Lepton Number Violation at the LHC

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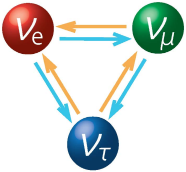
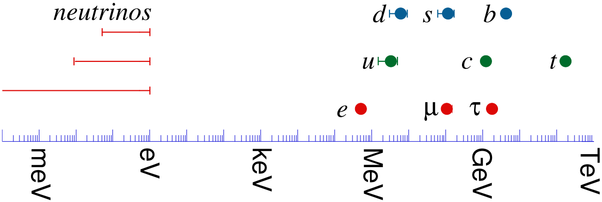
Why Lepton Number Violation?



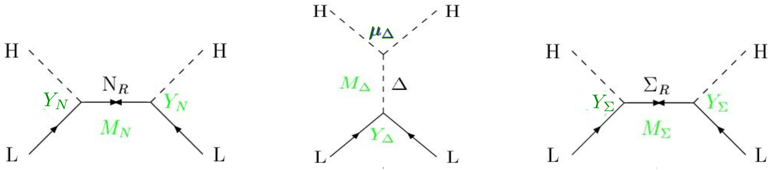
Non-zero neutrino mass $\Longrightarrow$ physics beyond the SM



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.



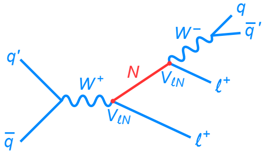
- Generically predict lepton number and/or (charged) lepton flavor violation.
- Pertinent question in the LHC era:

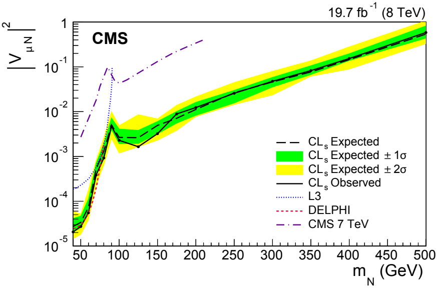
Can we probe the seesaw mechanism at the LHC (or future colliders)?

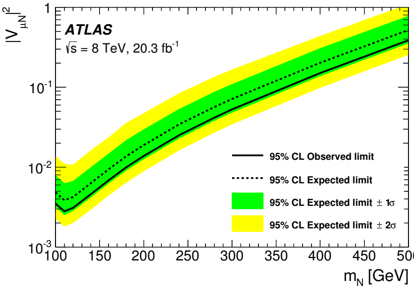
- Experimentally feasible if the seesaw scale is (in)directly accessible.

(Minimal) Type-I Seesaw at the LHC

- 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 $\not{E}_T$ [Keung, Senjanović (PRL ’83); Datta, Guchait, Pilaftsis (PRD ’94); Han, Zhang (PRL ’06); del Aguila, Aguilar-Saavedra, Pittau (JHEP ’07); · · ·]



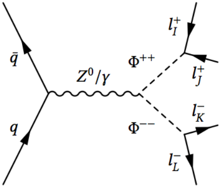




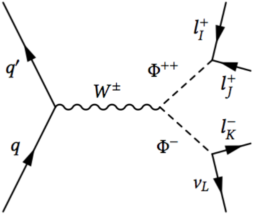
[Talks by A. Salvucci and J. Kim]

Type-II Seesaw at the LHC

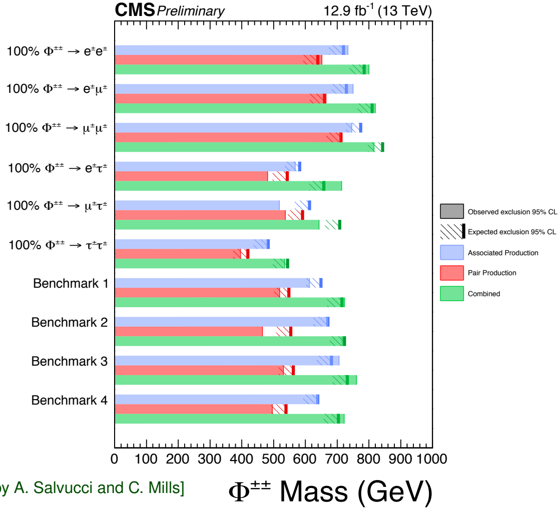
- $SU(2)_L$-triplet scalar $(\Phi^{++}, \Phi^{+}, \Phi^{0})$. [Schechter, Valle (PRD '80); Magg, Wetterich (PLB '80); Cheng, Li (PRD '80); Lazarides, Shafi, Wetterich (NPB '81); Mohapatra, Senjanović (PRD '81)]
- Multi-lepton signatures. [Akeroyd, Aoki (PRD '05); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); del Aguila, Aguilar-Saavedra (NPB '09); Melfo, Nemevsek, Nesti, Senjanović, Zhang (PRD '12)]



