Lepton Number Violation at the LHC

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Why Lepton Number Violation?

Non-zero neutrino mass $\Rightarrow$ physics beyond the SM

$\nu_e \quad \nu_\mu \quad \nu\tau$

neutrinos

$\begin{array}{cccc}
d & s & b & u
\end{array}$

$\begin{array}{cccc}
c & t
\end{array}$

$\begin{array}{cc}
e & \mu & \tau
\end{array}$

meV eV keV MeV GeV TeV

Something beyond the Higgs mechanism?
Seesaw Mechanism

- A natural way to generate neutrino masses.
- Break the \((B - L)\)-symmetry of the SM.
- Parametrized by the dim-5 operator \((LLHH)/\Lambda\). [Weinberg (PRL '79)]
- Three tree-level realizations: Type I, II, III seesaw mechanisms.

Generically predict lepton number and/or (charged) lepton flavor violation.

Pertinent question in the LHC era:

**Can we probe the seesaw mechanism at the LHC (or future colliders)?**

Experimentally feasible if the seesaw scale is (in)directly accessible.
SM-singlet heavy Majorana neutrinos. [Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]

Same-sign dilepton plus jets without $E_T$ [Keung, Senjanović (PRL '83); Datta, Guchait, Pilaftsis (PRD '94); Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); ... ]

[ Talks by A. Salvucci and J. Kim]
Type-II Seesaw at the LHC

- **SU(2)_L-triplet scalar** (\(\Phi^{++}, \Phi^+, \Phi^0\)). [Schechter, Valle (PRD '80); Magg, Wetterich (PLB '80); Cheng, Li (PRD '80); Lazarides, Shafi, Wetterich (NPB '81); Mohapatra, Senjanović (PRD '81)]

- **Multi-lepton signatures.** [Akeroyd, Aoki (PRD '05); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); del Aguila, Aguilar-Saavedra (NPB '09); Melfo, Nemevsek, Nesti, Senjanović, Zhang (PRD '12)]

### References

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>±±Φ</th>
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<tr>
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Benchmark 1
Benchmark 2
Benchmark 3
Benchmark 4

### Figure 9

Summary of expected and observed limits for each production mode and the combined limit. The shaded region represents the excluded mass points and the thick solid line represents the expected exclusion with the hashed region indicating the direction.

[Talks by A. Salvucci and C. Mills]
**Type-III Seesaw at the LHC**

- **SU(2)_L-triplet fermion (Σ⁺, Σ⁰, Σ⁻).** [Foot, Lew, He, Joshi (ZPC ’89)]
- **Multi-lepton signatures.** [Franceschini, Hambye, Strumia (PRD ’08); Li, He (PRD ’09); Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović (PRD ’10); Ruiz (JHEP ’15)]

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**Backgrounds**

Figure 4: Branching ratios from the pair-produced fermions to the bosonic level of the most relevant decay modes. Within the type-III seesaw model [11], the neutrino is considered a Majorana particle whose mass is of the order of square of the heavy neutrino mass, which is at least 10 orders of magnitude smaller than that of the electron.

In the case of τ → V, the process-specific kinematics are harder to capture using a fully data-driven method; we thus extract the kinematics from MC, while the misidentification rate remains data-driven. The remaining 9% of the background are due to rare processes like τ → ννν.

The remaining backgrounds as shown in Figure 4: the Z + jets estimate is fully data-driven using a method that also covers similar, albeit smaller backgrounds like WW + jets. In our figures, this background is labeled “Misidentified.”

**Table 1: Background control regions (left) are defined by the criteria listed at the top.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Criteria</th>
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<tbody>
<tr>
<td>ZZ</td>
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<tr>
<td>Wν</td>
<td></td>
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<tr>
<td>τV</td>
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**Multi-lepton signatures.**

- **Figure 4:** The 95% confidence level upper limits on the cross section sum for production of heavy fermion pair production for masses below 850 GeV (expected 790 GeV).

**Figure 4:** Branching ratios from the pair-produced fermions to the bosonic level of the most relevant decay modes. The normalization factor is 0.95 ± 0.07 (stat).
Outline

- Low-scale seesaw (mostly focus on type-I)
- Lepton number violating and conserving signals (both are important)
- Beyond the minimal seesaw (gauge extensions)
- Complementarity with low-energy probes (LFV and $0\nu\beta\beta$)
- Consequences for leptogenesis
Why low-scale seesaw?

