A GENUINE TYPE-V SEESAW MODEL: PHENOMENOLOGICAL INTRODUCTION

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Based on arXiv:2012.15609[hep-ph] by S. Ashanujjaman and K. Ghosh

WEINBERG OPERATOR

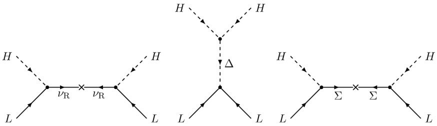
- The lowest dimensional *non-renormalizable* operator

$$\mathcal{L}_{d=5} \propto \frac{1}{\Lambda} LLHH$$

- Majorana neutrino mass

$$m_\nu \propto \frac{v^2}{\Lambda}$$ "Majorana seesaw formula"

- Three tree level realisations of Weinberg operator: type-I, type-II and type-III seesaw

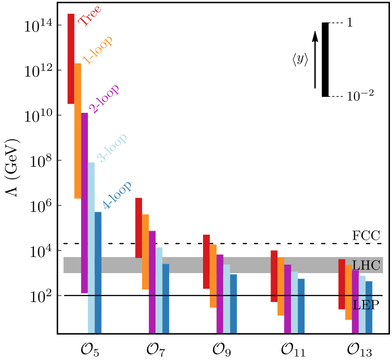


S. Weinberg, Phys.Rev.Lett. 43, 1566 (1979) , R.Foot, H.Lew, X.G.He and G.C.Joshi, Z.Phys. C44, 441 (1989) , Ernest Ma, Phys.Rev.Lett. 81, 1171 (1998) , Ernest Ma and Utpal Sarkar, Phys.Rev.Lett. 80, 5716 (1998)

GENERALISATION OF WEINBERG OPERATOR

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

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



- For $\mathcal{O}_5$ at tree level
  1. $Y \sim \mathcal{O}(1)$, $\Lambda \sim (10^{14} - 10^{15})$ GeV
     $\Rightarrow$ Direct tests impossible.
  2. $\Lambda \sim \mathcal{O}(1)$ TeV, $Y \sim \mathcal{O}(10^{-12})$
     $\Rightarrow$ Philosophically displeasing.
- For $\mathcal{O}_{d\geq 9}$: High-dimensional operators brings down Λ to TeV even for large enough Yukawa $\Rightarrow$ Testable at collider.

GENUINE MODELS

- In general

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

- How can we make the higher dimensional contribution(s) to neutrino masses dominant?
  - Introduce a discrete symmetry to forbid the lower order operator
  - Choose the particle content of the model such a way that it does not allow to complete the lower order operator

- A model is considered to be genuine at dimension d, if all lower dimensional contributions to neutrino masses are automatically absent, without the need for additional discrete symmetries.

S.Kanemuraa & T.Ota, Phys.Lett.B 694 (2010) 233
Cepedello et al JHEP 1707 (2017) 079, JHEP 1801 (2018) 009
Anamiati,G. et al., JHEP 1812 (2018) 066, and ...

GENUINE MODELS (CNTD.)

- Mass operator of dimension d

$$\mathcal{L}_d \propto \frac{1}{\Lambda^{(d-4)}} LLHH \; (H^\dagger H)^{(d-5)/2}$$

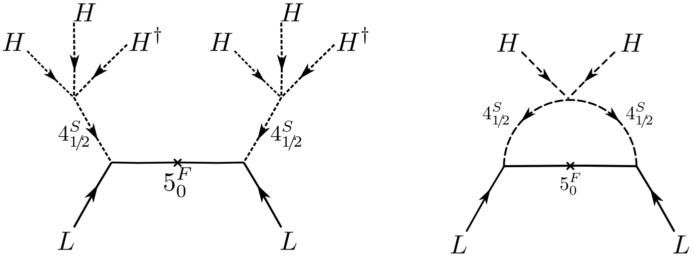
- The very same operators will always lead to lower order loop models

$$\frac{1}{\Lambda^{(d-4)}} LLHH(H^\dagger H)^{(d-5)/2} \to \frac{1}{16\pi^2} \frac{1}{\Lambda^{(d-6)}} LLHH(H^\dagger H)^{(d-7)/2}$$

- For the d-dimensional tree-level contribution to dominate over the $(d-2)$-dimensional 1-loop one, $\Lambda/v < 4\pi$, *i.e.* $\Lambda < 3$ TeV .

