# Overview of Neutrino Mass Models After LHC Run-II Data

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# Neutrino Mass Models

The neutrino oscillation experiments provided evidences for neutrino flavour oscillations, and hence nonzero neutrino masses and mixings.

**The usual Higgs mechanism:** $N_R$ (1,1,0)

$$-\mathcal{L}_Y = Y_N^{i\alpha} \bar{L}_i \widetilde{H} N_{R\alpha} + \mathrm{H.c.}$$

Dirac neutrino mass: $M_D \sim \frac{Y_N v}{\sqrt{2}}$

1. $m_\nu \sim 0.1\text{eV}$, $Y_N \sim 10^{-12}$: philosophically displeasing
2. Conservation of Lepton Number

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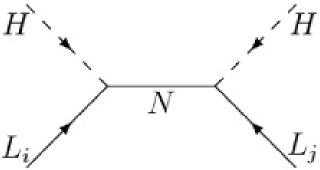
"Of the supposedly exact conservation laws of physics, two are especially questionable: the conservation of baryon number and lepton number."
Weinberg, 1979




*Type-I Seesaw*

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^{\mathsf{T}} & M_N \end{pmatrix}$$

$$M_\nu \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$$

$$V_{\ell N_\alpha} \sim M_D M_N^{-1}$$

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

Majorana mass

$$m_\nu \propto \frac{v^2}{\Lambda}$$

The seesaw mechanism

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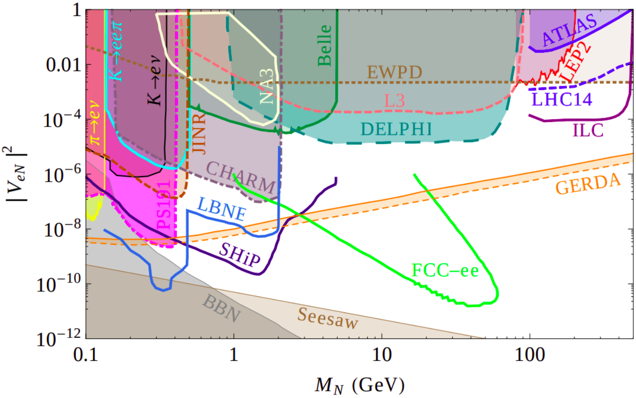
Deppisch, Bhupal Dev, Pilaftsis

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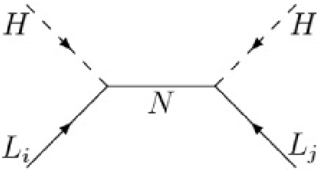


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$$M_\nu \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$$

$$m_\nu \propto \frac{v^2}{\Lambda}$$

The seesaw mechanism

Lagrangian generating

$\nu$-masses

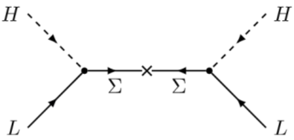
$$M_\Sigma \overline{\tilde{\Sigma}_R}\Sigma_R + \sqrt{2}Y_\Sigma \tilde{H}^\dagger \overline{\Sigma_R} L + \text{h.c.}$$

Seesaw formula

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

$SU(2)_L$ Triplet fermion

$$\begin{pmatrix} \Sigma_R^0/\sqrt{2} & \Sigma_R^+ \\ \Sigma_R^- & -\Sigma_R^0/\sqrt{2} \end{pmatrix}$$




$$U^T m_\nu U = D_{m_\nu} = \text{diag}(m_1, m_2, m_3)$$

Most general texture of $Y_\Sigma$

$$Y_\Sigma = i\frac{\sqrt{2}}{v}\sqrt{M_\Sigma} R \sqrt{D_{m_\nu}} U^\dagger$$

**Production:**

- Drell-Yan processes: $q\,\overline{q'} \to \gamma/Z \to \Sigma^+\Sigma^-$ , $q\,\overline{q'} \to W^\pm \to \Sigma^\pm\Sigma^0$

**Decays:**

- Heavy state transitions: $\Sigma^\pm \to \Sigma^0\pi^\pm$ , $\Sigma^\pm \to \Sigma^0\ell^\pm\nu_\ell$
- SM 2-body decays:
  - $\Sigma^0 \to \nu h$ , $\Sigma^0 \to \nu Z$ , $\Sigma^0 \to \ell^\mp W^\pm$ .
  - $\Sigma^\pm \to \ell^\pm h$ , $\Sigma^\pm \to \ell^\pm Z$ , $\Sigma^\pm \to \nu W^\pm$ .