- In flavor basis \( \{ \nu^c, N \} \), type-I seesaw mass matrix
  \[
  \mathcal{M}_\nu = \begin{pmatrix}
  0 & M_D \\
  M_D^T & M_N
  \end{pmatrix}
  \]

- For \( \| M_D M_N^{-1} \| \ll 1 \), \( M_\nu^{\text{light}} \approx -M_D M_N^{-1} M_D^T \).

- In traditional GUT models, \( M_N \sim 10^{14} \) GeV.

- But in a bottom-up approach, allowed to be anywhere (down to eV-scale).
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**Suggestive upper limit** \( M_N \lesssim 10^7 \text{ GeV} \) from naturalness arguments.

[Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya, BD, Goswami, Khan, Rodejohann (PRD '17)]
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Similar naturalness arguments in the context of neutral top partners [Batell, McCullough (PRD '15)] and warped seesaw [Agashe, Hong, Vecchi (PRD '16)] also predict a low seesaw scale.
Low-scale seesaw with large mixing

- Naively, active-sterile neutrino mixing is small for low-scale seesaw:
  \[ V_{iN} \simeq M_D M_N^{-1} \simeq \sqrt{\frac{M_\nu}{M_N}} \lesssim 10^{-6} \sqrt{\frac{100 \text{ GeV}}{M_N}} \]

- ‘Large’ mixing effects possible with special structures of \( M_D \) and \( M_N \). [Pilaftsis (ZPC ’92); Kersten, Smirnov (PRD ’07); Gavela, Hambye, Hernandez, Hernandez (JHEP ’09); Ibarra, Molinaro, Petcov (JHEP ’10); Deppisch, Pilaftsis (PRD ’11); Adhikari, Raychaudhuri (PRD ’11); Mitra, Senjanović, Vissani (NPB ’12)]
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- One example: [Kersten, Smirnov (PRD '07)]

\[
M_D = \begin{pmatrix}
    m_1 & \delta_1 & \epsilon_1 \\
    m_2 & \delta_2 & \epsilon_2 \\
    m_3 & \delta_3 & \epsilon_3 \\
\end{pmatrix}
\quad \text{and} \quad
M_N = \begin{pmatrix}
    0 & M_1 & 0 \\
    M_1 & 0 & 0 \\
    0 & 0 & M_2 \\
\end{pmatrix}
\quad \text{with} \, \epsilon_i, \delta_i \ll m_i.
\]

- In the limit \( \epsilon_i, \delta_i \to 0 \), all three light neutrino masses vanish at tree-level, while the mixing given by \( V_{ij} \sim m_i/M_j \) can still be large.

- The textures can be stabilized by invoking discrete symmetries. [Kersten, Smirnov (PRD '07); BD, Lee, Mohapatra (PRD '13)]

- But LNV is suppressed, as generically expected due to constraints from neutrino oscillation data and 0νββ. [Abada, Biggio, Bonnet, Gavela, Hambye (JHEP '07); Ibarra, Molinaro, Petcov (JHEP '10); Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, Lucente (JHEP '15)]
For suitable choice of CP phases, resonant enhancement of the LNV amplitude for $\Delta m_N \lesssim \Gamma_N$. [Bray, Pilaftsis, Lee (NPB ’07)]

$$A_{\text{LNV}} \propto V_{\ell N}^2 \frac{2\Delta m_N}{\Delta m_N^2 + \Gamma_N^2} + \mathcal{O} \left( \frac{\Delta m_N}{m_N} \right)$$

Just like resonant enhancement of CP-asymmetry.

\[ V_{e1} = V_{\mu 1} = V_{\mu 2} = 0.05, \quad V_{e2} = 0.05i \]
A Natural Low-scale Seesaw