EXAMPLE OF A NON-GENUINE MODEL

- The following model generates a $d = 9$ tree-level diagram (on the left) via the four scalar vertex $\lambda_4(\mathbf{4}^S_{1/2})^\dagger HHH^\dagger$

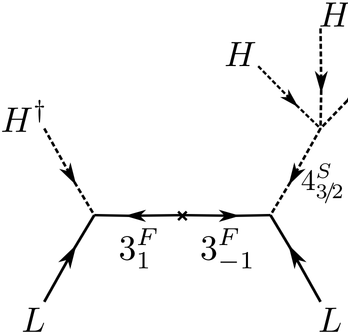


Kumericki, Picek, & Radovcic, Phys.Rev.D 86, 013006 (2012)

- Connecting the two quadruplet scalars via a quartic interaction $\lambda_5(\mathbf{4}^S_{1/2})^\dagger(\mathbf{4}^S_{1/2})^\dagger HH$ allows one to draw the 1-loop $d = 5$ diagram on the right

EXAMPLE OF A GENUINE MODEL

- The following model generates a $d = 7$ tree-level diagram via the four scalar vertex $\lambda_4(\mathbf{4}^S_{3/2})^\dagger HHH$.



(BNT model)

Babu, Nandi & Tavartkiladze, Phys. Rev. D 80, 071702 (2009)

A BRIEF IDEA ABOUT THE EXISTING LITERATURE

- In the literaure
  - $d = 5$ neutrino masses at tree, 1-loop, 2-loop and 3-loop level
  - $d = 7$ neutrino masses at tree and 1-loop level

  have been extensively studied.

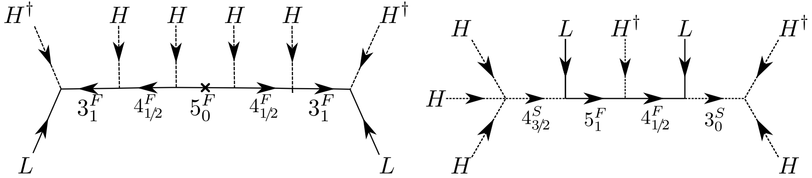
  Bonnet, Hernandez, Ota & Winter, JHEP 0910 (2009) 076
  Bonnet, Hirsch, Ota & Winter, JHEP 1207 (2012) 153
  Sierra, Degee, Dorame & Hirsch, JHEP 1503 (2015) 040, ...

- Also, few models at $d = 9$ tree level have been studied, but all those models are non-genuine in our sense.

  K.L.McDonald, JHEP 1307 (2013) 020, JHEP 1311 (2013) 131
  I.Picek and B.Radovcic, Phys.Lett.B 687 (2010) 338, ...

GENUINE MODELS AT $d = 9$ TREE LEVEL

- There are only two diagrams that lead to genuine models.
  G. Anamiati, O. Castillo-Felisola, R.M. Fonseca, J.C. Helo & M. Hirsch, JHEP 12 (2018) 066



- The model associated with the first diagram is a fermion-only extension of the SM, which is of our interest.

Exotic contents of the Model

Gauge: $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

$$\Sigma_{L,R} = \begin{pmatrix} \Sigma^{++} \\ \Sigma^{+} \\ \Sigma^{0} \end{pmatrix}_{L,R} \sim (1, 3, 1)$$

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

$$\Phi_{R} = \begin{pmatrix} \Phi^{++} \\ \Phi^{+} \\ \Phi^{0} \\ \Phi^{-} \\ \Phi^{--} \end{pmatrix}_{R} \sim (1, 5, 0)$$

GENUINE TYPE-V SEESAW MODEL: IS THE NAME APT?

- Genuine: ✓
- Seesaw: ✓
  - Type: ?

    If one follows the convention of labeling a seesaw model with the size of the $SU(2)_L$ representation of the seesaw anchor or, more precisely, the field which yields lepton number violation (LNV) , then one may call this model a Type-V or quintuplet seesaw model.

    Is this convention consistent with the widely studied classical seesaws?

    - Type-I: LNV results via Majorana mass for singlet neutrino(s). ✓
    - Type-III: LNV results via Majorana mass for triplet neutrino(s). ✓
    - Type-II: Two potential sources of LNV — $H^T i\sigma_2 \Delta^\dagger H$ and $L^T C i\sigma_2 \Delta L$. However, the former one will break the lepton number spontaneously once Δ acquires a vev. $\Rightarrow$ LNV results via SM lepton doublet(s). ✓

