Experimental Constraints on Neutrino Mass Models

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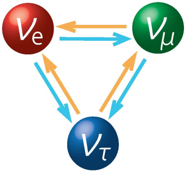
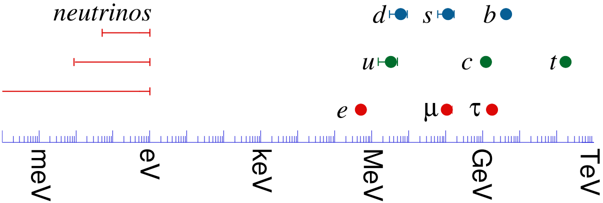
Neutrino Mass



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



Something beyond the standard Higgs mechanism?

Neutrino Mass Models

For overview, see talks by K. S. Babu and N. Sahu

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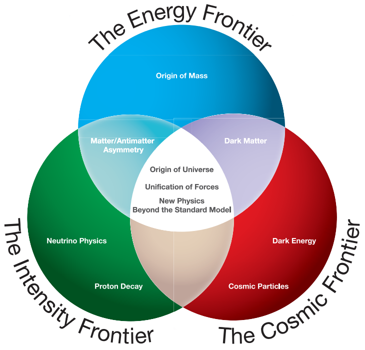
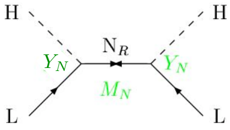
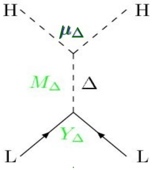


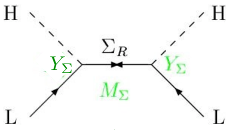
A synergistic approach at all three fundamental frontiers.

Seesaw Mechanism

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







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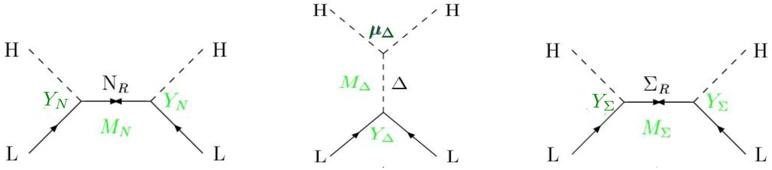

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Can we test the seesaw mechanism experimentally?

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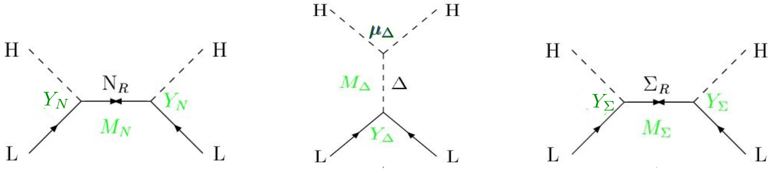

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Can we test the seesaw mechanism experimentally?

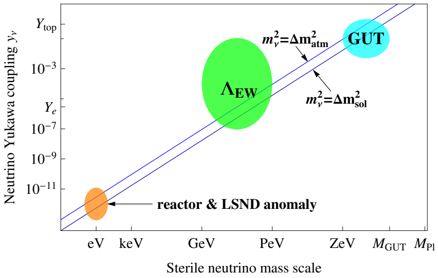
- Feasible only if the seesaw scale is (in)directly accessible.
- Theoretical motivations for low seesaw scale?

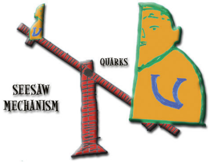
Type-I Seesaw

- Add SM-singlet heavy Majorana neutrinos. [Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]
- In flavor basis $\{\nu^c, N\}$, type-I seesaw mass matrix

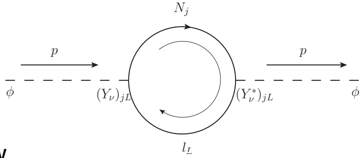
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\mathsf{T} & M_N \end{pmatrix}$$

- 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 $SO(10)$ GUT, $M_N \sim 10^{14}$ GeV for $\mathcal{O}(1)$ Dirac Yukawa couplings.
- But in a bottom-up approach, allowed to be anywhere (down to eV-scale).





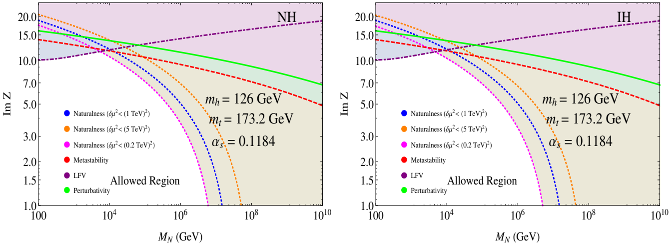
Higgs Naturalness Argument



- In the minimal seesaw,

$$\delta\mu^2 \approx \frac{1}{4\pi^2}\frac{2}{v^2}\mathrm{Tr}[D_\nu R^\dagger D_N^3 R] = \frac{M_N^3}{2\pi^2 v^2}\cosh(2\,\mathrm{Im}[z]) \times \begin{cases} (m_2+m_3) & (\mathrm{NH}) \\ (m_1+m_2) & (\mathrm{IH}) \end{cases}$$

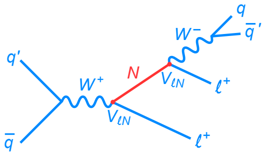
- Suggests an *upper* limit $M_N \lesssim 10^7$ GeV. [Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya, BD, Goswami, Khan, Rodejohann (PRD '17)]