(a) 4ℓ



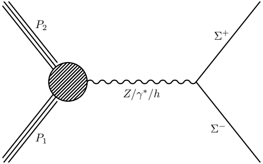
(b) 3ℓ

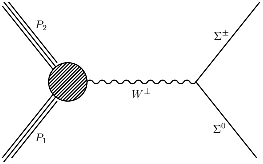


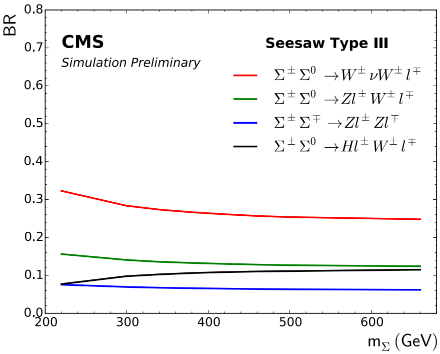
[Talks by A. Salvucci and C. Mills]

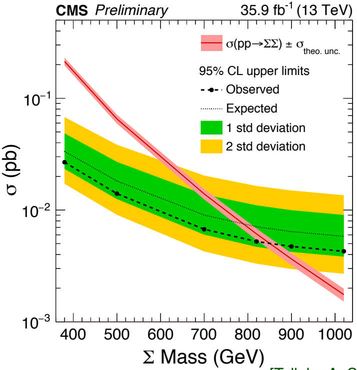
Type-III Seesaw at the LHC

- $SU(2)_L$-triplet fermion $(\Sigma^+, \Sigma^0, \Sigma^-)$. [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)]









[Talk by A. Salvucci]

Outline

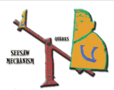
- Low-scale seesaw (mostly focus on type-I)
- Lepton number violating and conserving signals (both are important)
- Beyond the minimal seesaw (gauge extensions)
- Complementarity with low-energy probes (LFV and $0\nu\beta\beta$)
- Consequences for leptogenesis

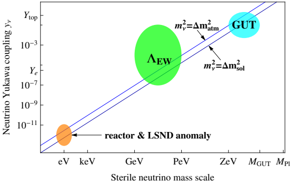
Why low-scale seesaw?

- In flavor basis $\{\nu^c, N\}$, type-I seesaw mass matrix

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

- For $||M_D M_N^{-1}|| \ll 1$, $\boxed{M_\nu^{\rm light} \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}}$.
- 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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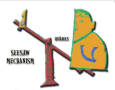

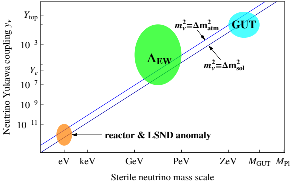

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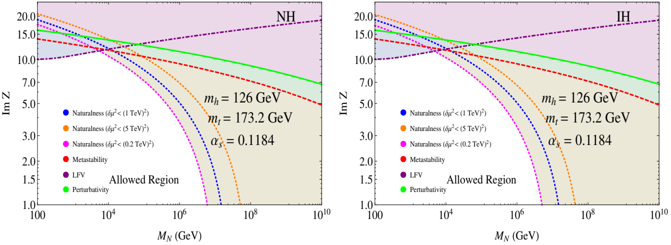
Suggestive *upper* limit $M_N \lesssim 10^7$ GeV from naturalness arguments.

[Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya, BD, Goswami, Khan, Rodejohann (PRD '17)]



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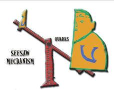

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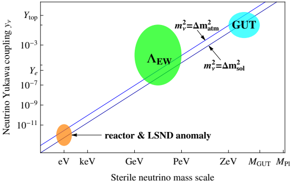

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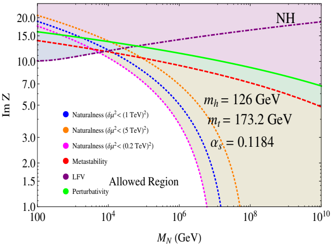

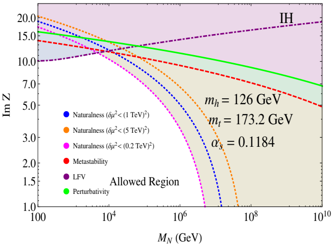

Similar naturalness arguments in the context of neutral top partners [Batell, McCullough (PRD '15)] and warped seesaw [Agashe, Hong, Vecchi (PRD '16)] also predict a low seesaw scale.

