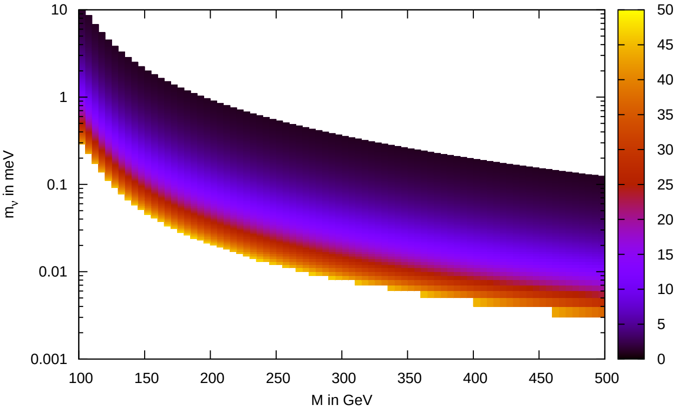


Decay widths of the triplet fermions



Decay length of the triplet fermions



Benchmark Points for the collider simulation

- For the collider simulation we took $m_\Sigma = 250, 400$ GeV and $\tilde{m} = 10$ meV as benchmark points

Production cross-sections (fb)		
m_Σ	250 GeV	400 GeV
$\Sigma^+\Sigma^0$	439.1	73.8
$\Sigma^+\Sigma^-$	320.0	50.0
$\Sigma^-\Sigma^0$	221.8	32.3

Table: Production cross-sections for the benchmark points.

Decay branching fraction for the Benchmark Points

Decay modes	Branching fractions	
m_Σ	250 GeV	400 GeV
$\Sigma^0 \to h\nu$	0.17	0.22
$\Sigma^0 \to Z\nu$	0.27	0.26
$\Sigma^0 \to W^\pm l^\mp$	0.56	0.52
$\Sigma^\pm \to hl^\pm$	0.17	0.22
$\Sigma^\pm \to Zl^\pm$	0.27	0.26
$\Sigma^\pm \to W^\pm \nu$	0.55	0.52
$\Sigma^\pm \to \Sigma^0 \pi^\pm$	0.009	0.003

Table: Branching fractions for the triplets with $\tilde{m}_\nu = 10$ meV.

Final state topologies for collider simulation

- Dominant decay modes are final states with Higgs and/or Gauge bosons associated with leptons.
- Higgs searches with multi-lepton final state could be interesting.
- We analyse all plausible leptonic final states.
- Here we discuss only $2b + 3l$ and $2b + SSD$ at the LHC at 14 TeV.

Collider simulation

- We generate the events with MadGraph
- Generated events thus interfaced with PYTHIA via LHEF
- Hadronization, ISR/FSR effects and Jet formation (PYCELL) are done inside PYTHIA
- `CTEQ6L` is used parton distribution function (PDF)
- The renormalization/factorization scale is set at $\sqrt{\hat{s}}$.

Status of $2b + 3l$ @14TeVLHC

- Typically $hlZl$,$hlWl$,$ZlZl$,$ZlWl$ dominantly contribute to the final state.
- In particular final state with Higgs, i.e., $hlZl$,$hlWl$ are interesting.
- b pair can come from h and Z
- Strategically we try to construct $2b + 3l$ final state
- Invariant mass of b-jet pair could give the Higgs peak we are interested in
- Invariant mass of $b - b - l$ where b-jets are from the Z and h window can give rise to Σ mass peak.

Status of $2b + 3l$ @14TeVLHC

- With the ISR/FSR, jet formation and b mis-tagging other decay modes also could contribute.
- We define the signal by following cuts:
    - $p_{T,min}^{jet} = 20$ GeV and jets are ordered in p_T
    - leptons $(\ell = \mathrm{e},\ \mu)$ are selected with $p_T \geq 20$ GeV and $|\eta| \leq 2.5$
    - no jet should match with a hard lepton in the event $(\Delta R_{j,l} \geq 0.4,\ \Delta R_{l,l} \geq 0.2)$
- Considering the b and lepton final state the main SM backgrounds are: $t\bar{t},\ t\bar{t}Z,\ t\bar{t}W, t\bar{t}h,\ t\bar{t}b\bar{b}, WW, ZZ, WZ$