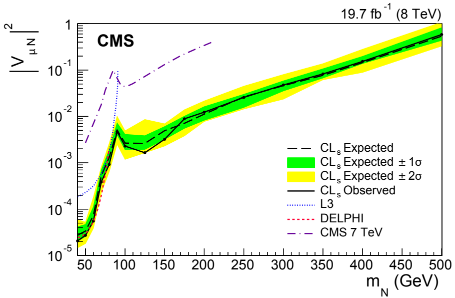


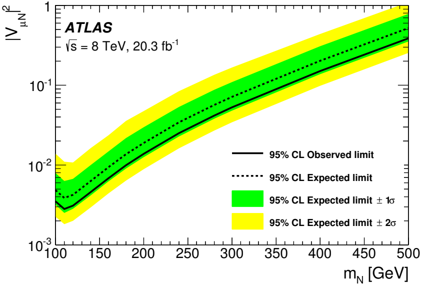
- Similar arguments in the context of neutral top partners [Batell, McCullough (PRD '15)] and warped seesaw [Agashe, Hong, Vecchi (PRD '16)].

(Minimal) Type-I Seesaw at the LHC

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); BD, Pilaftsis, Yang (PRL '14); · · ·]







Need (sub)-TeV scale heavy neutrinos with 'large' mixing with active neutrinos.

Low-scale Seesaw with Large Mixing

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

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

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- Strictly valid only for the one generation case.
- '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); Babu, Ghosh '17]

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- One example: [Kersten, Smirnov (PRD '07)]

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

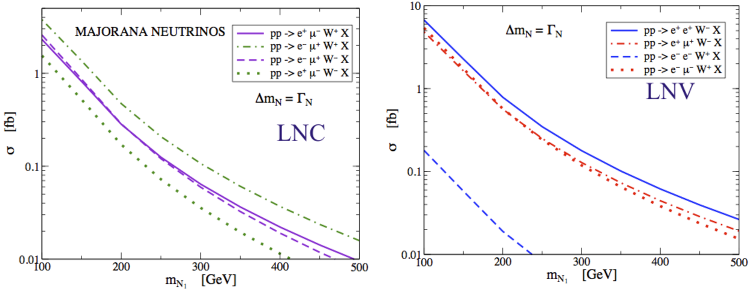
- In the limit $\epsilon_i, \delta_i \to 0$, all three light neutrino masses vanish at tree-level, while the mixing given by $V_{ij} \sim m_i/M_j$ can still be large.
- UV-completion and stabilization of texture possible. [BD, Lee, Mohapatra (PRD '13)]
- But in the minimal setup, LNV is suppressed. [Abada, 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); BD, Pilaftsis, Yang (PRL '14)]

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

- Just like resonant enhancement of CP-asymmetry.



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

Inverse Seesaw

- Two sets of SM-singlet fermions with opposite lepton numbers. [Mohapatra (PRL '86); Mohapatra, Valle (PRD '86)]
- 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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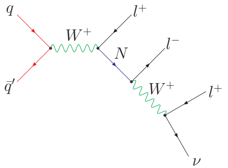
- L-symmetry is restored when $\mu \to \mathbf{0}$.
- Technically natural (in the 't Hooft sense).
- Naturally allows for large mixing with low seesaw scale:

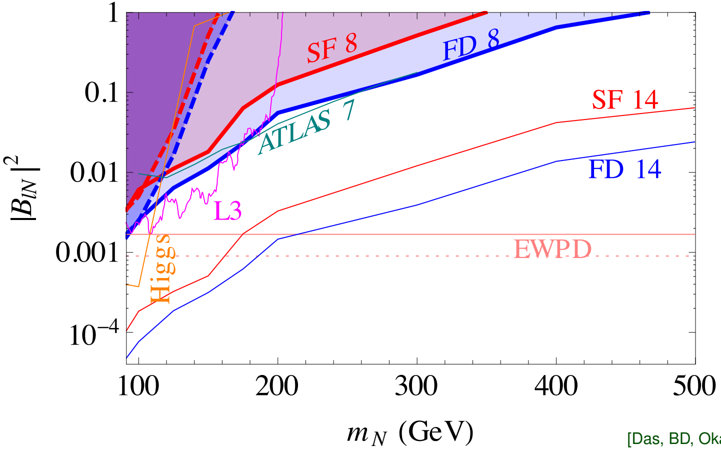
$$V_{lN} \simeq \sqrt{\frac{M_\nu}{\mu}} \approx 10^{-2}\sqrt{\frac{1\ {\rm keV}}{\mu}}$$

- Potentially large (LNC, but LFV) signals at colliders. [del Aguila, Aguilar-Saavedra (PLB '09); Chen, BD (PRD '12); Das, Okada (PRD '13); Das, BD, Okada (PLB '14); Bambhaniya, Goswami, Khan, Konar, Mondal (PRD '15); BD, Mohapatra (PRL '15); Anamiati, Hirsch, Nardi (JHEP '16); Das, BD, Mohapatra '17]

