

A GENUINE FERMIONIC QUINTUPLET SEESAW MODEL: PHENOMENOLOGICAL INTRODUCTION

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Based on **JHEP 06 (2021) 084** by S. Ashanujjaman and K. Ghosh

2021 Meeting of the Division of Particles and Fields of the American Physical Society [Online]

WEINBERG OPERATOR & NEUTRINO MASS

Weinberg operator(s)

① $\mathcal{L}_5 \propto \frac{1}{\Lambda} LLHH \Rightarrow m_\nu \propto \frac{v^2}{\Lambda}$

② $\mathcal{L}_{5+2n} \propto \frac{1}{\Lambda^{2n+1}} LLHH (H^\dagger H)^n$

$\Rightarrow m_\nu \propto \epsilon \left(\frac{1}{16\pi^2} \right)^\# \left(\frac{v}{\Lambda} \right)^{d-5} \frac{v^2}{\Lambda}$

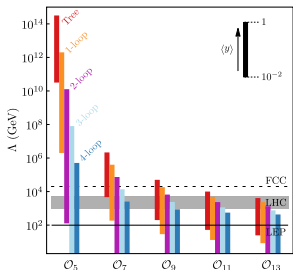
① \mathcal{L}_5 at tree level \rightarrow classical seesaws

- for $y \sim \mathcal{O}(1)$, $\Lambda \sim (10^{14} - 10^{15})$ GeV \Rightarrow direct tests impossible.
- for $\Lambda \sim \mathcal{O}(1)$ TeV, $y \sim \mathcal{O}(10^{-12})$ \Rightarrow philosophically displeasing.

② \mathcal{L}_9 at tree level

- $y \sim \mathcal{O}(0.1)$ as well as $\Lambda \sim \mathcal{O}(1)$ TeV

\Rightarrow philosophically pleasing & collider testable.



$$\mathcal{L} = \mathcal{L}_{SM} + \underbrace{\mathcal{L}_{d=5}}_{\text{dominant}} + \underbrace{\mathcal{L}_{d=7}}_{\text{subdominant}} + \underbrace{\mathcal{L}_{d=9}}_{\text{subsubdominant}}$$

How to make \mathcal{L}_9 contribution to m_ν dominant?

- ① Introduce a discrete symmetry
- ② Choose the particle content such a way that it doesn't allow to complete lower order operator \Rightarrow genuine models

A GENUINE QUINTUPLET SEESAW MODEL

Exotic fields: [JHEP 12 \(2018\) 066](#)

$$\Sigma_{L,R} = (++, +, 0)_{L,R} \sim (1, 3, 1)$$

$$\Delta_{L,R} = (++, +, 0, -)_{L,R} \sim (1, 4, \frac{1}{2})$$

$$\Phi_R = (++, +, 0, -, --)_R \sim (1, 5, 0)$$

Relevant Lagrangian:

$$\mathcal{L}_Y = Y_{23} \bar{\Sigma}_L H \tilde{L} + Y_{34} \bar{\Delta}_R \Sigma_L H^\dagger + Y'_{34} \bar{\Delta}_L \Sigma_R H^\dagger \\ + Y_{45} \bar{\Delta}_L \Phi_R H + Y'_{45} \bar{\Delta}_R \tilde{\Phi}_R H$$

$$\mathcal{L}_M = M_\Sigma \bar{\Sigma}_R \Sigma_L + M_\Delta \bar{\Delta}_R \Delta_L + \frac{1}{2} M_\Phi \bar{\Phi}_R \Phi_R$$

Light neutrino mass:

$$m_\nu \approx \frac{v^6}{48} Y_{23}^\dagger M_\Sigma^{-1} Y_{34}'^\dagger M_\Delta^{-1} Y_{45}' M_\Phi^{-1} Y_{45}'^T M_\Delta^{-1} Y_{34}'^* M_\Sigma^{-1} Y_{23}^* \\ = \frac{v^2}{2} Y_{23}^\dagger \mathcal{M}^{-1} Y_{23}^*$$

Casas-Ibarra parametrisation: [Nucl. Phys. B 618 \(2001\) 171](#)

$$Y_{23}^* = \frac{\sqrt{2}}{v} U_{\mathcal{M}} \sqrt{\hat{M} R} \sqrt{\hat{m}_\nu} U_{\text{PMNS}}^\dagger \quad (R^T R = \mathbf{1})$$