$\geq 2b + \geq 3l$

- The numbers for the signal and the background for the final topology $\geq 2b + \geq 3l$

$2b-\mathrm{jet}+3\mathrm{l}$							
Signal		Backgrounds					
BP1	BP2	$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	VV	$t\bar{t}W$
116.89	40.32	5.0	1.77	31.53	9.86	0.0	8.67

- The dominant background is $t\bar{t}Z$ as expected

Higgs peak in $2b + 3l$ final state

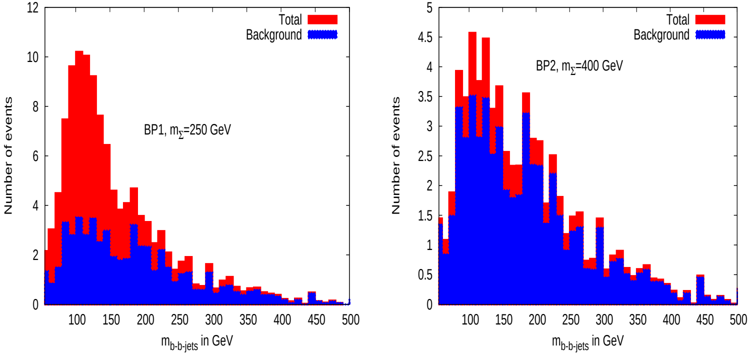


Figure: Invariant mass distributions of b-jet pair from $\geq 2b + \geq 3l$ final states for BP1, BP2 and SM background.

Higgs peak in $2b + 3l$ final state

- The number of events in the window $95\mathrm{GeV} \leq \mathrm{m_{b-b}} \leq 145\mathrm{GeV}$

$95\mathrm{GeV} \leq \mathrm{m_{b-b}} \leq 145\mathrm{GeV}$							
Signal		Backgrounds					
BP1	BP2	$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	VV	$t\bar{t}W$
28.44	4.46	1.0	0.50	8.3	2.2	0.0	2.5

Sigma peak in $2b + 3l$ final state

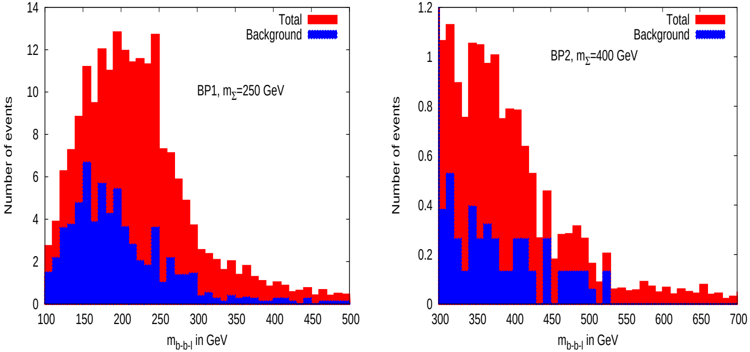


Figure: Invariant mass distributions of b-jet pair plus a charge lepton from $\geq 2b + 3l$ final state for BP1, BP2 and SM background.

Sigma peak in $2b + 3l$ final state

- The number of events in the window m_{b-b-l} within $250(400) \pm 50$ GeV.

m_{b-b-l}							
Signal		Backgrounds					
		$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	VV	$t\bar{t}W$
BP1	61.89	2.0	0.1	5.9	1.5	0.0	0.9
BP2	5.19	0.0	0.0	1.5	0.06	0.0	0.5

Results for $2b + 3l$ final state

- For $\geq 2b + \geq 3l$ at 10 fb^{-1} integrated luminosity the reach for BP1 is $\sim 9\sigma$, where as for BP2 $\sim 4\sigma$
- Higgs peak reconstructed with m_{bb} a 5σ signal significance for BP1 will require 13 fb^{-1} integrated luminosity and for BP2, couple of 100 fb^{-1}.
- m_{bbl} at 10 fb^{-1} integrated luminosity the reach for BP1 is $\sim 7\sigma$
- Thus the significance drops very fast as we increase the triplet mass.
- Harder lepton p_T cuts and lepton invariant mass veto cut near Z peak will reduce the background further.