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

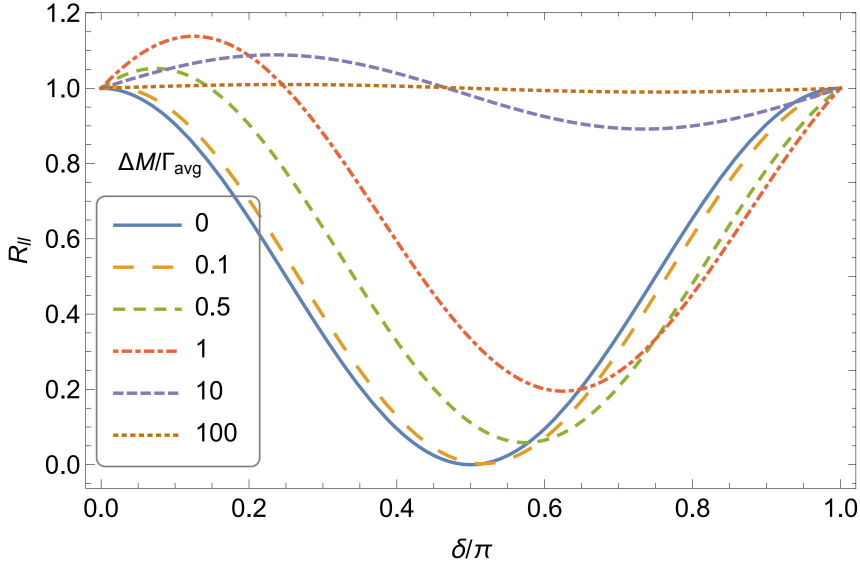
Trilepton Signal





[Das, BD, Okada (PLB '14)]

Same Sign vs Opposite Sign Signal



[BD, Mohapatra (PRL '15); Anamiati, Hirsch, Nardi (JHEP '16); Das, BD, Mohapatra '17]

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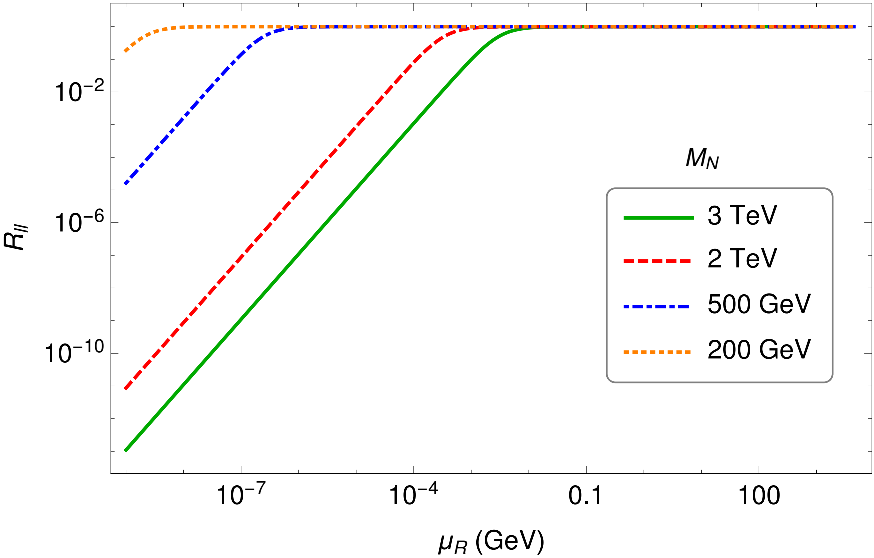
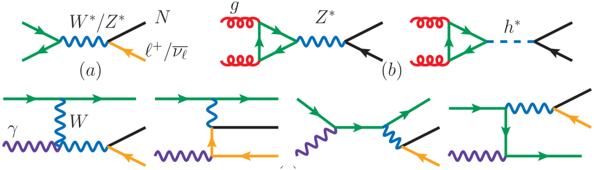
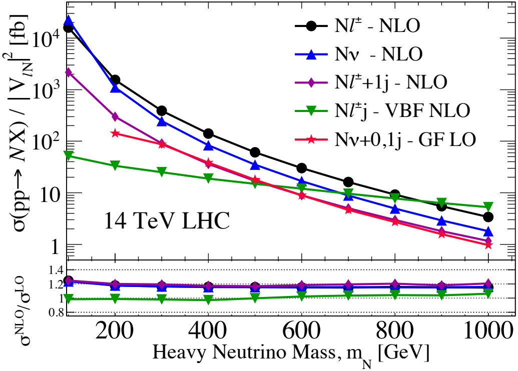


[BD, Mohapatra (PRL '15); Anamiati, Hirsch, Nardi (JHEP '16); Das, BD, Mohapatra '17]

New Contributions to Heavy Neutrino Production

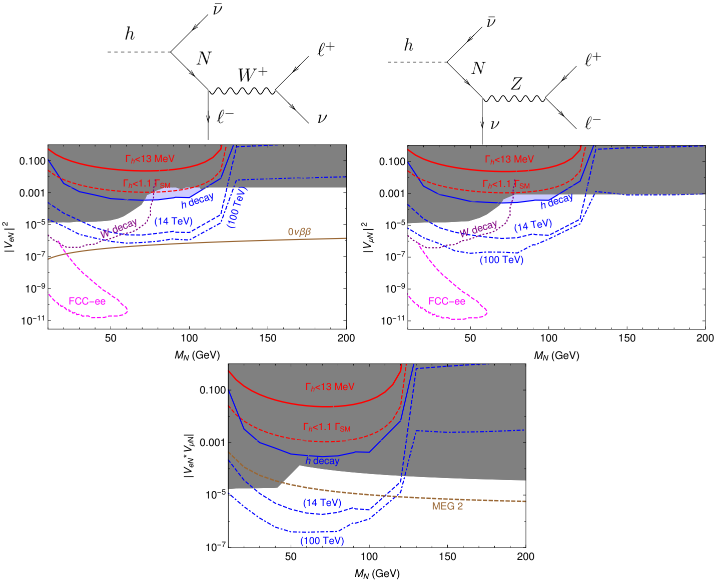
Collinear-enhancement mechanism via photon fusion [BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15); Degrande, Mattelaer, Ruiz, Turner (PRD '16); Das, Okada (PRD '16)]





[Cai, Han, Li, Ruiz '17]