- **Inverse seesaw** mechanism [Mohapatra (PRL '86); Mohapatra, Valle (PRD '86)]
- Two sets of SM-singlet fermions with opposite lepton numbers.
- Neutrino mass matrix in the flavor basis \(\{\nu^c, N, S^c\}\):

\[
\mathcal{M}_\nu = \begin{pmatrix}
0 & M_D & 0 \\
M_D^T & 0 & M_N^T \\
0 & M_N & \mu
\end{pmatrix} \equiv \begin{pmatrix}
0 & \mathcal{M}_D \\
\mathcal{M}_D^T & \mathcal{M}_N
\end{pmatrix}
\]

\[
\mathcal{M}_{\nu}^{\text{light}} = (M_D M_N^{-1}) \mu (M_D M_N^{-1})^T + \mathcal{O}(\mu^3).
\]

- \(L\)-symmetry is restored when \(\mu \to 0\).
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\]

- \( L \)-symmetry is restored when \( \mu \to 0 \).
- Naturally allows for large mixing: \( V_{lN} \approx \sqrt{\frac{M_\nu}{\mu}} \approx 10^{-2} \sqrt{\frac{1 \text{ keV}}{\mu}} \) as long as constraints from EWPD [Akhmedov, Kartavtsev, Lindner, Michaels, Smirnov (JHEP '13); de Blas '13] are satisfied.
- Potentially large (LNC) signals at colliders. [del Aguila, Aguilar-Saavedra (PLB '09); Chen, BD (PRD '12); Das, BD, Okada (PLB '14); Dev, Mohapatra (PRL '15); Anamiati, Hirsch, Nardi (JHEP '16)]

**Important to also look for opposite-sign dilepton and trilepton signals.**
New Contributions to Heavy Neutrino Production

Collinear-enhancement mechanism [BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15); Degrande, Mattelaer, Ruiz, Turner (PRD '16); Das, Okada (PRD '16)]

\[
\frac{\sigma_{N^3LL}}{\sigma_{LO}} \sim 2 - 3
\]

Neutral current production of \(N\) is the largest rate at LHC [Preliminary] RR, Spannowsky, Waite [Very Soon]

[Nv DY@NLO + GF@N^3LL]
[Nf^+ - NLO]
[Nf^+ - NLO]
[Nv - GF N^3LL]
[Nv - GF LO]
[Nf^+ - VBF NLO]

\[14 \text{ TeV LHC}\]

Preliminary

[Talk by R. Ruiz (Pheno17)]
Higgs Decay

Also potentially measurable effects in triple Higgs coupling [Baglio, Weiland (PRD '16, JHEP '17)]
Z Decay

(a) Decay length 10-100 cm, $10^{12} Z^0$

(b) Decay length 10-100 cm, $10^{12} Z^0$

[Blondel, Graverini, Serra, Shaposhnikov '14]
For masses $0.001 \leq M_N \leq 10$, we have access to the resources needed for data-driven use a data-driven approach to estimate lepton fakes fied for this case. 

are very rare and may rely on improperly modelled jet requirement that the heavy-flavor meson decay, or from light hadrons that decay products' separation increases. Furthermore, the either come from an actual lepton originating from a final-state jets is mis-tagged as a lepton; this "fake" can the sensitivity of this analysis could be further improved backgrounds can fake trilepton signatures if one of the internal state, we consider only parton-level events. We show next-to-leading-order values [85–87].

The dominant backgrounds are reframed in the trilepton final state with no OSSF lepton pairs in the final state, SM backgrounds involving constraints from the constraints on the low-mass signal region [65], and here we recast the analysis to determine the low $N$ GeV, $H_T < 200$ GeV, OSSF-0 bin with 0 $b$-jets from Ref. [80], we find that the CMS trilepton analysis is competitive with other search channels, this suggests that a

produced in the decay of $N$ for our proposed prompt trilepton search with no OSSF leptons. The first is the trilepton invariant mass, $M_{\ell^+\ell^-\ell^\mp}$; because the invariant mass of the three leptons

are not separately resolved. Therefore, the alignment of

wee perform a Monte Carlo Fastjet 3 package [84]. Signal tables that are powerful discriminants between signal and constraints from the ground looks nearly identical to the signal. Thus, the

for signal events, one of the final-state jets is uncorrelated for

produced in the decay of $N$ instead the purely leptonic decay,

for $N$ GeV, $H_T < 40, 50$ GeV bin. For both signal mass points, there constraints on the low-mass signal region

are either very tiny signal events, or worst than the LEP constraints for $N$. This search has been recast for

arbitrary

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should

larger than or worse than the LEP constraints for $N$. This search was originally de-