Neutrino Mass and Casas-Ibarra Parametrisation

$$\begin{aligned} -\mathcal{L}_{\rm Yuk} &= Y_\ell\, \overline{L}_i H^i \ell_R + Y_{23}\, \left(\overline{\Sigma_L}\right)^i_j\, H^j\, \widetilde{L}_i \;+\; Y_{34}\, \left(\overline{\Delta_R}\right)_{ijk}\, \left(\Sigma_L\right)^i_{j'}\, H^*_{k'}\, \epsilon^{jj'}\, \epsilon^{kk'} + Y'_{34}\, \left(\overline{\Delta_L}\right)_{ijk}\, \left(\Sigma_R\right)^i_{j'}\, H^*_{k'}\, \epsilon^{jj'}\, \epsilon^{kk'} \\ &\quad + Y_{45}\, \left(\overline{\Delta_L}\right)_{ijk}\, \left(\Phi_R\right)^{ijk\ell}\, H^{\ell'}\, \epsilon_{\ell\ell'} \;+\; Y'_{45}\, \left(\overline{\Delta_R}\right)_{ijk}\, \left(\widetilde{\Phi}_R\right)_{i'j'k'\ell}\, H^\ell\, \epsilon^{ii'}\, \epsilon^{jj'}\, \epsilon^{kk'}\;; \\ -\mathcal{L}_{\rm mass} &= M_\Sigma\, \left(\overline{\Sigma_R}\right)^i_j\, \left(\Sigma_L\right)^j_i \;+\; M_\Delta\, \left(\overline{\Delta_R}\right)_{ijk}\, \left(\Delta_L\right)^{ijk} + \frac{M_\Phi}{2}\, \left(\overline{\widetilde{\Phi}_R}\right)^{ijk\ell}\, \left(\Phi_R\right)^{i'j'k'\ell'}\, \epsilon_{ii'}\, \epsilon_{jj'}\, \epsilon_{kk'}\, \epsilon_{\ell\ell'}\;; \end{aligned}$$

- Light neutrino mass matrix

$$m_\nu \approx \frac{v^2}{2} Y_{23}^\dagger \mathcal{M}^{-1} Y_{23}^*$$

$$\left(\mathcal{M}^{-1} = \frac{v^4}{24} M_\Sigma^{-1} Y_{34}'^\dagger M_\Delta^{-1} Y'_{45} M_\Phi^{-1} Y_{45}'^T M_\Delta^{-1} Y_{34}'^* M_\Sigma^{-1}\right)$$

- Casas-Ibarra parametrisation

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

Casas and Ibarra, Nucl. Phys. B 618 (2001) 171

A SIMPLIFIED MODEL FOR COLLIDER STUDY

We assume

$$M_\Sigma \;=\; m_\Sigma\,\mathbf{I}_{3\times 3}\;,\;\; M_\Delta \;=\; m_\Delta\,\mathbf{I}_{3\times 3}\;\text{and}\;M_\Phi \;=\; m_\Phi\,\mathbf{I}_{3\times 3}\;;$$

$$Y'_{34} \;=\; y'_{34}\,\mathbf{I}_{3\times 3}\;\text{and}\;Y'_{45} \;=\; y'_{45}\,\mathbf{I}_{3\times 3}\;;$$

we further assume that $R \;=\; \mathbf{I}_{3\times 3}$:

$$Y_{23} = \frac{\sqrt{48}}{v^3}\frac{m_\Sigma m_\Delta m_\Phi^{1/2}}{y'_{34}y'_{45}}\sqrt{\hat{m}_\nu}\,V^T_{\rm PMNS}\;.$$

LEPTON FLAVOUR VIOLATING DECAYS: $\ell_\alpha \to \ell_\beta\gamma$

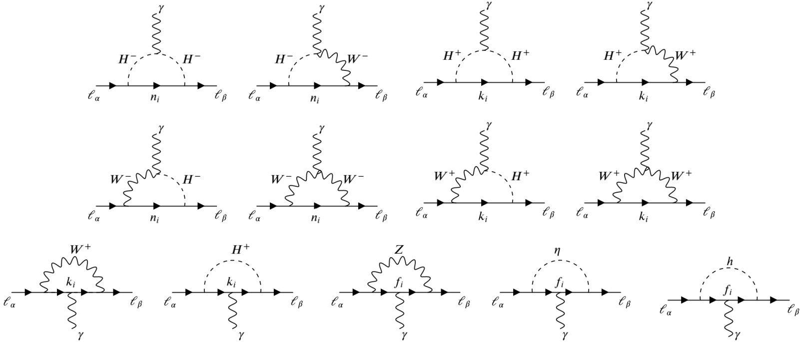


FIGURE: Vertex-type diagrams. n_i,f_i and k_i symbollically stand for any of the neutral, singly-charged and doubly-charged fermions, respectively.

Also, there are 14 self-energy diagrams (not shown for brevity).

LEPTON FLAVOUR VIOLATING DECAYS: $\ell_\alpha \to \ell_\beta\gamma$ (CNTD.)

$$\mathrm{Br}(\ell_\alpha \to \ell_\beta\gamma) = \frac{48\pi^3\alpha}{G_F^2 m_\alpha^2}\left|\sigma_R^{\beta\alpha}\right|^2 \times \underbrace{\mathrm{Br}(\ell_\alpha \to \ell_\beta\bar{\nu_\beta}\nu_\alpha)}_{1 \textit{ for } \mu\to e\gamma \textit{ and } 0.1784 \textit{ for } \tau\to\ell\gamma\ (\ell=e,\mu)} ,$$