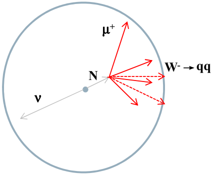
Higgs Decay

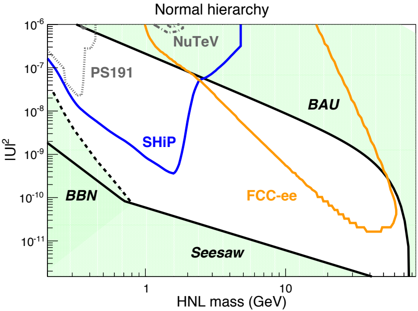


[BD, Franceschini, Mohapatra (PRD '12); Cely, Ibarra, Molinaro, Petcov (PLB '13); Das, BD, Kim (PRD '17)]

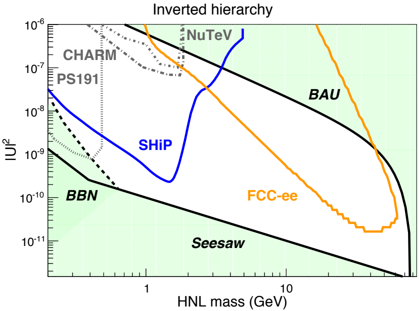
Also potentially measurable effects in triple Higgs coupling [Baglio, Weiland (PRD '16, JHEP '17)]

Z Decay





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



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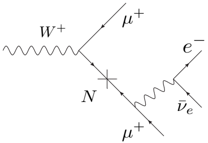
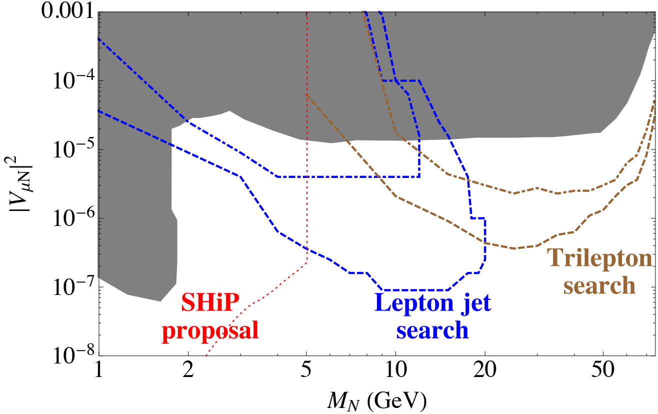
[Blondel, Graverini, Serra, Shaposhnikov ’14]

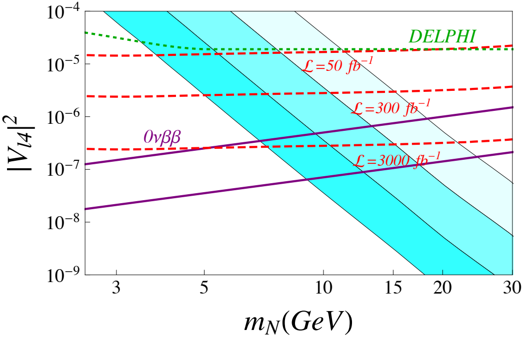
W Decay



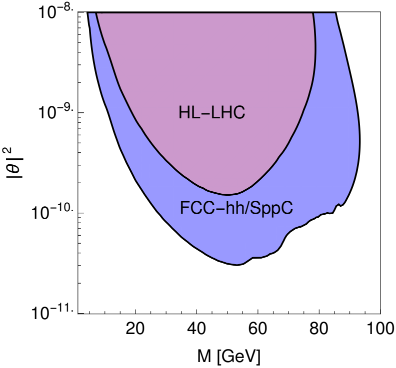


[Izaguirre, Shuve (PRD ’15); Dib, Kim (PRD ’15); Dib, Kim, Wang, Zhang (PRD ’16)]

Displaced Vertex

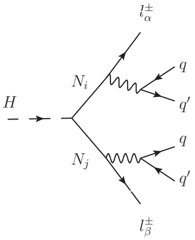


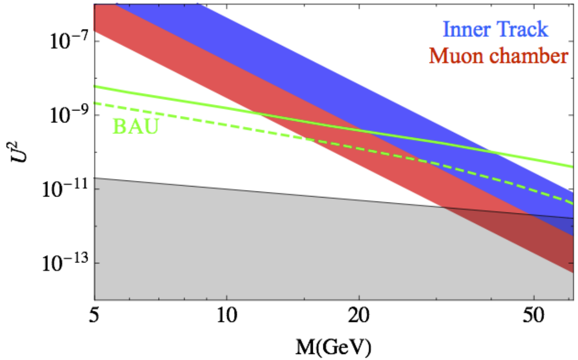
[Helo, Kovalenko, Hirsch (PRD '14)]



[Antusch, Cazzato, Fischer '16]

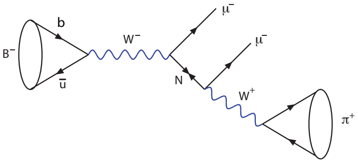
Displaced Vertex in Higgs Decay

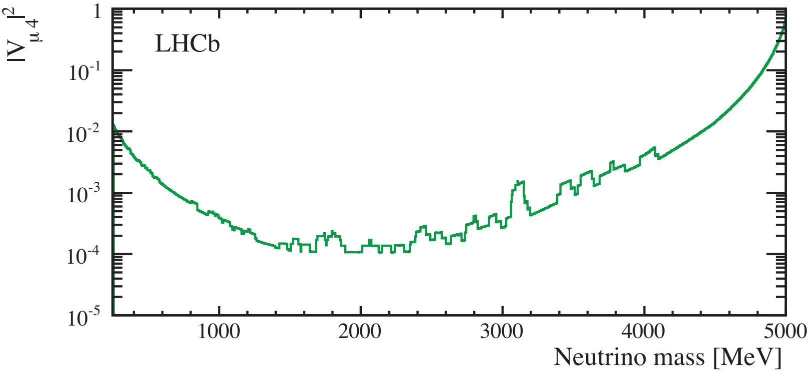




[Caputo, Hernandez, Lopez-Pavon, Salvado '17]