**Multilepton Final States Search:**

- A recent CMS multilepton search (137.1 fb$^{-1}$) excluded triplet fermions below 880 GeV at 95% CL in flavour democratic scenario. JHEP 03 (2020) 051
- **This CMS limit is not straightforwardly applicable for a realistic type-III seesaw model.**

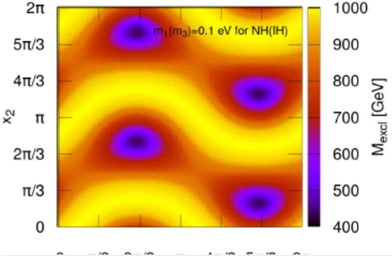
**3RHN**: $\theta_{12} = x_3 + iy_3$, $\theta_{23} = x_1 + iy_1$ and $\theta_{13} = x_2 + iy_2$ with $x_{1,2,3}, y_{1,2,3} \in \mathbb{R}$:

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

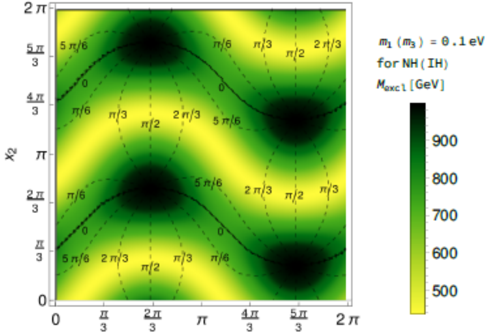
**2RHN**

$$R = \begin{cases} \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} & \text{for NH} \\[2ex] \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \end{pmatrix} & \text{for IH} \end{cases}$$

Only $\Sigma_1$ is produced




Only $\Sigma_2$ is produced




LHC limits are derived for a simplified type-III ssesaw model, not applicable for a realistic model accounting for the neutrino oscillation data.

**Proposal:** Look for $\tau$-rich final states

A. Tumasyan *et al.* [CMS], Phys. Rev. D **105** (2022)

## Type-II Seesaw

### $SU(2)_L$ Triplet Scalar

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

Triplet VEV after the EWSB

$$\langle\Delta\rangle = \begin{pmatrix} 0 & 0 \\ v_t/\sqrt{2} & 0 \end{pmatrix},$$

$$v_t \approx \frac{\mu v_d^2}{\sqrt{2} m_\Delta^2}$$

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Phenomenology: $m_{H^{\pm\pm}}$, $v_t$ and $\Delta m = m_{H^{\pm\pm}} - m_{H^\pm}$

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Constraint on $v_t$ and $\Delta m$

1. Oblique parameters: $|\Delta m| \leq 40$ GeV
2. $\rho$ parameter:
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_w} = \frac{v_d^2 + 2v_t^2}{v_d^2 + 4v_t^2}$$
3. LFV decays: $l_\alpha \to l_\beta \gamma$@1-loop and $l_\alpha \to l_\beta l_\gamma l_\delta$@tree-level.

### Scalar potential

$$-m_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \boxed{[\mu(\Phi^T i\sigma^2 \Delta^\dagger \Phi) + \mathrm{h.c.}]} +$$
$$\lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2 \left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3 \left[\mathrm{Tr}(\Delta^\dagger\Delta)^2\right] + \boxed{\lambda_4 \Phi^\dagger\Delta\Delta^\dagger\Phi}$$

### Triplet Yukawa

$$\boxed{-\mathcal{L}_\nu = Y_{ij}^\nu L_i^T C i\sigma^2 \Delta L_j + \mathrm{h.c.}} \xRightarrow{EWSB} \boxed{m_\nu = \sqrt{2} Y^\nu v_t}$$