Low-scale seesaw with large mixing

- Naively, active-sterile neutrino mixing is small for low-scale seesaw:

$$V_{lN} \simeq M_D M_N^{-1} \simeq \sqrt{\frac{M_\nu}{M_N}} \lesssim 10^{-6}\sqrt{\frac{100\ \mathrm{GeV}}{M_N}}$$

- '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)]

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

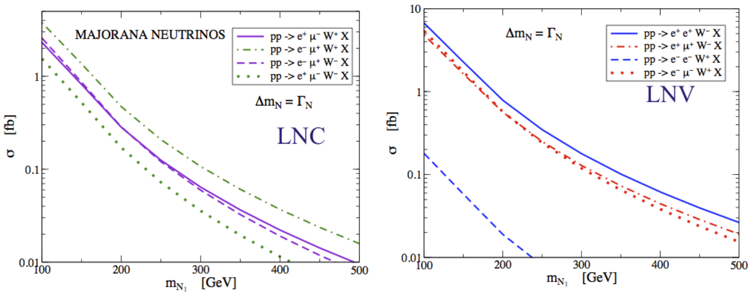
- In the limit $\epsilon_i, \delta_i \to 0$, all three light neutrino masses vanish at tree-level, while the mixing given by $V_{ij} \sim m_i/M_j$ can still be large.
- The textures can be stabilized by invoking discrete symmetries. [Kersten, Smirnov (PRD '07); BD, Lee, Mohapatra (PRD '13)]
- But LNV is suppressed, as generically expected due to constraints from neutrino oscillation data and $0\nu\beta\beta$. [Abada, Biggio, Bonnet, Gavela, Hambye (JHEP '07); Ibarra, Molinaro, Petcov (JHEP '10); Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, Lucente (JHEP '15)]

An Exception

- For suitable choice of CP phases, resonant enhancement of the LNV amplitude for $\Delta m_N \lesssim \Gamma_N$. [Bray, Pilaftsis, Lee (NPB '07)]

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

- Just like resonant enhancement of CP-asymmetry.



$$V_{e1} = V_{\mu 1} = V_{\mu 2} = 0.05,\ V_{e2} = 0.05i$$

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 $\{\nu^c, N, S^c\}$:

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

$$M_\nu^{\rm light} = (M_D M_N^{-1})\, \mu\, (M_D M_N^{-1})^{\mathsf{T}} + \mathcal{O}(\mu^3).$$

- L-symmetry is restored when $\mu \to \mathbf{0}$.

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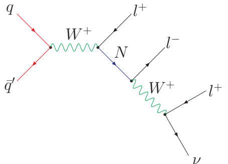
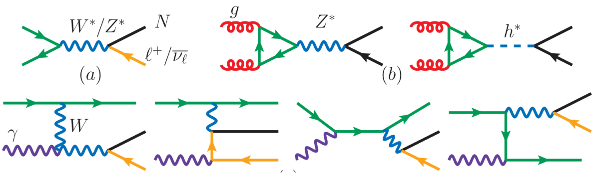
- L-symmetry is restored when $\mu \to \mathbf{0}$.
- Naturally allows for large mixing: $V_{lN} \simeq \sqrt{\frac{M_\nu}{\mu}} \approx 10^{-2}\sqrt{\frac{1\ \rm keV}{\mu}}$ as long as constraints from EWPD [Akhmedov, Kartavtsev, Lindner, Michaels, Smirnov (JHEP '13); de Blas '13] are satisfied.
- Potentially 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)]

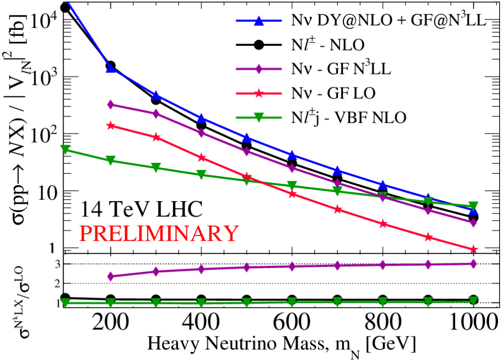
Important to also look for opposite-sign dilepton and trilepton signals.