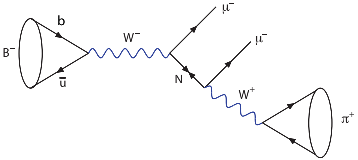
LNV in *B*-meson decays

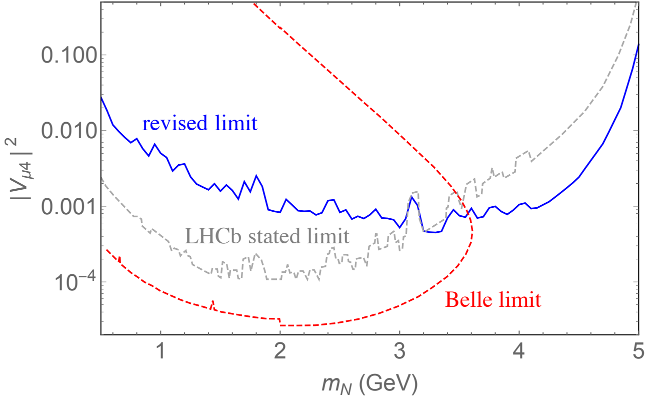




[Aaij *et al.* (PRL '14)]

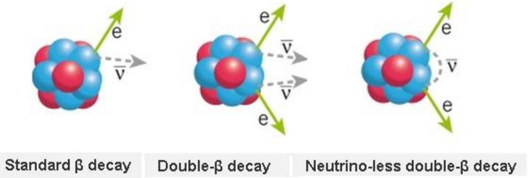
LNV in B-meson decays

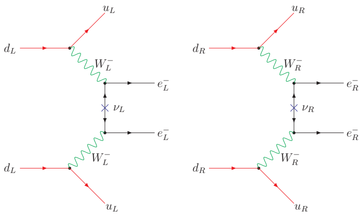




[Shuve, Peskin (PRD '16)]

Neutrinoless Double Beta Decay



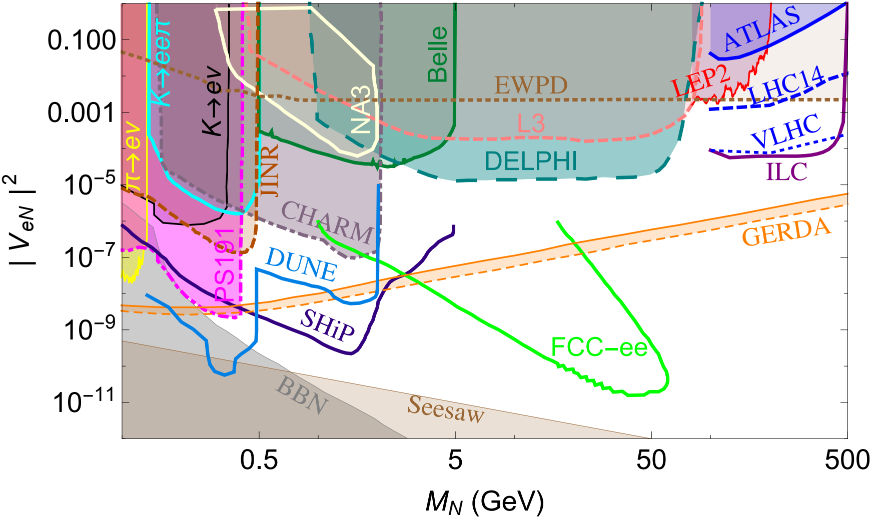


$$\frac{1}{T_{1/2}} = G_{0\nu} g_A^4 (\mathcal{M}_N m_p)^2 \left| \frac{U_{ei}^2 m_i}{\langle p^2 \rangle} + \sum_\alpha \frac{V_{e\alpha}^2 M_\alpha}{\langle p^2 \rangle + M_\alpha^2} \right|^2$$

[Ibarra, Molinaro, Petcov (JHEP '10); Tello, Nemevsek, Nesti, Senjanovic (PRL '11); Mitra, Senjanovic, Vissani (NPB '12); BD, Goswami, Mitra, Rodejohann (PRD Rapid Commun '13); Pascoli, Mitra, Wong (PRD '14); $\cdots$]

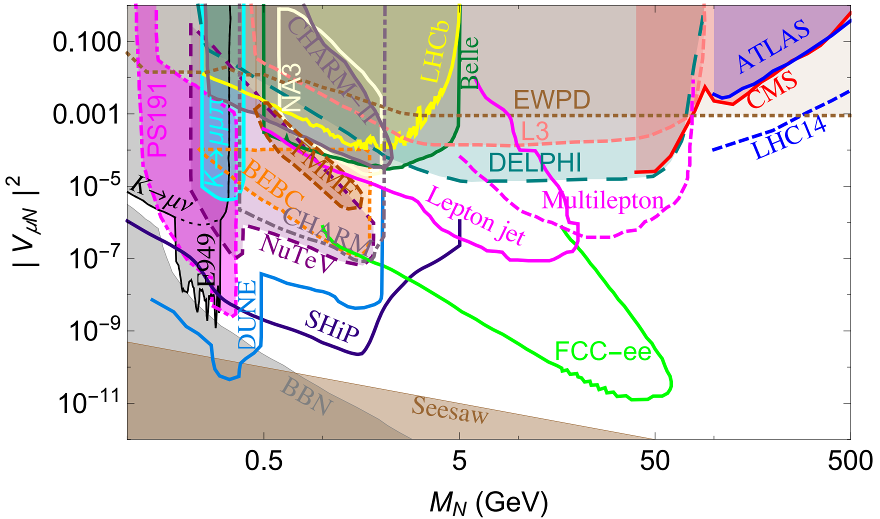
Comparing with $T_{1/2}^{\rm expt} \gtrsim 10^{25}$ yr, get severe limits on V_{eN}.