A Simplified Model:

$$M_\Sigma = \text{diag}(m_\Sigma, m_\Sigma, m_\Sigma)$$

$$M_\Delta = \text{diag}(m_\Delta, m_\Delta, m_\Delta)$$

$$M_\Phi = \text{diag}(m_\Phi, m_\Phi, m_\Phi)$$

$$Y_{34}' = \text{diag}(y_{34}, y_{34}, y_{34})$$

$$Y_{45}' = \text{diag}(y_{45}, y_{45}, y_{45})$$

$$R = \mathbf{I}_{3 \times 3}$$

LFV, PRODUCTION AND DECAYS OF EXOTIC FERMIONS

- **LFV:** $l_\alpha \rightarrow l_\beta \gamma$, $l_\alpha \rightarrow l_\beta l_\gamma l_\delta$ and $\mu \rightarrow e$ conversion. The most stringent bounds result from $\mu \rightarrow e$ conversion on Gold from SINDRUM-II collaboration.

$$\frac{m_\Delta^2 m_\Phi}{v^3 |y'_{34} y'_{45}|^2} \lesssim \mathcal{O}(10^7) \quad \Rightarrow |y'_{34} y'_{45}|^2 > (0.05)^4$$

- **Drell-Yan:** $q \bar{q}' \rightarrow \gamma/Z \rightarrow \chi^{++} \chi^{--} / \chi^+ \chi^- / \chi^0 \chi^0$, $q \bar{q}' \rightarrow W^\pm \rightarrow \chi^{\pm\pm} \chi^\mp / \chi^\pm \chi^0$.
- **Photon-photon fusion:** $\gamma\gamma \rightarrow \chi^{++} \chi^{--} / \chi^+ \chi^-$
- **Heavy state transition:** $\chi^Q \rightarrow \chi^{Q-1} \pi^+$, $\chi^{Q-1} K^+$, $\chi^{Q-1} \ell^+ \nu$, $\chi^{Q-1} \pi^+ \rho$
- **SM 2-body decays:**

$$\chi_i^{++} \rightarrow \ell_j^+ W^+$$

$$\chi_i^+ \rightarrow \ell_j^+ Z/h, \nu W^+$$

$$\chi_i^0 \rightarrow \ell_j^\pm W^\mp, \nu Z/h$$

	$\chi^{++} \rightarrow \ell^+ W^+$	$\chi^+ \rightarrow \nu W^+, \ell^+ Z, \ell^+ h$			$\chi^0 \rightarrow \ell^\pm W^\mp, \nu Z, \nu h$		
$\chi^{--} \rightarrow \ell^- W^-$	$\ell^- \ell^+ W^- W^+$	$\ell^- \nu W^- W^+$	$\ell^- \ell^+ W^- Z$	$\ell^- \ell^+ W^- h$	-	-	-
$\chi^- \rightarrow \nu W^-$	$\nu \ell^+ W^- W^+$	$\nu \nu W^- W^+$	$\nu \ell^+ W^- Z$	$\nu \ell^+ W^- h$	$\nu \ell^\pm W^- W^\mp$	$\nu \nu W^- Z$	$\nu \nu W^- h$
$\chi^- \rightarrow \ell^- Z$	$\ell^- \ell^+ Z W^+$	$\ell^- \nu Z W^+$	$\ell^- \ell^+ Z Z$	$\ell^- \ell^+ Z h$	$\ell^- \ell^\pm Z W^\mp$	$\ell^- \nu Z Z$	$\ell^- \nu Z h$
$\chi^- \rightarrow \ell^- h$	$\ell^- \ell^+ h W^+$	$\ell^- \nu h W^+$	$\ell^- \ell^+ h Z$	$\ell^- \ell^+ h h$	$\ell^- \ell^\pm h W^\mp$	$\ell^- \nu h Z$	$\ell^- \nu h h$
$\chi^0 \rightarrow \ell^\pm W^\mp$	-	$\ell^\pm \nu W^\mp W^\mp$	$\ell^\pm \ell^+ W^\mp Z$	$\ell^\pm \ell^+ W^\mp h$	$\ell^\pm \ell^\pm (\mp) W^\mp W^\mp (\pm)$	$\ell^\pm \nu W^\mp Z$	$\ell^\pm \nu W^\mp h$
$\chi^0 \rightarrow \nu Z$	-	$\nu \nu Z W^+$	$\nu \ell^+ Z Z$	$\nu \ell^+ Z h$	$\nu \ell^\pm Z W^\mp$	$\nu \nu Z Z$	$\nu \nu Z h$
$\chi^0 \rightarrow \nu h$	-	$\nu \nu h W^+$	$\nu \ell^+ h Z$	$\nu \ell^+ h h$	$\nu \ell^\pm h W^\mp$	$\nu \nu h Z$	$\nu \nu h h$

MULTILEPTON FINAL STATES SEARCH BY CMS

A recent CMS search (137.1 fb^{-1}) excluded triplet fermions below 880 GeV at 95% CL in the simplified type-III seesaw model. [JHEP 03 \(2020\) 051](#)

This limit is not straightforwardly applicable to the present model. However, because of similar multilepton final states signatures, this search is expected to be sensitive as well in probing the present model.