$$\sigma_R^{\beta\alpha} = \frac{G_F}{\sqrt{2}}\frac{1}{4\pi^2} m_\alpha \sum_{i=1}^{3}\Big[\{(\mathbf{I}+\lambda)V_{\mathrm{PMNS}}\}_{\beta i}\left\{\left(V^\dagger_{\mathrm{PMNS}}\right)_{i\alpha} F_1(w_{\nu_i}) - \left\{V^\dagger_{\mathrm{PMNS}}(\mathbf{I}+\lambda)\right\}_{i\alpha} F_2(w_{\nu_i})\right\} +$$
$$v^2\left(Y_{23}^T M_\Sigma^{-1}\right)_{\beta i}\left(M_\Sigma^{-1} Y_{23}^*\right)_{i\alpha}\left\{F_3(w_{\Sigma_i}) + F_6(z_{\Sigma_i}) + F_7(h_{\Sigma_i})\right\} + 4\lambda_{\beta\alpha}\left\{F_4(z_{\ell_i}) + F_5(z_{\ell_i})\sin^2\theta_w\right\}\Big] .$$

In the limit $M_\Sigma >> m_{W,Z,h}$,

$$\mathrm{Br}(\ell_\alpha \to \ell_\beta\gamma) \approx \frac{3\alpha}{2\pi}\left|\frac{51+16\sin^2\theta_w}{12}\lambda_{\beta\alpha}\right|^2 \times \mathrm{Br}(\ell_\alpha \to \ell_\beta\bar{\nu_\beta}\nu_\alpha) ,$$

where $\lambda = \frac{v^2}{8} Y_{23}^T M_\Sigma^{-2} Y_{23}^*$.

LEPTON FLAVOUR VIOLATING DECAYS: $\ell_\alpha \to \ell_\beta\gamma$ (CNTD.)

Using the current experimental bounds on $\ell_\alpha \to \ell_\beta\gamma$:

$$\begin{aligned} \left|\lambda_{e\mu(e\tau)[\mu\tau]}\right| &= \left|\left(\frac{v^2}{8} Y_{23}^T M_\Sigma^{-2} Y_{23}^*\right)_{e\mu(e\tau)[\mu\tau]}\right| \\ &\leq 2.3\times 10^{-6}\ (1.5\times 10^{-3})\ [1.8\times 10^{-3}]\ . \end{aligned}$$

These limits are more constraining ($\sim 2.5\times$) than those in type-III seesaw:

- In this model, there is a LFV contribution from diagrams with a doubly charged lepton, a W-boson and/or a 'would-be Goldstone boson' circulating in the loop.
- The LFV contribution from diagrams with a heavy neutral lepton, a W-boson and/or a 'would-be Goldstone boson' circulating on the loop is absent in the present model upto $\mathcal{O}(Y^2 v^2/\Lambda^2)$, which is not the case with the type-III seesaw model.

OTHER LEPTON FLAVOUR VIOLATING DECAYS (CNTD.)

We numerically evaluate the LFV observables using SARAH, SPheno and FlavorKit .

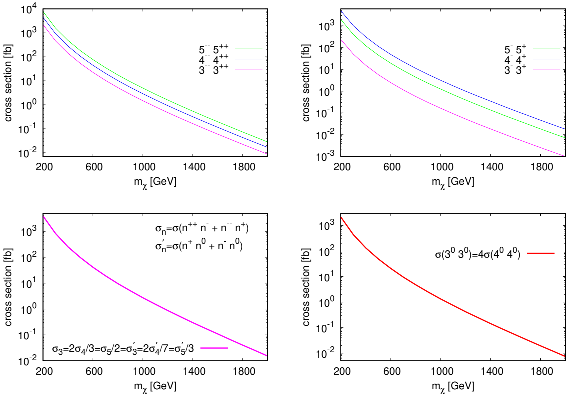
- In the *simplified scenario*, using the experimental bounds from various LFV decays, we constrain the model parametre space.
- The most stringent bounds result from $\mu \to e$ conversion on Gold from SINDRUM-II collaboration.
- For brevity, we avert to quote the numbers here, instead we consider the following **BP**s:
  - **BP1**:$m_\Delta, m_\Phi \sim 1$ TeV and $y'_{34}, y'_{45} \sim 0.05$ and $m_1 = 10^{-5}$ eV ,
  - **BP2**:$m_\Delta, m_\Phi \sim 1$ TeV and $y'_{34}, y'_{45} \sim 0.15$ and $m_1 = 10^{-5}$ eV ,
  - While **BP2** is allowd by all the LFV decays, **BP1** is ruled out by $\mu \to e$ conversion on Gold.