Status of $2b+$ Same-sign di-lepton

$\geq 2b-\mathrm{jet}+\mathrm{SSD}$							
Signal		Backgrounds					
BP1	BP2	$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	VV	$t\bar{t}W$
127.38	29.09	24.0	7.5	41.6	29.0	0.0	41.4

Status of $2b+$ Same-sign di-lepton

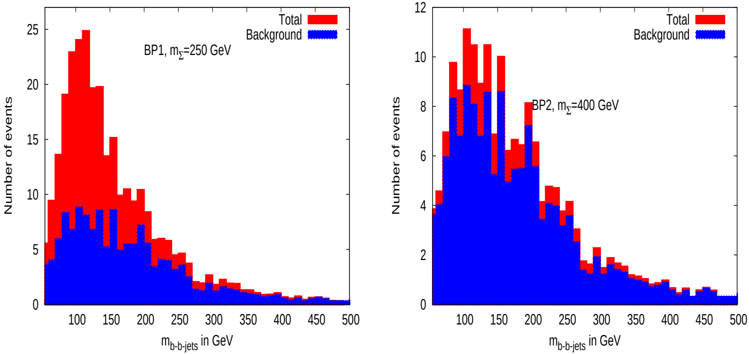


Figure: Invariant mass for b-jet pair from $\geq 2b + SSD$ final state for BP1, BP2 and SM backgrounds.

$2b+$ Same-sign di-lepton

$95\mathrm{GeV} \leq \mathrm{m_{b-b}} \leq 145\mathrm{GeV}$							
Signal		Backgrounds					
BP1	BP2	$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	VV	$t\bar{t}W$
60.61	10.39	8.0	3.0	10.6	6.5	0.0	9.6

Status of $2b+$ Same-sign di-lepton

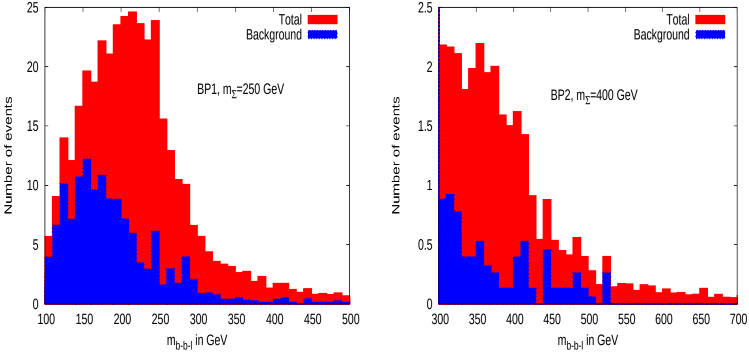


Figure: Invariant mass for *b*-jet pair plus a charged lepton from $\geq 2b + SSD$ final state for BP1, BP2 and SM backgrounds.

$2b+$ Same-sign di-lepton

m_{b-b-l}							
Signal		Backgrounds					
		$t\bar{t}$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}h$	VV	$t\bar{t}W$
BP1	117.37	4.0	0.35	7.00	2.67	0.0	2.50
BP2	11.74	0.0	0.0	1.71	0.12	0.0	1.05

Result for $2b+$ Same-sign di-lepton

- For $\geq 2b + SSD$ at 10 fb^{-1} integrated luminosity the reach for BP1 is $\sim 8\sigma$, where as for BP2 $\sim 2\sigma$
- Higgs peak reconstructed with m_{bb} have a significance of 6σ for BP1 at 10 fb^{-1} integrated luminosity and for BP2 it is 1.5σ.
- m_{bbl} at 10 fb^{-1} integrated luminosity the reach is $\simeq 10\sigma$ for BP1, and 3σ for BP2.
- Thus the significance drops very fast as we increase the triplet mass.
- Harder lepton p_T cuts and lepton invariant mass veto cut near Z peak will reduce the background further.

Conclusions

- Higgs searches from triplet fermions decay could be interesting at the LHC
- For low seesaw scale the reach could be possible at early data of LHC
- For higher seesaw mass scale as the production cross-section drops down the reach is possible only at higher luminosity.
- Triplet decay to relatively harder leptons is a good handle to kill the standard model backgrounds.
- In particular multi-lepton scenarios are good for mass measurements; Higgs and the triplet fermions.
- $4l$, $5l$ scenarios are also possible but cross-sections are very small.

Thank you