New Contributions to Heavy Neutrino Production

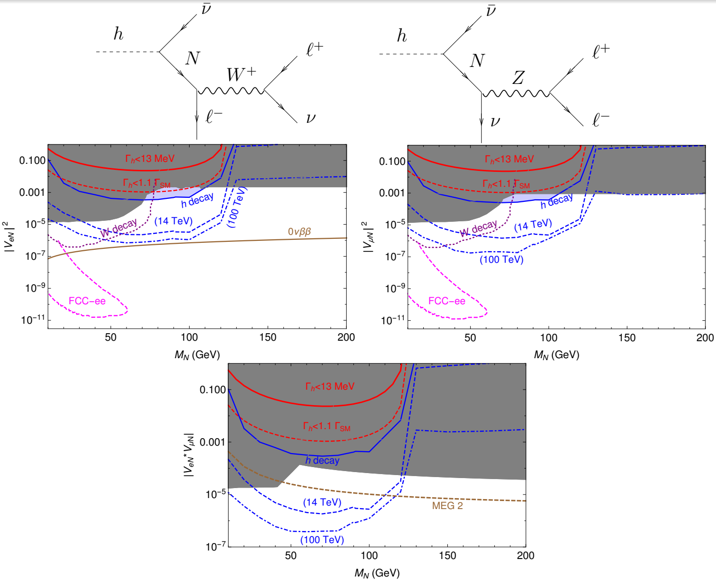
Collinear-enhancement mechanism [BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15); Degrande, Mattelaer, Ruiz, Turner (PRD '16); Das, Okada (PRD '16)]





[Talk by R. Ruiz (Pheno17)]

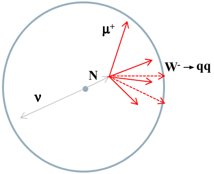
Higgs Decay

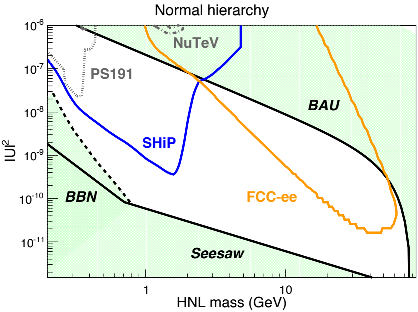


[BD, Franceschini, Mohapatra (PRD ’12); Cely, Ibarra, Molinaro, Petcov (PLB ’13); Das, BD, Kim (PRD ’17)]

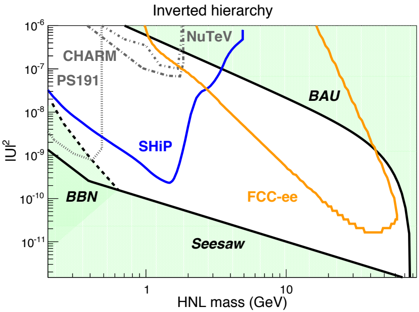
Also potentially measurable effects in triple Higgs coupling [Baglio, Weiland (PRD ’16, JHEP ’17)]

Z Decay





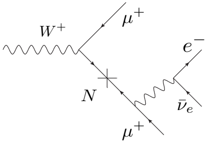
(a) Decay length 10-100 cm, 10^{12} Z^0

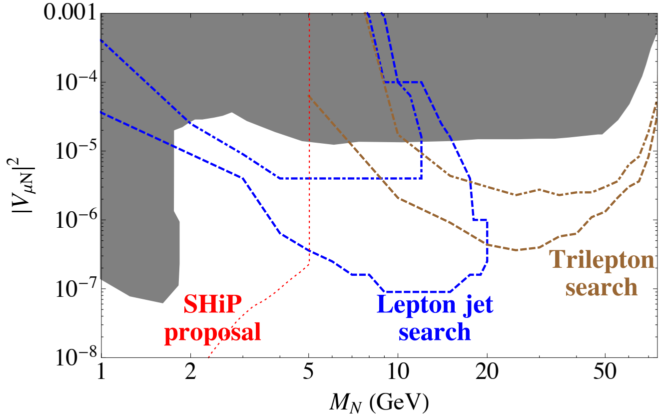


(a) Decay length 10-100 cm, 10^{12} Z^0

[Blondel, Graverini, Serra, Shaposhnikov ’14]

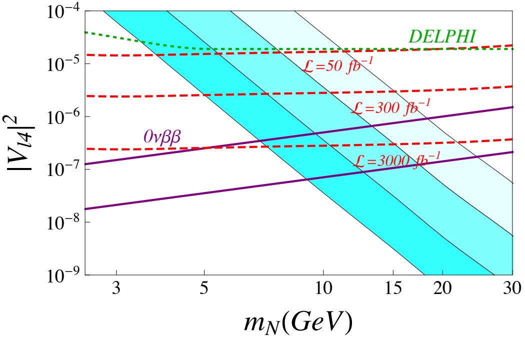
W Decay



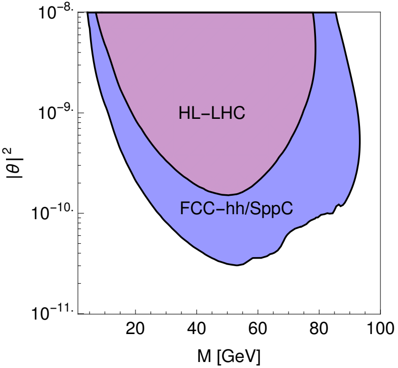


[Izaguirre, Shuve (PRD ’15); Dib, Kim (PRD ’15); Dib, Kim, Wang, Zhang (PRD ’16)]