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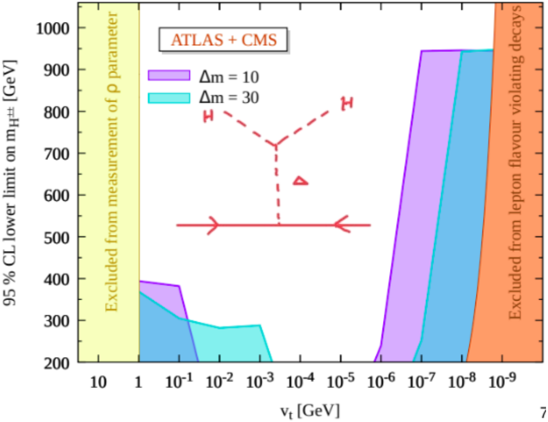
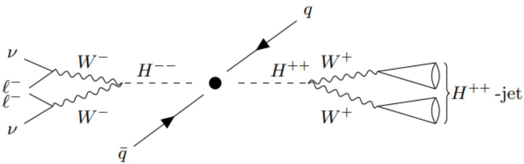
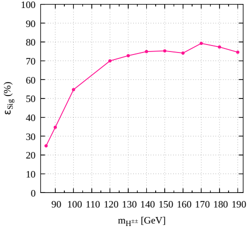
Ashanujjaman, KG, JHEP 03 (2022) 195

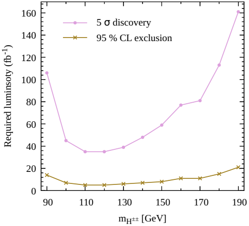


## Search for light (within 84–200 GeV) $H^{\pm\pm} \to W^{\pm} W^{\pm(*)}$




BDT classifier for tagging boosted hadronically decaying $H^{\pm\pm}$

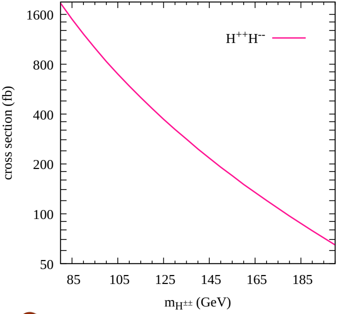



[Ashanujjaman, Ghosh, Sahu, PRD 2023]

## Motivation

Such a low-mass triplet $H^{\pm\pm}$, slightly heavier singly-charged and neutral components can explain the CDF measurement of the $W$-bosoon mass. [Kanemura and Yagyu; Heeck; Bahl, Chiu, Gao, Wang, and Zhong; Cheng, He, Huang, Sun, and Xing]




1. Large Prod. Cross section
2. Soft leptons and jets in the final state

Weinberg operator(s)

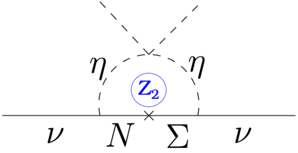
1. $\mathcal{L}_5 \propto \frac{1}{\Lambda} LLHH \Rightarrow \boxed{m_\nu \propto \frac{v^2}{\Lambda}}$
2. $\mathcal{L}_{5+2n} \propto \frac{1}{\Lambda^{2n+1}} LLHH\,(H^\dagger H)^n$

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

1. $\mathcal{L}_5$ at tree level $\longrightarrow$ 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.**

## $\mathcal{L}_5$@loop-level




- Without additional symmetries:
  Interesting Collider Signatures
- With additional symmetries:
  Candidate for dark matter.

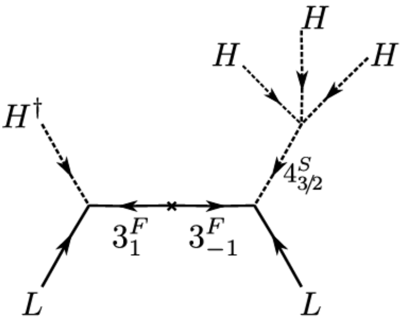
## $\mathcal{L}_5$@tree-level:
## *Type I, Type II and Type III seesaw*

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

How to make $\mathcal{L}_9$ contribution to $m_\nu$ 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**

## Higher Dimensional Neutrino Mass Models

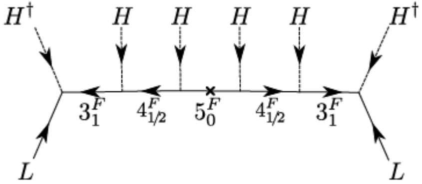


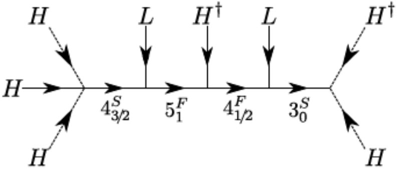

UV completion of generalized Weinberg operator at dimension-7

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

Dimension-9

Anamiati, Castillo-Felisola, Fonseca, Helo, Hirsch, JHEP 12 (2018) 066



# A Genuine Quintuplet (*Type-V*) Seesaw

**Exotic fields:**

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

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

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

**Relevant Lagrangian:**

$$\mathcal{L}_Y = Y_{23}\,\overline{\Sigma_L} H \widetilde{L} + Y_{34}\,\overline{\Delta_R}\Sigma_L H^\dagger + Y'_{34}\,\overline{\Delta_L}\Sigma_R H^\dagger + Y_{45}\overline{\Delta_L}\Phi_R H + Y'_{45}\,\overline{\Delta_R}\widetilde{\Phi}_R H$$