Summary Plot (Electron Sector)



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

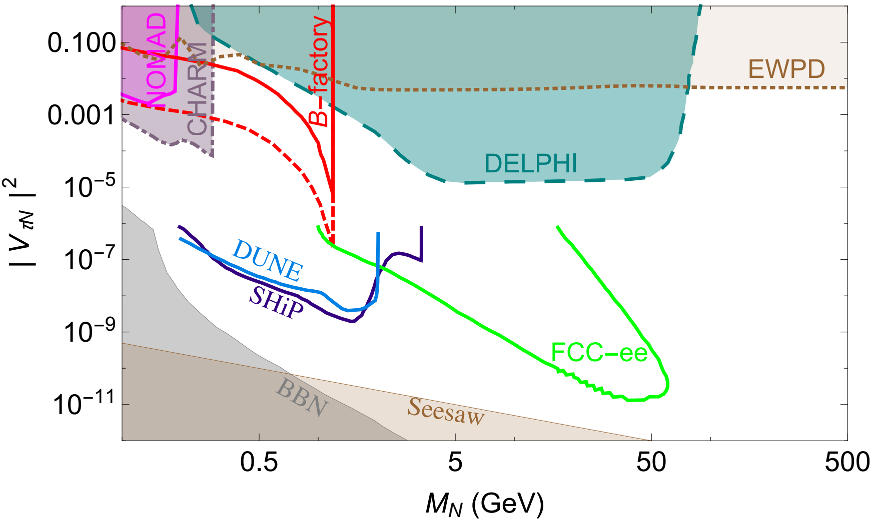
Summary Plot (Muon Sector)



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

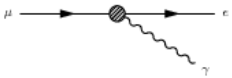
New limits from NA48/2

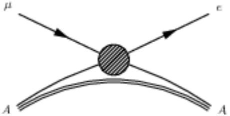
Summary Plot (Tau Sector)

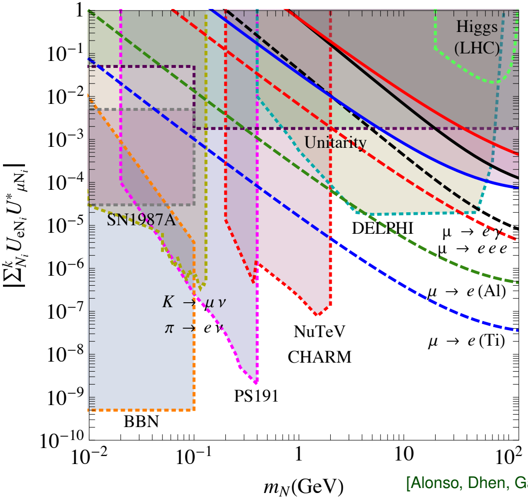


[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]

Charged Lepton Flavor Violation

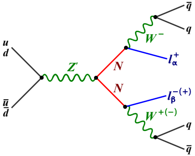


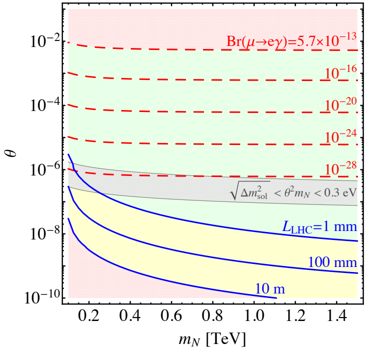


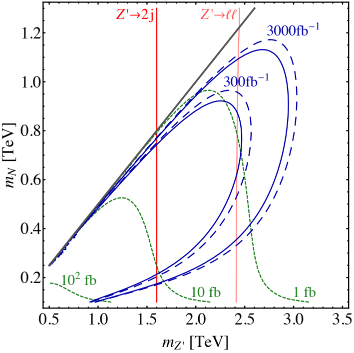


[Alonso, Dhen, Gavela, Hambye (JHEP ’13)]