PRODUCTION OF EXOTIC FERMIONS AT THE LHC

Pair productions via the Drell-Yan processes:

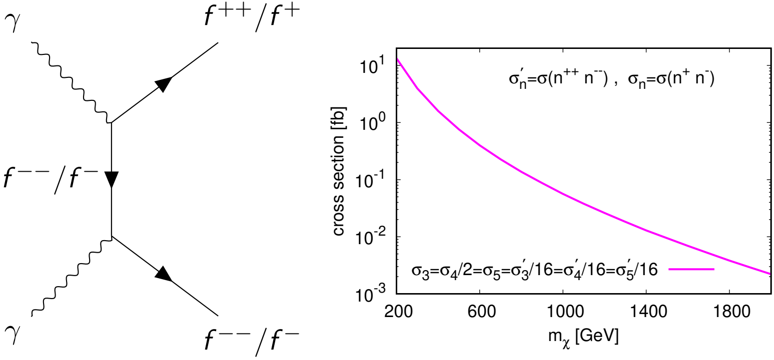
$$q\ \overline{q'} \to \gamma/Z \to \chi^{++}\chi^{--}/\chi^{+}\chi^{-}/\chi^{0}\chi^{0}\ , \quad q\ \overline{q'} \to W^{\pm} \to \chi^{\pm\pm}\chi^{\mp}/\chi^{\pm}\chi^{0}\ ,$$

where χ stands for the heavy fermionic multiplets Σ, Δ and Φ.



PRODUCTION OF EXOTIC FERMIONS AT THE LHC (CNTD.)

Pair productions via photon-photon fusion:



DECAYS OF EXOTIC FERMIONS

Their decays can be classified into two categories:

- *Category I:* the decays of the heavier exotics to the lighter ones

$$\chi^Q \to \chi^{Q-1}\pi^+, \chi^{Q-1}K^+, \chi^{Q-1}\ell^+\nu, \chi^{Q-1}\pi^+\rho$$

- *Category II:* two-body decays into a SM lepton and a boson
    - $\chi_i^{++} \to \ell_j^+ W^+$
    - $\chi_i^+ \to \ell_j^+ Z/h$ and $\chi_i^+ \to \nu W^+$
    - $\chi_i^0 \to \ell_j^\pm W^\mp$ and $\chi_i^0 \to \nu Z/h$

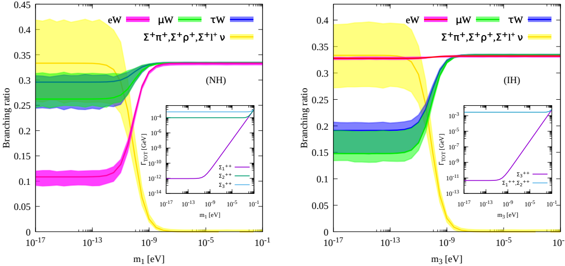
It is not possible to distinguish among the degenerate copies of a given multiplet at the LHC. Therefore, instead of branching ratios for individual copies, we consider the average branching ratios of them:

$$\mathrm{BR}_{\mathrm{avg}}\left(\sum_i \chi_i \to XY\right) = \frac{1}{3}\sum_{i=1}^{3} \mathrm{BR}\left(\chi_i \to XY\right) ,$$

where XY is a generic decay mode of χ_i.

DECAYS OF EXOTIC FERMIONS (CNTD.)

Doubly-charged triplet fermions:

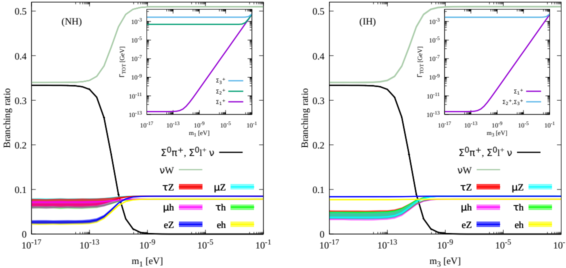


- For $m_1(m_3) > 10^{-9}$ eV, $BR_{\rm avg}(\Sigma^{++} \to \ell^+ W^+) \sim 100/3\%$

Lepton flavour universality of the average leptonic branching ratios of Σ^{++}'s breaks down below $m_1(m_3) \sim 10^{-9}$ eV.

DECAYS OF EXOTIC FERMIONS (CNTD.)

Singly-charged triplet fermions:



For $m_1(m_3) > 10^{-9}$ eV,

- $BR_{\text{avg}}(\Sigma^+ \to \ell Z) \sim 25/3\%$
- $BR_{\text{avg}}(\Sigma^+ \to \ell h) \sim 25/3\%$
- $BR_{\text{avg}}(\Sigma^+ \to \nu W^+) \sim 50\%$
- Same as type-III seesaw.

Lepton flavour universality of the average leptonic branching ratios of Σ^+'s breaks down below $m_1(m_3) \sim 10^{-10}$ eV.

DECAYS OF EXOTIC FERMIONS (CNTD.)

Only possible decay modes for the neutral fermions are the SM two-body decays.

The present model:

- $BR_{\text{avg}}(\Sigma^0 \to \ell_j^{\pm} W^{\mp}) \sim 0\%$
- $BR_{\text{avg}}(\Sigma^0 \to \nu Z) \sim 50\%$
- $BR_{\text{avg}}(\Sigma^0 \to \nu h) \sim 50\%$

Type-III seesaw:

- $BR_{\text{avg}}(\Sigma^0 \to \ell_j^{\pm} W^{\mp}) \sim 50\%$
- $BR_{\text{avg}}(\Sigma^0 \to \nu Z) \sim 25\%$
- $BR_{\text{avg}}(\Sigma^0 \to \nu h) \sim 25\%$

As $m_1(m_3) \to 0$, the decay length of the first(third) generation of heavy neutral fermions can be arbitrarily large making them long-lived.