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

**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:**

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

**A Simplified Model:**

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

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

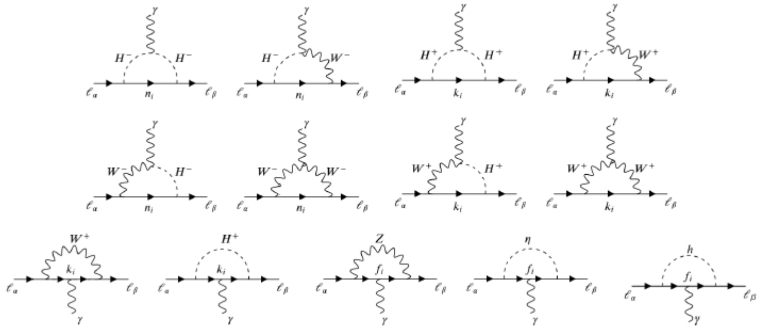
$$M_\Phi = \mathrm{diag}(m_\Phi, m_\Phi, m_\Phi)$$

$$Y'_{34} = \mathrm{diag}(y_{34}, y_{34}, y_{34})$$

$$Y'_{45} = \mathrm{diag}(y_{45}, y_{45}, y_{45})$$

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

## Bounds: Lepton Flavour Violating Decays: $l_\alpha \to l_\beta \gamma$



Plus 14 self-energy diagrams

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

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

Bounds from MEG collaboration

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

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

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

$$\chi_i^{++} \to \ell_j^{+}W^{+} \qquad \chi_i^{+} \to \ell_j^{+}Z/h, \nu W^{+} \qquad \chi_i^{0} \to \ell_j^{\pm}W^{\mp}, \nu Z/h$$

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

- Masses below 720, 970, and 1200 GeV are excluded for triplet, quadruplet and quintuplet, respectively from CMS 3/4 lepton final state search [JHEP 03 (2020) 051].
- Mutilepton + fat-jets final states@LHC
- Displaced vertices, LLPs, vanishing charge track signature, etc. may result for smaller values of the lightest neutrino mass i.e. $m_1(m_3) \to 0$ for NH(IH).

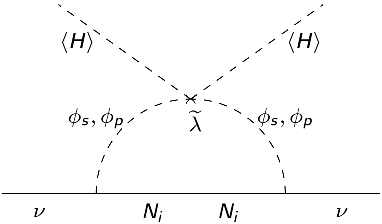
| | $3^{++}(4^{++})\{5^{++}\}[3^{+}]$ | $4^{+}(5^{+})$ | $4^{-}/3^{0}/4^{0}/5^{0}$ |
|---|---|---|---|
| $c\tau_{\max}$ (in mm) | 0.04 (0.22) {0.43} [1.0] | 3.6 (16.0) | arbitrarily large |
| where to look for | LHeC, FCC-he | HL-LHC, LHeC, FCC-he | MATHUSLA |

# Radiative Neutrino Mass Generation

| Symmetry | The SM fields | | | | | | Exotics | |
|---|---|---|---|---|---|---|---|---|
| | $Q_L^\alpha$ | $u_R^\alpha$ | $d_R^\alpha$ | $L_L^\alpha$ | $e_R^\alpha$ | $H$ | $N_R^i$ | $\Phi$ |
| $SU(3)_C$ | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 1 |
| $SU(2)_L$ | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 1 |
| $U(1)_Y$ | $\frac{1}{6}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ | $-\frac{1}{2}$ | $-1$ | $\frac{1}{2}$ | 0 | $\frac{1}{2}$ |
| $Z_2$ | $+$ | $+$ | $+$ | $+$ | $+$ | $+$ | $-$ | $-$ |

The model features a dark matter candidate, but its collider detection remains challenging.