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



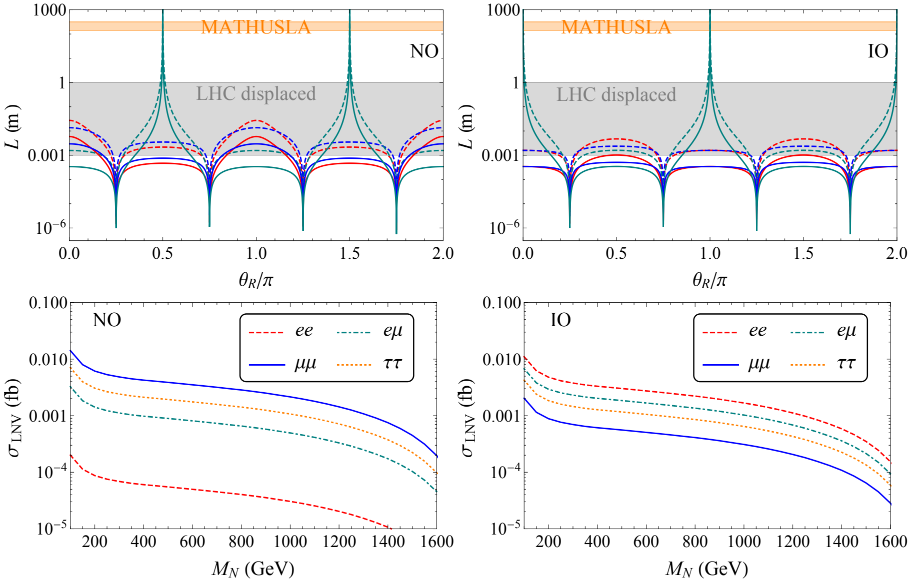




Displaced vertex signal (LNV/LFV)

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

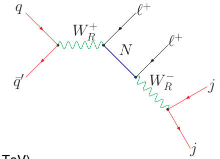
Probing Neutrino Mass Hierarchy at the LHC

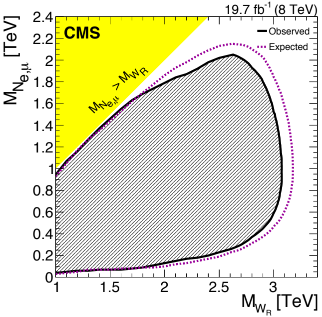


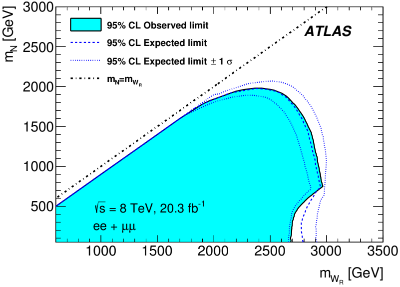
[BD, Hagedorn, Molinaro (in prep.)]

Left-Right Seesaw

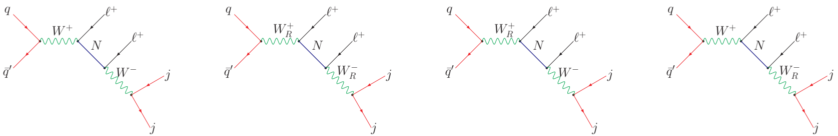
New contribution to Drell-Yan via W_R exchange. [Keung, Senjanović (PRL ’83); Ferrari *et al* (PRD ’00); Nemevsek, Nesti, Senjanović, Zhang (PRD ’11); Das, Deppisch, Kittel, Valle (PRD ’12); Chen, BD, Mohapatra (PRD ’13); BD, Kim, Mohapatra (JHEP ’15); Lindner, Queiroz, Rodejohann, Yaguna (JHEP ’16); Mitra, Ruiz, Scott, Spannowsky (PRD ’16)]



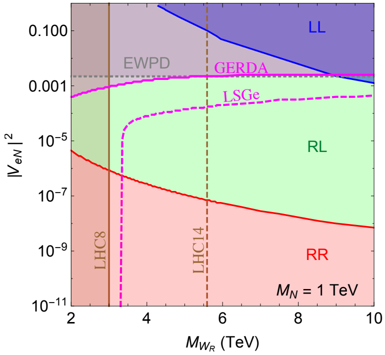


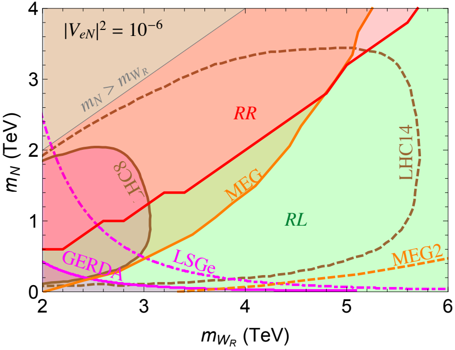


L-R Seesaw Phase Diagram



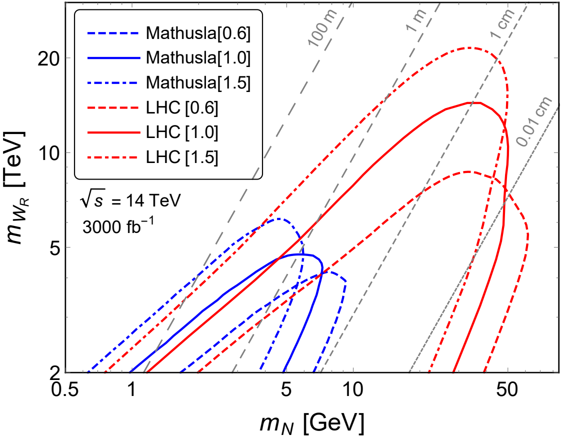
(a) LL (b) RR (c) RL (d) LR





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

Displaced Vertex Signal

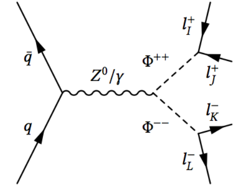


Applicable for light RH neutrinos

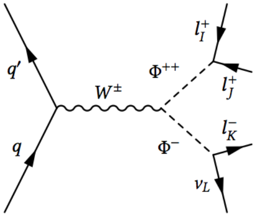
[Castillo-Felisola, Dib, Helo, Kovalenko, Ortiz (PRD '15); BD, Mohapatra, Zhang (NPB '17)]