POSSIBLE FINAL STATE SIGNATURES AT COLLIDER

	$\chi^{++} \to \ell^+ W^+$	$\chi^{+} \to \nu W^+, \ell^+ Z, \ell^+ h$			$\chi^{0} \to \ell^\pm W^\mp, \nu Z, \nu h$		
$\chi^{--} \to \ell^- W^-$	$\ell^-\ell^+W^-W^+$	$\ell^-\nu W^-W^+$	$\ell^-\ell^+W^-Z$	$\ell^-\ell^+W^-h$	–	–	–
$\chi^{-} \to \nu W^-$	$\nu\ell^+W^-W^+$	$\nu\nu W^-W^+$	$\nu\ell^+W^-Z$	$\nu\ell^+W^-h$	$\nu\ell^\pm W^-W^\mp$	$\nu\nu W^-Z$	$\nu\nu W^-h$
$\chi^{-} \to \ell^- Z$	$\ell^-\ell^+ZW^+$	$\ell^-\nu ZW^+$	$\ell^-\ell^+ZZ$	$\ell^-\ell^+Zh$	$\ell^-\ell^\pm ZW^\mp$	$\ell^-\nu ZZ$	$\ell^-\nu Zh$
$\chi^{-} \to \ell^- h$	$\ell^-\ell^+hW^+$	$\ell^-\nu hW^+$	$\ell^-\ell^+hZ$	$\ell^-\ell^+hh$	$\ell^-\ell^\pm hW^\mp$	$\ell^-\nu hZ$	$\ell^-\nu hh$
$\chi^{0} \to \ell^\pm W^\mp$	–	$\ell^\pm\nu W^\mp W^+$	$\ell^\pm\ell^+W^\mp Z$	$\ell^\pm\ell^+W^\mp h$	$\ell^\pm\ell^{\pm(\mp)}W^\mp W^{\mp(\pm)}$	$\ell^\pm\nu W^\mp Z$	$\ell^\pm\nu W^\mp h$
$\chi^{0} \to \nu Z$	–	$\nu\nu ZW^+$	$\nu\ell^+ZZ$	$\nu\ell^+Zh$	$\nu\ell^\pm ZW^\mp$	$\nu\nu ZZ$	$\nu\nu Zh$
$\chi^{0} \to \nu h$	–	$\nu\nu hW^+$	$\nu\ell^+hZ$	$\nu\ell^+hh$	$\nu\ell^\pm hW^\mp$	$\nu\nu hZ$	$\nu\nu hh$

- Some of the final states also allow kinematic reconstruction of the masses of the exotic fermions: *e.g.*, $\chi^{++}\chi^{--} \to \ell^+\ell^-W^+W^-$.
- Multilepton signatures are considered as one of the cleanest channels to probe new physics scenarios.
- SM contributions to multilepton final states
  - Reducible: processes like Z+jets, $t\bar{t}$+jets, *etc.*.
  - Irreducible: diboson and triboson production and processes like $t\bar{t}W$, $t\bar{t}Z$ and Higgs boson production, *etc*.

MULTILEPTON FINAL STATES SEARCH

- A recent CMS multilepton search (137.1 fb^{-1},$\sqrt{s} = 13$ TeV), targetted to probe type-III seesaw, excluded triplet fermions below 880 GeV at 95% CL in the flavour democratic scenario. JHEP 03 (2020) 051
- The CMS bounds on the type-III seesaw can not be directly applicable to the multiplets of the present model.
- In fact, the CMS limits are not even applicable for a realistic type-III seesaw model [1].
- Therefore, we proceed to derive 95% CL upper limits in type-V seesaw by closely implementing the aforecited search.
- We closely follow the CMS multilepton search strategy for object reconstruction and selection, defining signal regions and event selection.

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[1] For a realistic type-III seesaw model, the corresponding limits may vary from 400 to 1100 GeV. S. Ashanujjaman & K. Ghosh, to appear.