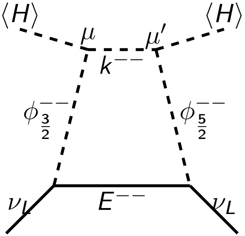
$$\mathcal{L} \ni -{\mu_\phi}^2\, \Phi^\dagger\Phi - \lambda_0(\Phi^\dagger\Phi)^2 - \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) - \lambda_2|H^\dagger\Phi|^2$$
$$-\frac{\widetilde{\lambda}}{2}\left[(H^\dagger\Phi)^2 + \mathrm{h.c.}\right] + \frac{1}{2}M_{N_i}\,\overline{N_i^C}\,N_i - \left[Y^{\alpha i}\,\overline{L_L^\alpha}\,\tilde{\Phi}\,N_R^i + \mathrm{h.c.}\right]$$

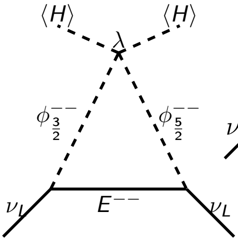



$$M_\nu \simeq \frac{\widetilde{\lambda}v^2}{32\pi^2}\left(Y\mathcal{M}^{-1}Y^T\right)$$

| $G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$ | |
|---|---|
| **Fermions:** | $Q_{\alpha L} = \begin{pmatrix} u_\alpha \\ d_\alpha \end{pmatrix}_L \sim (3, 2, \frac{1}{6}),\quad L_{\alpha L} = \begin{pmatrix} \nu_\alpha \\ e_\alpha \end{pmatrix}_L \sim (1, 2, -\frac{1}{2})$ |
| | $u_{\alpha R} \sim (3, 1, \frac{2}{3}),\quad d_{\alpha R} \sim (3, 1, -\frac{1}{3}),\quad e_{\alpha R} \sim (1, 1, -1)$ |
| | $E^{++}_{\alpha L(R)} \sim (1, 1, 2)$ |
| **Scalars:** | $H = \begin{pmatrix} h^+ \\ \frac{h+i\eta}{\sqrt{2}} \end{pmatrix} \sim (1, 2, \frac{1}{2})$ |
| | $\Phi_{\frac{3}{2}} = \begin{pmatrix} \phi^{++}_{\frac{3}{2}} \\ \phi^{+}_{\frac{3}{2}} \end{pmatrix} \sim (1, 2, \frac{3}{2})$ |
| | $\Phi_{\frac{5}{2}} = \begin{pmatrix} \phi^{+++}_{\frac{5}{2}} \\ \phi^{++}_{\frac{5}{2}} \end{pmatrix} \sim (1, 2, \frac{5}{2})$ |
| | $k^{++} \sim (1, 1, 2)$ |

## Loop-induced Weinberg operator

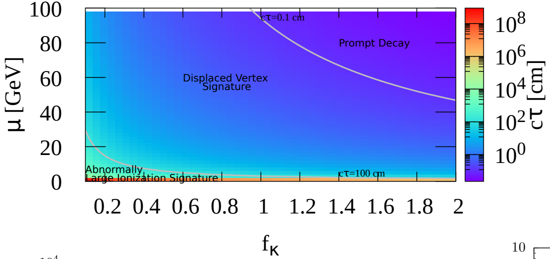


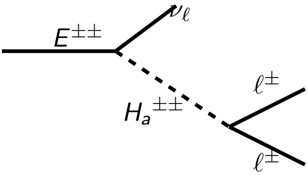



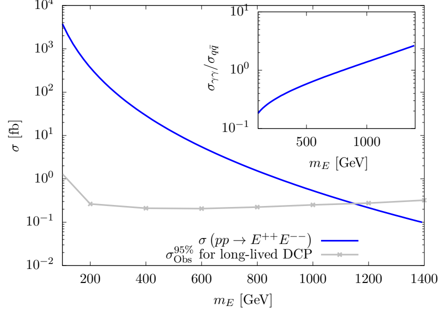

$$\mathcal{L} \supset m_E^{\alpha\beta}\, \overline{E^{++}_\alpha} E^{++}_\beta + y^{\alpha\beta}_{\frac{3}{2}}\, \overline{L_{\alpha L}}\, \Phi_{\frac{3}{2}} \left(E^{++}_{\beta L}\right)^C + y^{\alpha\beta}_{\frac{5}{2}}\, \overline{L_{\alpha L}}\, i\sigma_2\, \Phi^*_{\frac{5}{2}}\, E^{++}_{\beta R} + y_k^{\alpha\beta}\, \overline{e_{\alpha R}}\, k^{--} \left(e_{\beta R}\right)^C -$$