... FIG. 7: Production and decay of $N$ for our proposed prompt trilepton search with no OSSF leptons. The first is the trilepton invariant mass,

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produced in the decay of $N$ instead the purely leptonic decay,
In this section we summarize our findings regarding the sensitivity of the detector response and the backgrounds is required. For a realistic estimate of the sensitivity a thorough study have then be used to estimate the sensitivity of the LHC assuming less than five signal events as the exception. Furthermore, from the jet reconstruction. For a more realistic estimate we thus have to lower the threshold for jet search in displaced vertex electron as much as possible is absolutely necessary to note that already run 2 at the LHC can provide mass reach to masses up to 20 GeV. We presented a first look at the possible mass energies than the FCC-hh/SppC, respectively. We emphasize that our estimates are 200 GeV in fig. 10, assuming a total integrated luminosities for sterile neutrinos at future colliders to 30 GeV, e.g. via the lepton-dijet signature via this channel. The increase in center-of-mass energy of up to 80% [101–103] that will collide with 100% e with 100% e, very large luminosities or significantly improved the sensitivities of all signatures.

\[ L = c \bar{\gamma} \tau_N \approx 0.12 \bar{\gamma} \left( \frac{10 \text{GeV}}{m_N} \right)^5 \left( \frac{1}{10 \text{T eV}} \right)^4 \]

Displaced Vertex calculated at the parton level, and for all the new signatures hh/SppC, respectively. We note that the hadron colliders are sensitive to dilepton-trijet signature via the lepton-dijet final states hanges this mass reach to 50 TeV. The red dashed lines are the expected sensitivity for interesting to note that already run 2 at the LHC can provide

\[ \langle |V_{14}|^2 \rangle \]

\[ m_N (\text{GeV}) \]

\[ |e|^2 \]

\[ M (\text{GeV}) \]

[Helio, Kovalenko, Hirsch (PRD '14)]

[Antusch, Cazzato, Fischer '16]
Our aim in this section is to do a simple estimate of the bounds on the coupling $g_{N/\nu}$ from searches of higgs decays to two displaced vertices at LHC. A closely related calculation has been done in the context of $U(1)_0$ models in [50], where the signal selection has been performed following recent searches by the CMS collaboration [51, 52]. We have considered two different analyses: 1) a search of displaced tracks in the inner tracker where at least one displaced lepton, $e$ or $\mu$, is reconstructed from each vertex; 2) a search for displaced tracks in the muon chambers and outside the inner tracker where at least one $\mu$ is reconstructed from each vertex. The charges are not restricted and therefore events with same-sign or opposite sign leptons are possible.

For simplicity we will consider only semileptonic decays of the $N_i$ which give rise to two lepton final states through the decay $N_i \to l^\pm W \to l^\pm q\bar{q}$. (3.17)

We consider a parton-level Monte Carlo analysis using Madgraph5 [53] at LHC with a center-of-mass energy of 13TeV and 300 fb$^{-1}$ luminosity. We include only the dominant gluon fusion higgs production and we consider the production of just one neutrino species, $N_1$. The production cross section $pp \to h \to N_1N_1$ is shown in Fig. 5 as a function of the heavy neutrino mass for various values of the coupling $g_{N/\nu}^2$. In Fig. 6 we show the $\text{Br}(H \to N_1N_1)$ as a function of $g_{N/\nu}$ for various values of the mass (here we assume the higgs decays just to one neutrino).