Displaced Vertex

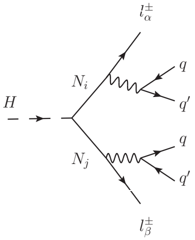


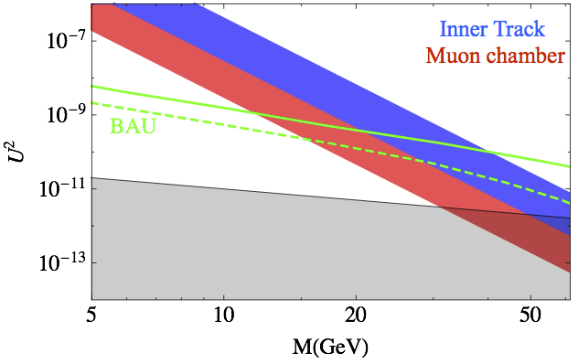
[Helo, Kovalenko, Hirsch (PRD '14)]



[Antusch, Cazzato, Fischer '16]

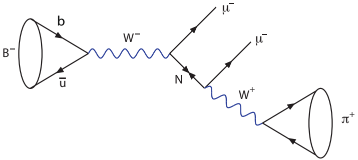
Displaced Vertex in Higgs Decay

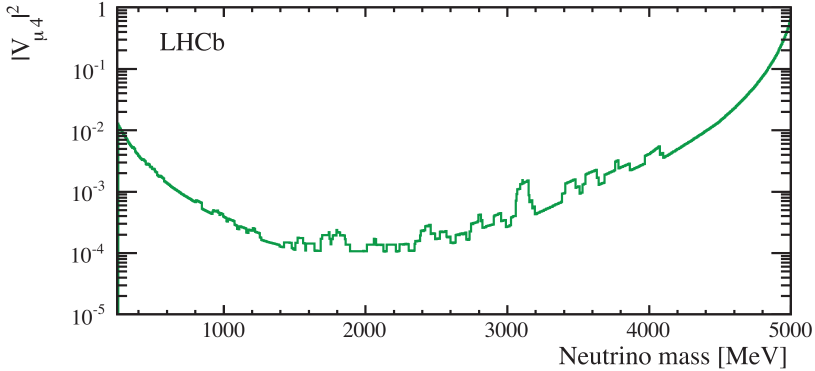




[Caputo, Hernandez, Lopez-Pavon, Salvado '17]

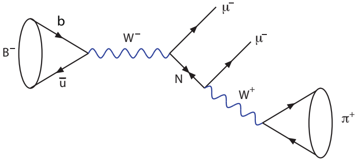
LNV in *B*-meson decays

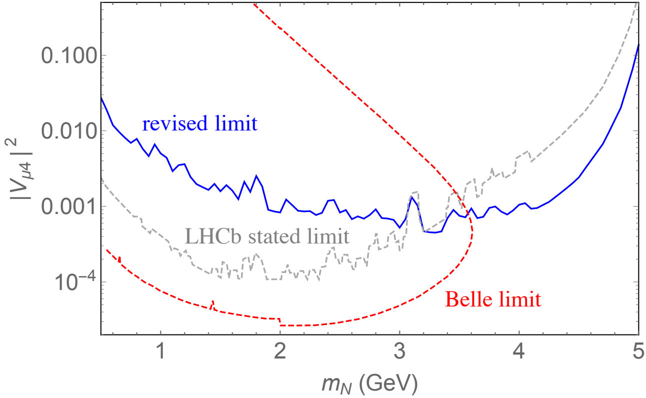




[Aaij *et al.* (PRL '14)]