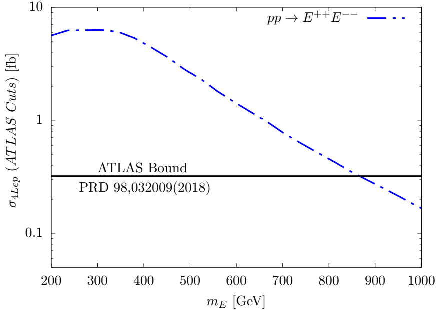
$$+ \mu \left(H^T i\sigma_2 \Phi_{\frac{3}{2}}\right) k^{--} + \mu' \left(H^\dagger \Phi_{\frac{5}{2}}\right) k^{--} + \lambda \left(H^T i\sigma_2 \Phi_{\frac{3}{2}}\right)\left(H^T \Phi^*_{\frac{5}{2}}\right) + \text{c.c.}$$

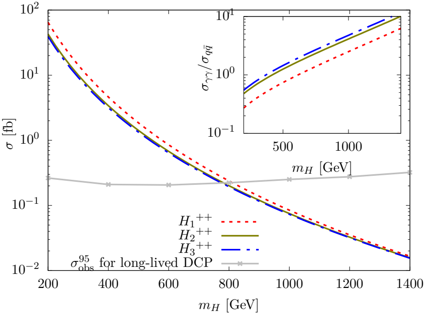
# Collider Signatures (Exotic Fermion)



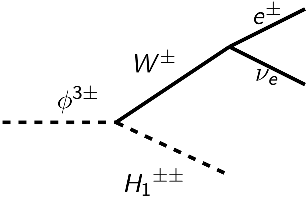



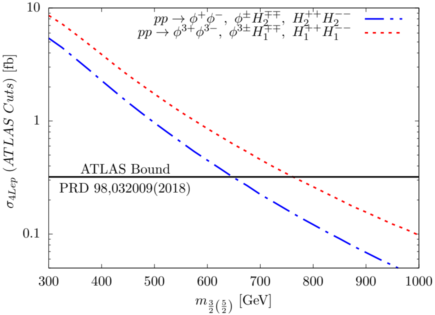



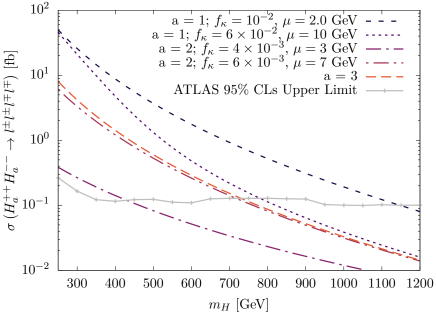






# Exotic Scalars



# Summary

- **Tree-level realizations of the Weinberg operator:**
  The effective dimension-5 operator $\mathcal{L}_{d=5} = \frac{1}{\Lambda}(LH)(LH)$ can arise at tree level through three possible seesaw mechanisms:
  1. **Type-I seesaw:** exchange of heavy Majorana singlet fermions ($N_R$)
  2. **Type-II seesaw:** exchange of scalar $SU(2)_L$ triplet ($\Delta$)
  3. **Type-III seesaw:** exchange of fermionic $SU(2)_L$ triplet ($\Sigma$)

  These generate small Majorana neutrino masses $m_\nu \simeq v^2/\Lambda$ after electroweak symmetry breaking.

- **Higher-dimensional tree-level operators:**
  Extensions of the Weinberg framework involve dimension-7, 9, or higher operators such as $(LH)(LH)(H^\dagger H)/\Lambda^3$, which yield further suppression of neutrino masses and often predict rich scalar or gauge structures.

- **Loop-induced Weinberg operator:**
  In radiative neutrino mass models, the Weinberg operator is realized at one or more loop levels. New scalar and/or fermion fields running in the loop generate

$$m_\nu \sim \frac{1}{(16\pi^2)^n} \frac{v^2}{\Lambda},$$

  naturally explaining the smallness of neutrino masses and often introducing a stable dark matter candidate protected by a discrete symmetry.

Thank You