The $p_T$ of the two leading leptons is shown in Fig. (7). Following [50], the signal selection is done by requiring two lepton tracks, $e$ or $\mu$ that satisfy the following kinematical cuts on transverse momentum, pseudorapidity and isolation of the two tracks:

$$p_T(l) > 26 \text{ GeV}, \quad \vert \eta \vert < 2, \quad R > 0.2, \quad \cos \theta_{\mu\mu} > 0.75.$$ (3.18)

In the case of muons a constraint in the opening angle $\theta_{\mu\mu}$ is imposed in order to reduce the cosmic muon background. The efficiencies resulting from these consecutive cuts for

[Caputo, Hernandez, Lopez-Pavon, Salvado '17]
LNV in $B$-meson decays

\[ |V_{\mu 4}|^2 \]

\[ \text{LHCb} \]

\[ |V_{\mu 4}|^2 \text{ as a function of } m_N \text{ for } L \text{ events.} \]

In conclusion, we have searched for on-shell Majorana neutrinos coupling to muons in $B$-meson decays $B \rightarrow \pi^+\mu^+\mu^-$, where $N$ is a putative Majorana neutrino. The mass spectra of the selected candidates are shown in Fig. 2. An extended unbinned maximum likelihood fit is used to set constraints on the signal yield. The resulting 95% C.L. limit on $|V_{\mu 4}|^2$ is shown in Fig. 6 as a function of $m_N$ for $L$ events.

We use the method to set upper limits [13], which requires the determination of the expected background yields and total number of events in the signal region. We find 282,774 events in the normalization channel. Backgrounds in the decay channel are estimated with a double-Crystal Ball function [12] plus a triple-Gaussian background to account for partially reconstructed vertex with a cosine of the angle between the trajectory back to a near approach with another combination.

ν-neutrino search from a few picoseconds to one nanosecond. The same criteria apply for the channel we use for normalization purposes, where...
Figure 1: Feynman diagram for $B^-$ meson decay to $\bar{b} u \rightarrow W^- N \rightarrow \mu^- \mu^+ \pi^+$. The mass spectra of the selected candidates are shown in Fig. 2. An extended unbinned likelihood fit is performed to the candidates appearing in both.

The same criteria apply for the channel we use for normalization purposes, with the primary vertex divided by its uncertainty must be greater than 10. The two cases are not exclusive, with 16% of the event vertex with a $N$ candidate decay vertex is searched for by extrapolating the trajectory back to a near approach with another $N$ candidate, which must form a common vertex with a $\mu^-$.

$V_{\mu 4}$ is inversely proportional to $m_N$ (below 2 GeV), the change in eq. (3) leads to a substantially smaller event rate at low values of $m_N$. At low values of $m_N$, the updated correction factors for $B^+ \rightarrow \mu^+ \mu^0$ and $B^0 \rightarrow \mu^+ \mu^−$ include the factor $g_{43}/g_{47}$.

In both categories, only tracks that start in the VELO are used. We require $N$ candidates we require that the $N$ trajectory back to a near approach with another $N$ case and the normalization channel, candidate $N$ decay via a Majorana neutrino labelled $\nu$.

$V_{\mu 4}$ is inversely proportional to $m_N$ (above 3 GeV), the updated correction factors for $B^+ \rightarrow \mu^+ \mu^0$ and $B^0 \rightarrow \mu^+ \mu^−$ lead to a substantially smaller event rate at low values of $m_N$.

$\tau$-decay events come from two $e^-$ and two $\mu^-$, which include the factor $g_{43}/g_{47}$. Muon candidate tracks are required to have hits in the muon chambers.
[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]
New limits from NA48/2 [Talk by M. Pepe]
Summary Plot (Tau Sector)

[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]
\[ U(1)_{B-L} \] Extension

**Diagram**

- **LHC Process**: \( Z' \rightarrow \ell \ell \)
- **Signal Events**: \( Z' \rightarrow 2j \)
- **Cross Sections**:
  - \( 10^2 \) fb
  - \( 10 \) fb
  - 1 fb

**Displaced Vertex Signal (LNV/LFV)**

- \( \text{FILE Viez Perez, Han, Li (PRD '09); Deppisch, Desai, Valle (PRD '14); Hecck, Teresi (PRD '16)}} \)
Probing Neutrino Mass Hierarchy at the LHC

\[ L (m) \]

\[ \theta_R/\pi \]

\[ M_{N} \text{ (GeV)} \]

\[ \sigma_{\text{LNV}} \text{ (fb)} \]