Search implementation steps:

- **MadGraph5** (MC event generation) → **Pythia8** (decays, ISR, FSR, showering, fragmentation and hadronization) → **Delphes** (object reconstruction and selection, defining SRs and event selection)

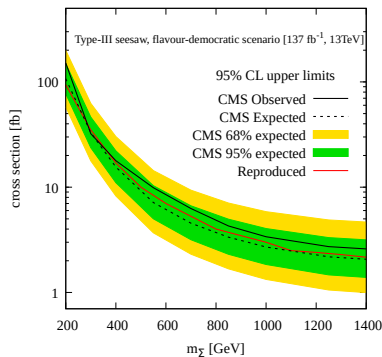
For the 'Delphes' step, we rigorously follow the said CMS search strategy.

Based on # leptons, # and mass of OSSF lepton pairs, the selected events are categorised into several mutually exclusive SRs.

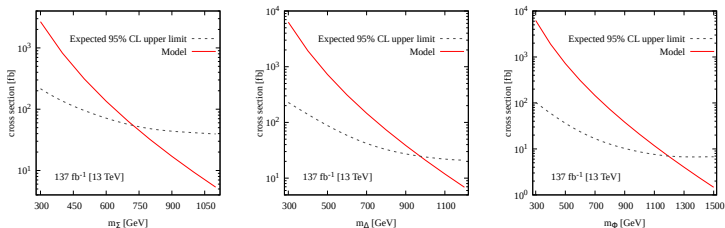
Label	N_{leptons}	N_{OSSF}	M_{OSSF} (GeV)	p_T^{miss} (GeV)	Variable and range (GeV)	Number of bins
3L below-Z	3	1	<76	—	$L_T+p_T^{\text{miss}}$ [0, 1200]	6
3L on-Z	3	1	76–106	>100	M_T [0, 700]	7
3L above-Z	3	1	>106	—	$L_T+p_T^{\text{miss}}$ [0, 1600]	8
3L OSSF0	3	0	—	—	$L_T+p_T^{\text{miss}}$ [0, 1200]	6
4L OSSF0	≥ 4	0	—	—	$L_T+p_T^{\text{miss}}$ [0, 600]	2
4L OSSF1	≥ 4	1	—	—	$L_T+p_T^{\text{miss}}$ [0, 1000]	5
4L OSSF2	≥ 4	2	—	>100 if both pairs are on-Z	$L_T+p_T^{\text{miss}}$ [0, 1200]	6

VALIDATION OF OUR IMPLEMENTATION OF CMS SEARCH

- To validate our implementation, we reproduce expected 95% CL upper limit on the triplets in the simplified type-III seesaw model.
- **Since the relevant SM backgrounds in our analysis are exactly same as that of CMS search, we do not simulate the backgrounds, instead we use distributions of expected SM backgrounds and observed events provided by CMS.**
- In doing so, we use a hypothesis tester to estimate exclusion significance.



95% CL LIMIT ON EXOTICS, AND DISPLACED VERTEX



Exotics with masses below 720, 970, and 1200 GeV are excluded for triplet, quadruplet and quintuplet, respectively.

Displaced vertices, LLPs, vanishing charge track signature, *etc.* may result for smaller values of the lightest neutrino mass *i.e.* $m_1(m_3) \rightarrow 0$ for NH(IH).

	$3^{++}(4^{++})\{5^{++}\}[3^+]$	$4^+(5^+)$	$4^-/3^0/4^0/5^0$
$c\tau_{\max}$ (in mm)	0.04 (0.22) {0.43} [1.0]	3.6 (16.0)	arbitrarily large
where to look for	LHeC, FCC-he	HL-LHC, LHeC, FCC-he	MATHUSLA

SUMMARY AND OUTLOOK

- A **genuine** model (potentially **testable**, and hence **falsifiable** at collider) generating neutrino masses at tree-level via \mathcal{O}_9 has been presented.
- This model possesses several new $SU(2)_L$ fermionic multiplets and thus a rich phenomenology at the LHC.
- Pair production of exotics for masses below 720, 970 and 1200 GeV are excluded for triplet, quadruplet and quintuplet, respectively.
- Exotics of the model could also be long-lived leaving disappearing track signatures or displaced vertices at detector.
- Final states discussed in this work are common to a large class of (seesaw-inspired) models. Once a positive search is found, one will have to identify whether it corresponds to heavy neutrinos (type-I seesaw), scalar triplets (type-II seesaw), fermionic triplets (type-III seesaw) or any other seesaw-inspired model like the present one —type-V seesaw.
- The Yukawa coupling of the exotics with the SM lepton doublet is large enough. Therefore, one would expect better prospect of this model at lepton colliders.