OBJECT RECONSTRUCTION AND SELECTION

- Jets are reconstructed using the anti-kT algorithm with $\Delta R = 0.4$.
- p_T threshold and η acceptance:
  - Jet: $p_T > 30$ GeV and $|\eta| < 2.1$
  - Electron: $p_T > 10$ GeV and $|\eta| < 2.5$
  - Muon: $p_T > 10$ GeV and $|\eta| < 2.4$
- Relative isolation (I) and radius (R) of the isolation cone:
  - Electron: $I = 5 - 15\%$ [scaling inversely with $p_T(e)$] with $R = 0.3$
    1. Within barrel ($|\eta| < 1.479$), $I = 0.0478 + 0.506/p_T$
    2. Within endcap ($|\eta| > 1.479$), $I = 0.0658 + 0.963/p_T$
  - Muon: $I = 15\%$ with $R = 0.4$
- d_z and d_{xy} with respect to primary vertex:
  - For electron
    1. Within barrel, $d_z < 0.10$ and $d_{xy} < 0.05$
    2. Within endcap, $d_z < 0.20$ and $d_{xy} < 0.10$
  - For muon, $d_z < 0.10$ and $d_{xy} < 0.05$

EVENT SELECTION

- Final states with three or more leptons (e, μ) are considered only.
- Events with at least one electron with $p_T > 30(35)$ GeV or at least one muon with $p_T > 29(26)$ GeV are considered.
- Events containing a lepton pair with $\Delta R < 0.4$ are rejected. Also, events containing a same-flavor lepton pair with dilepton invariant mass below 12 GeV are rejected.
- Based on #leptons, #OSSF lepton pairs and the invariant mass of OSSF pair, the events are categorised into seven signal regions, namely *4LOSSF0, 4LOSSF1, 4LOSSF2, 3LOSSF0, 3LOSSF below-Z, 3LOSSF on-Z and 3LOSSF above-Z*.
- 3LOSSF on-Z events with trilepton invariant mass within the Z boson mass window are vetoed.
- 3LOSSF on-Z events with $p_T^{\text{miss}} < 100$ GeV are vetoed.
- 4LOSSF2 events with $p_T^{\text{miss}} < 100$ GeV are vetoed if both OSSF lepton pairs are on-Z.

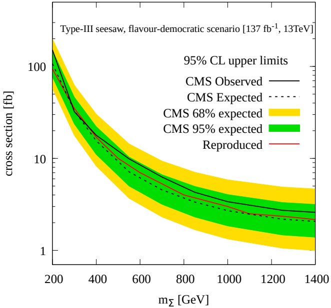
EVENT SELECTION (CNTD.)

- The signal regions are further classified into 40 statistically independent signal bins.
- $L_T + p_T^{\mathrm{miss}}$ is used as the primary kinematic discriminant for all signal regions except 3L on-Z. In 3L on-Z signal region, the transverse mass is used as discriminant.

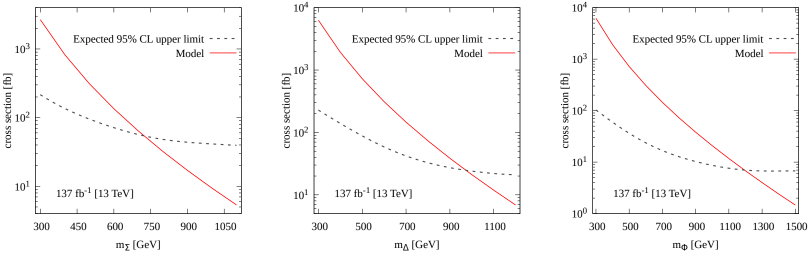
Label	N_{leptons}	N_{OSSF}	M_{OSSF} (GeV)	$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	Variable and range (GeV)		Number of bins
3L below-Z	3	1	<76	—	$L_{\mathrm{T}}+p_{\mathrm{T}}^{\mathrm{miss}}$	$[0, 1200]$	6
3L on-Z	3	1	76–106	>100	M_{T}	$[0, 700]$	7
3L above-Z	3	1	>106	—	$L_{\mathrm{T}}+p_{\mathrm{T}}^{\mathrm{miss}}$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

VALIDATION OF OUR APPROACH OF ESTIMATING 95% CL ON THE TOTAL PRODUCTION CROSS SECTION

- We use a hypothesis tester named 'Profile Likelihood Number Counting Combination' to estimate CL.
- We validate our approach by reproducing the CMS expected 95% CL bound on the total triplet pair production cross-section in simplified flavor democratic type-III seesaw.



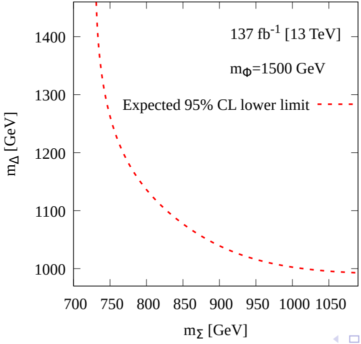
95% CL Upper Limit on the Total Production Cross Section of Exotic Fermions



- In the simplified model, the exotic fermion masses below 720, 970, and 1200 GeV are excluded for triplet, quadrupled and quintuplet.
- The exclusion limit on the triplet mass is less stringent than that on the quintuplet mass.
- The limit on the triplets in type-III seesaw is much more stringent than that in our model.