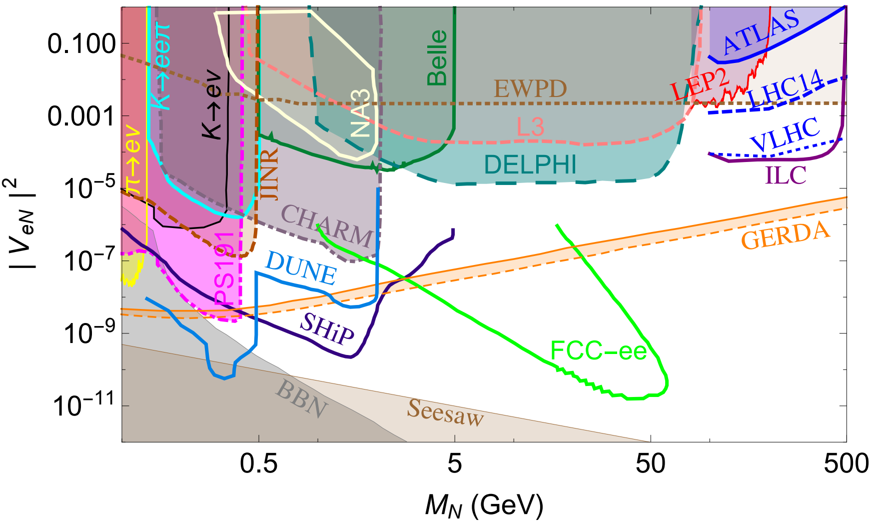
LNV in B-meson decays





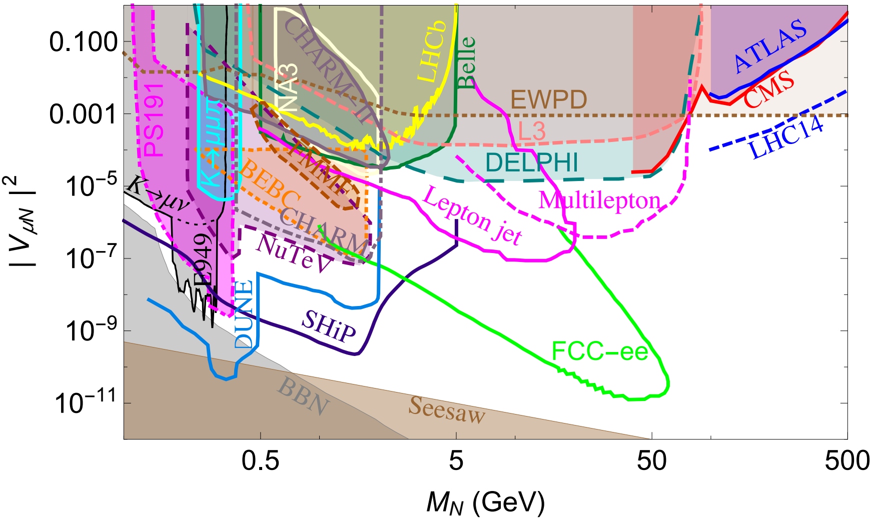
[Shuve, Peskin (PRD '16)]

Summary Plot (Electron Sector)



[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]

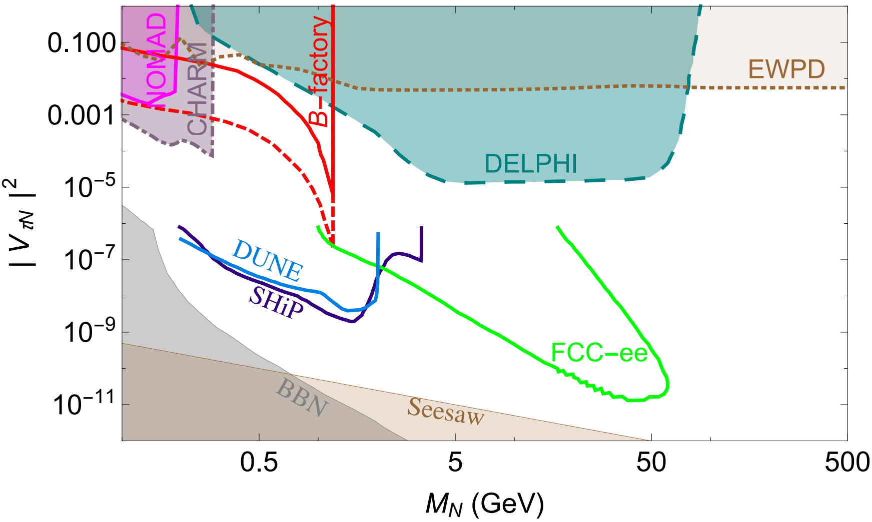
Summary Plot (Muon Sector)



[Atre, Han, Pascoli, Zhang (JHEP ’09); Deppisch, BD, Pilaftsis (NJP ’15)]

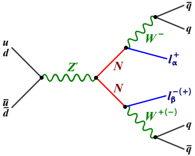
New limits from NA48/2 [Talk by M. Pepe]

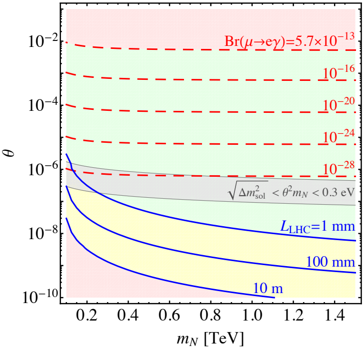
Summary Plot (Tau Sector)