[BD, Hagedorn, Molinaro (in prep.)]
New contribution to Drell-Yan process via $W_R$ exchange. [Keung, Senjanović (PRL '83); Ferrari et al (PRD '00); Nemevsek, Nesti, Senjanović, Zhang (PRD '11); Das, Deppisch, Kittel, Valle (PRD '12); Lindner, Queiroz, Rodejohann, Yaguna (JHEP '16); Mitra, Ruiz, Scott, Spannowsky (PRD '16)]
L-R Seesaw Phase Diagram

(a) LL  (b) RR  (c) RL  (d) LR

$|V_{eN}|^2 = 10^{-6}$

$M_N = 1 \text{ TeV}$

$M_{W_R}$ (TeV)  $m_{W_R}$ (TeV)

[Chen, BD, Mohapatra (PRD '13); BD, Kim, Mohapatra (JHEP '16)]
Displaced Vertex Signal

$\sqrt{s} = 14$ TeV

3000 fb$^{-1}$

$m_{W_R} \text{ [TeV]}$

$m_N \text{ [GeV]}$

Applicable for light RH neutrinos

[Castillo-Felisola, Dib, Helo, Kovalenko, Ortiz (PRD ’15); BD, Mohapatra, Zhang ’17]
Under $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, 

$$\Phi = \left( \begin{array}{c} \phi_1^0 \\ \phi_2^- \\ \phi_1^+ \\ \phi_2^0 \end{array} \right) : (1, 2, 2, 0), \quad \Delta_R = \left( \begin{array}{cc} \Delta_R^+ / \sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+ / \sqrt{2} \end{array} \right) : (1, 1, 3, 2).$$

(See [Fileviez Perez, Murgui, Ohmer (PRD '16)] for a simple alternative)

- 8 physical scalar fields, denoted by $\{ h, H_1^0, A_1^0, H_3^0, H_1^\pm, H_2^{\pm \pm} \}$.
- FCNC constraints require the bidoublet scalars $(H_1^0, A_1^0, H_1^\pm)$ to be $\gtrsim 10 - 20$ TeV.

[An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14)]
Extended Higgs Sector

- Under $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$,

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} : (1, 2, 2, 0), \quad \Delta_R = \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix} : (1, 1, 3, 2).$$

(See [Fileviez Perez, Murgui, Ohmer (PRD ‘16)] for a simple alternative)

- 8 physical scalar fields, denoted by $\{ h, H_1^0, A_1^0, H_3^0, H_1^\pm, H_2^{\pm\pm} \}$.
- FCNC constraints require the bidoublet scalars $(H_1^0, A_1^0, H_1^\pm)$ to be $\gtrsim 10 – 20$ TeV. [An, Ji, Mohapatra, Zhang (NPB ‘08); Bertolini, Maiezza, Nesti (PRD ‘14)]

- Doubly-charged scalars can give rise to distinct LNV signals at the LHC.

[Daly, Ohmer (JHEP ‘16)]

\[ \sqrt{s} = 14 \text{ TeV, } \mathcal{L} = 3 \text{ ab}^{-1} \]
Light Scalar as a New Probe of Seesaw

- The CP-even neutral triplet component $H_3^0$ can be light (GeV-scale).
- Suppressed coupling to SM particles (either loop-level or small mixing).
- FCNC constraints necessarily require it to be long-lived.
- Unique displaced diphoton signal at the LHC.

![Graph showing cosmo logical limits and particle decay channels.](image)

[BD, Mohapatra, Zhang '16; '17]
Any observation of LNV signal at the LHC will falsify high-scale leptogenesis.

[Deppisch, Harz, Hirsch (PRL '14)]

In specific seesaw models, can also falsify low-scale leptogenesis. [Blanchet, Chacko, Granor, Mohapatra (PRD '10); Frere, Hambye, Vertongen (JHEP '09); BD, Lee, Mohapatra '15; Dhuria, Hati, Rangarajan, Sarkar (PRD '15)]
Neutrino mass is so far the only laboratory evidence for BSM physics.

Understanding the neutrino mass mechanism will provide important insights into the BSM world.

LHC provides a ripe testing ground for low-scale neutrino mass models.

Important to search for both lepton number violating and conserving channels.

Healthy complementarity at the intensity frontier (e.g. LFV and $0\nu\beta\beta$ experiments).

LNV searches have important consequences for leptogenesis.