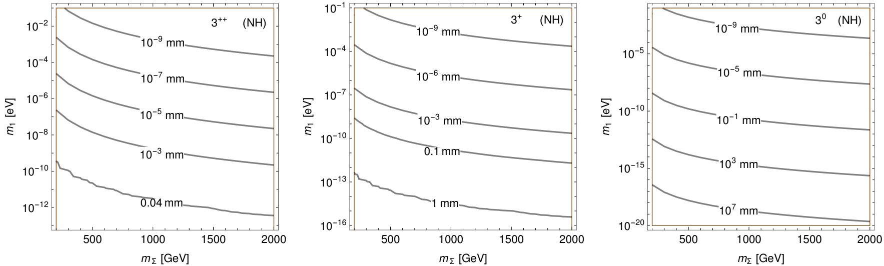
95% CL Upper Limit on ... Exotics (cntd.)

- The 95% CL limits (in previous slide) are based on the assumption that the given multiplet is the lightest and the other two multiplets are too heavy to contribute significantly in the signal bins.
- If we relax this assumption then all three multiplets of the type-V seesaw model start contributing to the multilepton final states:



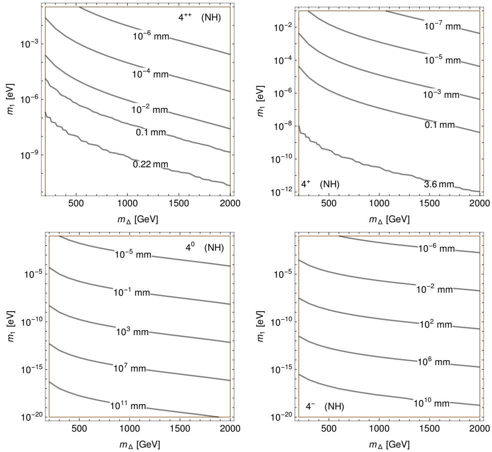
DISPLACED VERTEX

Displaced vertices, LLPs, vanishing charge track signature, *etc.* may result for smaller values of the lightest neutrino mass.



A limited region of $m_1 - m_\Sigma$ parameters' space can be probed at MATHUSLA. For example, $m_\Sigma \sim 1$ TeV and $m_1 \in [\mathcal{O}(10^{-19}) - \mathcal{O}(10^{-18})]$ eV give rise to $\mathcal{O}(100\ \mathrm{m})$ decay length for 3^0 and can be probed at MATHUSLA. On the other hand, 3^+ with $c\tau_{\mathrm{max}} \sim 1$ mm decays into very soft poin and 3^0 and hence, gives rise to interesting disappearing track signature for $m_1 < 10^{-10}$ eV at future *ep*-colliders like LHeC and FCC-he.

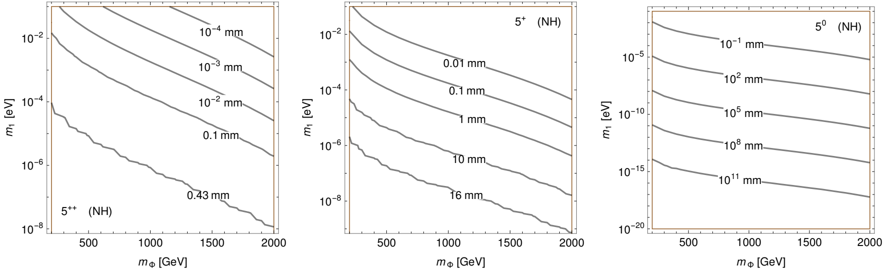
DISPLACED VERTEX (CNTD.)



4^{++} and 4^{+} have $c\tau_{\max}$ of $\sim$ 0.22 and 3.6 mm, respectively. So, one would expect disappearing track signatures at LHeC and FCC-he for $m_1 \leq 10^{-9}$.

A limited region of $m_1 - m_\Delta$ parameters' space can be probed at MATHUSLA for both 4^0 and 4^-. For example, for $m_\Delta \sim 1$ TeV, $m_1 \in [\mathcal{O}(10^{-13}) - \mathcal{O}(10^{-14})]$ eV can be probed at MATHUSLA.

DISPLACED VERTEX (CNTD.)



5^{++} and 5^{+} have $c\tau_{\max}$ of ~ 0.43 and 16 mm, respectively. So, one would expect disappearing track signatures at LHeC and FCC-he for $m_1 \leq 10^{-8}$.

A limited region of $m_1 - m_\Phi$ parameters' space can be probed at MATHUSLA for 5^0. For example, for $m_\Phi \sim 1$ TeV, $m_1 \in [\mathcal{O}(10^{-11}) - \mathcal{O}(10^{-10})]$ eV can be probed at 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.
- LFV arises very naturally in such setup.
- Pair production of exotics for masses below 720, 970 and 1200 GeV are excluded for triplet, quadruplet and quintuplet, respectively.
- The exotics of the model could also be long-lived leaving disappearing track signatures or displaced vertex at the detector.
- The final states (including the disappearing tracks and other displaced vertex signatures) discussed in this work are common to a large class of (seesaw-inspired) models. Once a positive search is found, one has 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.