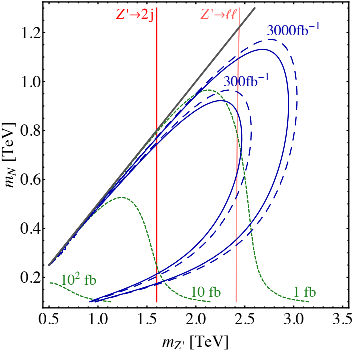


[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]

$U(1)_{B-L}$ Extension



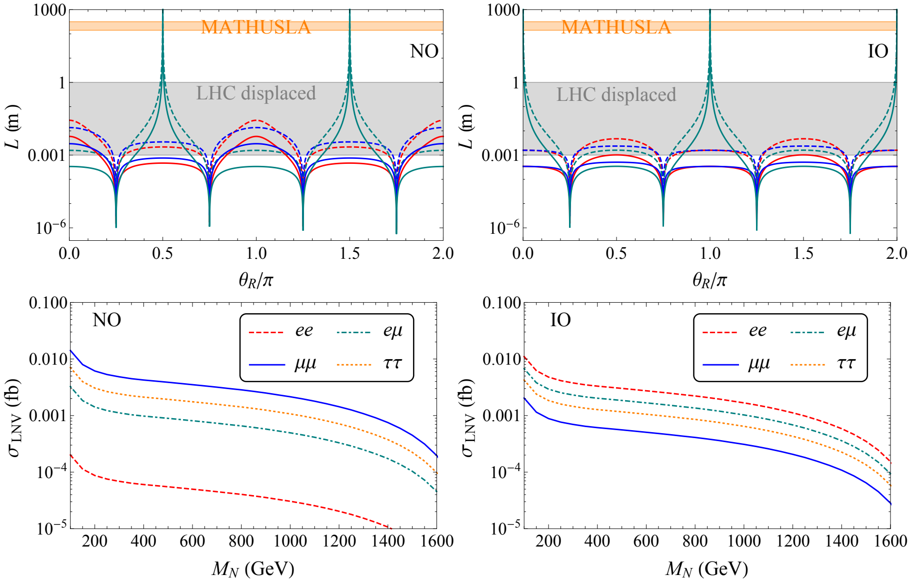




Displaced vertex signal (LNV/LFV)

[Fileviez Perez, Han, Li (PRD '09); Deppisch, Desai, Valle (PRD '14); Heeck, Teresi (PRD '16)]

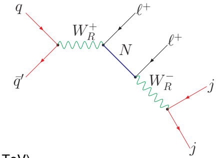
Probing Neutrino Mass Hierarchy at the LHC

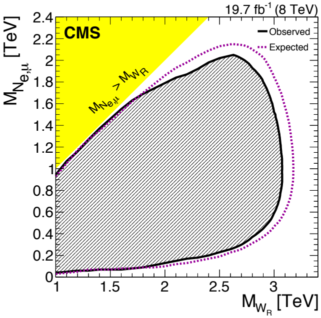


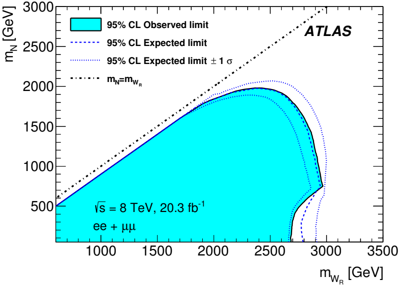
[BD, Hagedorn, Molinaro (in prep.)]

Left-Right Seesaw

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)]

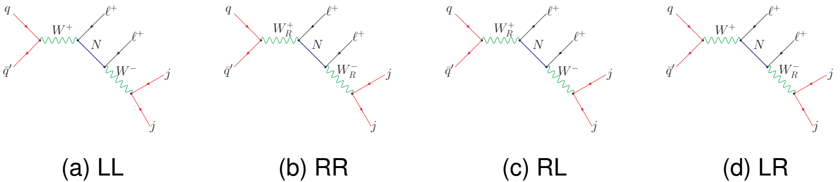


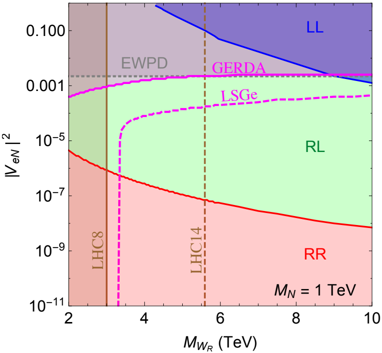


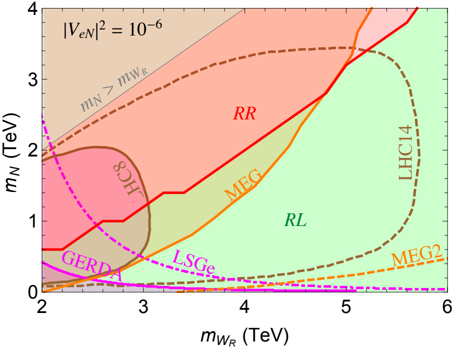


[Talks by A. Salvucci and J. Kim]