Type-II Seesaw at the LHC

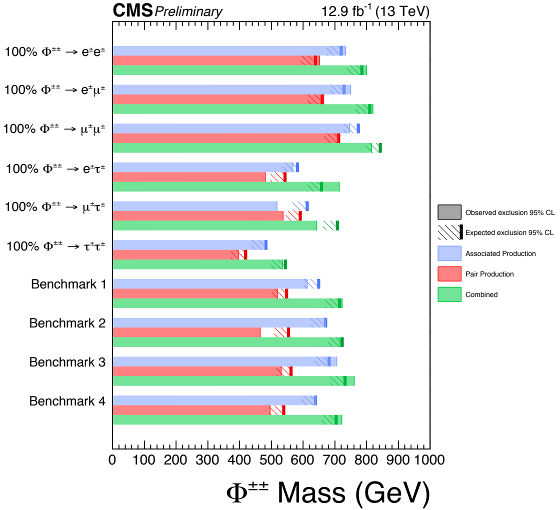
- $SU(2)_L$-triplet scalar $(\Phi^{++}, \Phi^{+}, \Phi^{0})$. [Schechter, Valle (PRD ’80); Magg, Wetterich (PLB ’80); Cheng, Li (PRD ’80); Lazarides, Shafi, Wetterich (NPB ’81); Mohapatra, Senjanović (PRD ’81)]
- Multi-lepton signatures. [Akeroyd, Aoki (PRD ’05); Fileviez Perez, Han, Huang, Li, Wang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



(a) 4ℓ

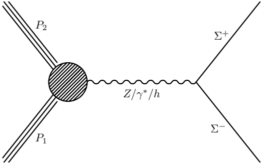


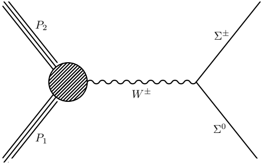
(b) 3ℓ

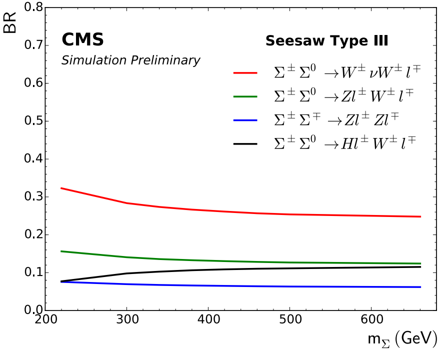


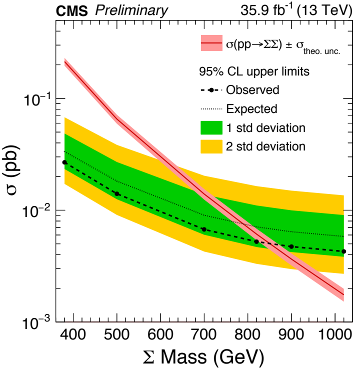
Type-III Seesaw at the LHC

- $SU(2)_L$-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)]



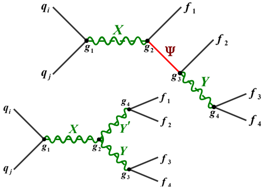


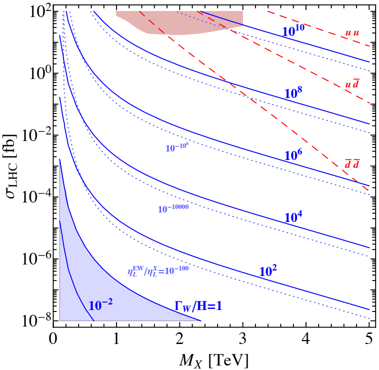




Cosmic Frontier Connection

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

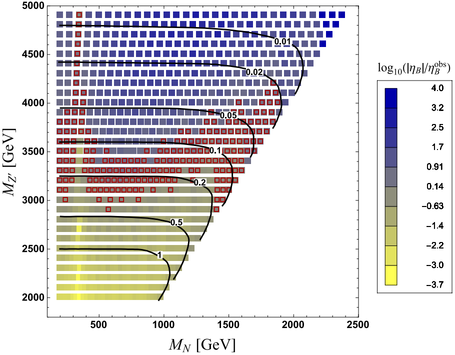


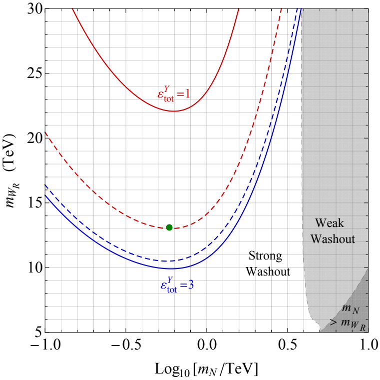


[Deppisch, Harz, Hirsch (PRL ’14)]

Cosmic Frontier Connection

In specific seesaw models, can falsify leptogenesis *at any scale*. [Frere, Hambye, Vertongen (JHEP '09); Blanchet, Chacko, Granor, Mohapatra (PRD '10); BD, Lee, Mohapatra '15; Dhuria, Hati, Rangarajan, Sarkar (PRD '15); BD, Hagedorn, Molinaro (in prep.)]





$NN \to Z' \to f\bar{f}$

$N\ell_R \to W_R \to q\bar{q}'$

Future Directions

- Future collider prospects (e^+e^-, *ep*, 100 TeV *pp*).
- Comparative study (*pp* vs others, LNV vs LNC, collider vs low-energy).

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- Comparative study (*pp* vs others, LNV vs LNC, collider vs low-energy).
- Precision calculations of the cross sections (NLO, NNLO) at the LHC.
- Importance of the photon fusion for other exotic models.
- Generic model-independent signatures (in the EFT approach).
- Deviations in precision observables (Higgs, Top, EW).

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 (and future colliders) 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.