L-R Seesaw Phase Diagram

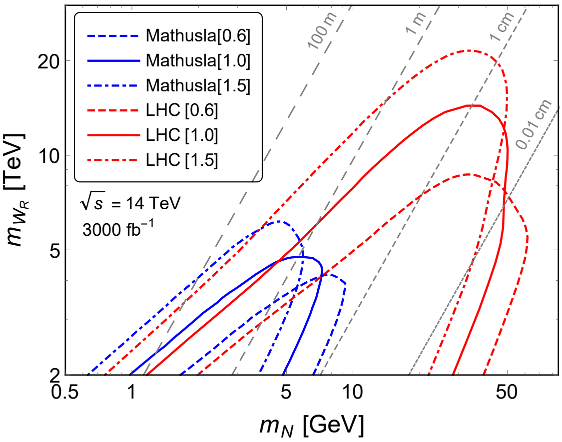






[Chen, BD, Mohapatra (PRD '13); BD, Kim, Mohapatra (JHEP '16)]

Displaced Vertex Signal



Applicable for light RH neutrinos

[Castillo-Felisola, Dib, Helo, Kovalenko, Ortiz (PRD '15); BD, Mohapatra, Zhang '17]

Extended Higgs Sector

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

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

  (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)]

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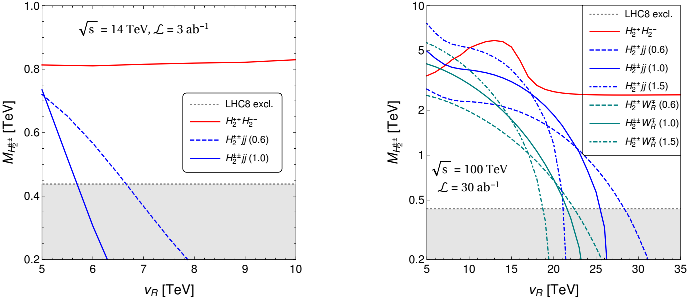
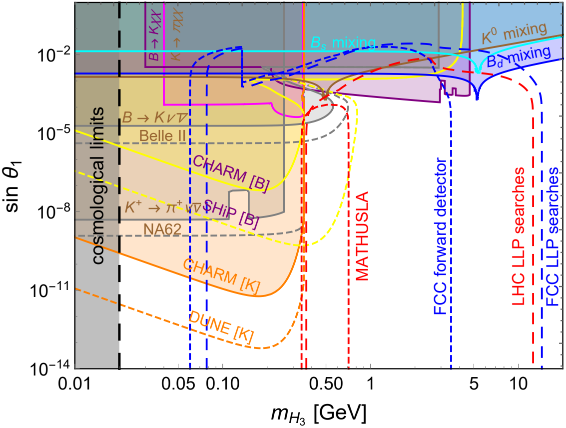
- Doubly-charged scalars can give rise to distinct LNV signals at the LHC.



[BD, Mohapatra, Zhang (JHEP '16)]

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.

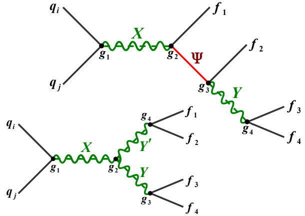


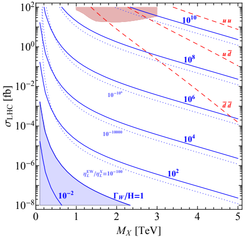
[BD, Mohapatra, Zhang '16; '17]

Falsifying Leptogenesis

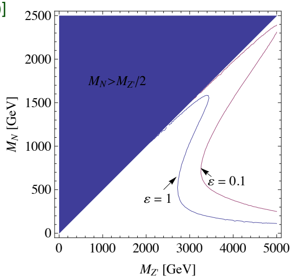
- Any observation of LNV signal at the LHC will falsify high-scale leptogenesis.

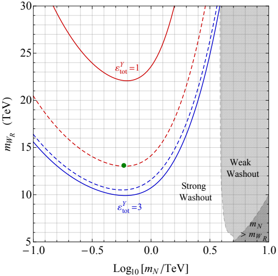
[Deppisch, Harz, Hirsch (PRL '14)]





- 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)]





Conclusion

- 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.