Heavy Neutrinos at Future Colliders

BHUPAL DEV

The University of Manchester → Technische Universität München

S. Banerjee, BD, A. Ibarra, T. Mandal and M. Mitra, arXiv:1503.05491;
F. F. Deppisch, BD and A. Pilaftsis, New J. Phys. **17**, 075019 (2015).

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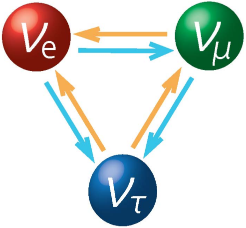
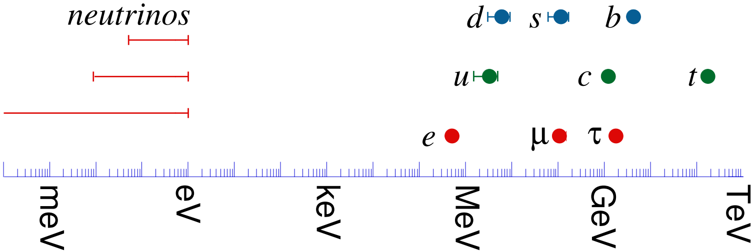
Outline

- Neutrino Physics at the Energy Frontier
- Low-scale Seesaw Mechanism
  - Theoretical Aspects
  - Experimental Status
  - Future Prospects
- Conclusion

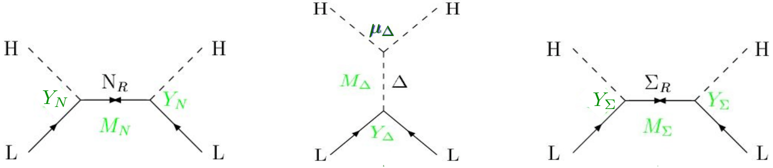
Neutrino Mass ⟹ BSM Physics





A Simple Paradigm

- A *natural* way to generate neutrino masses is by breaking $(B-L)$.
- Parametrized through the dim-5 operator $\frac{1}{\Lambda}(LLHH)$. [Weinberg (PRL '79)]
- Three tree-level realizations: Type I, II, III Seesaw mechanism.



- Majorana mass term breaks L by two units.
- Other profound implications of seesaw: Leptogenesis, Dark Matter, Vacuum Stability, Inflation, ...[Alekhin *et al.* '15]
- A pertinent question in the LHC era:

Is the seesaw mechanism *directly* testable?

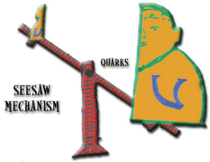
Type-I Seesaw

[Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79]

- Seesaw messenger: SM-singlet fermions (heavy neutrinos).
- A Majorana mass term $M_N \overline{N}_R^C N_R$, in addition to the Dirac mass $M_D = vY_N$.
- In the flavor basis $\{\nu_L^C, N\}$, leads to the mass matrix

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

- In the seesaw approximation $||M_D M_N^{-1}|| \ll 1$,
  - $M_\nu^{\rm light} \simeq -M_D M_N^{-1} M_D^\intercal$ is the light neutrino mass matrix.
  - $V_{\ell N} \equiv M_D M_N^{-1}$ is the active-sterile neutrino mixing.



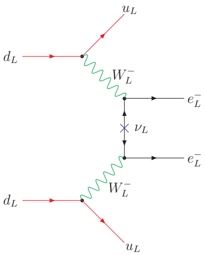
- From a bottom-up approach, no definite prediction for the seesaw scale.
- A natural justification for RH neutrinos can be found in UV-complete models.

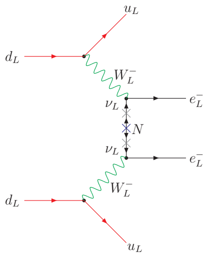
Two Key Aspects of Seesaw

Majorana Mass

⇓

LNV: Neutrinoless Double Beta Decay



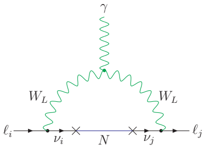


Does not probe the active-sterile mixing if the mixed diagram is sub-dominant. [Nemevsek, Senjanović, Tello (PRL ’13); BD, Goswami, Mitra, Rodejohann (PRD Rapid ’13)]

Active-sterile Mixing

⇓

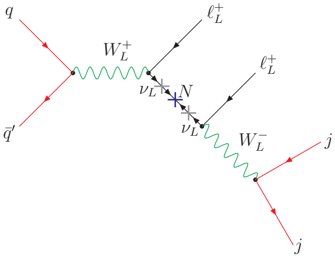
- Non-unitarity of the PMNS matrix.
- LFV (e.g. $\mu \to e\gamma$, $\mu \to 3e$, $\mu - e$ conversion in nuclei)



- Does not prove the Majorana nature since a Dirac neutrino can also give large LFV effects. [BD, Mohapatra (PRD ’10); Forero, Morisi, Tortola, Valle (JHEP ’11)]

Seesaw at Colliders

- *Both* aspects of seesaw can be *directly* tested in collider experiments.
- 'Smoking gun' signal at hadron colliders: **Same-sign dilepton + two jets with no $\not{E}_T$.** [Keung, Senjanović (PRL '83)]



- In the minimal SM seesaw, requires *both* the Majorana nature of N at TeV scale and a 'large' heavy-light mixing to have any observable effect.

  [Pilaftsis (ZPC '92); Han, Zhang (PRL '06); del Aguila, Aguilar-Saavedra, Pittau (JHEP '07); BD, Pilaftsis, Yang (PRL '14)]

Low-Scale Seesaw with Large Mixing

- In the traditional seesaw,

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

- Strictly valid only in the one-generation case.
- Possible to have 'large' mixing with TeV-scale M_N by exploiting the matrix structures of M_D and M_N. [Pilaftsis (ZPC '92); Kersten, Smirnov (PRD '07); de Gouvea '07; Gavela, Hambye, D. Hernandez, P. Hernandez (JHEP '09); Ibarra, Molinaro, Petcov (JHEP '10); Adhikari, Raychaudhuri (PRD '11); Mitra, Senjanović, Vissani (NPB '12)]
- Essentially two ways: (i) symmetry (ii) anarchy (fine-tuning).
- In principle, can generate large LNV and/or LFV effects.

An Example

[Kersten, Smirnov (PRD '07)]

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

- In the limit $\delta_i \to 0$, light neutrino masses given by $M_\nu \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$ vanish, while the mixing given by $V_{ij} \sim m_i / M_1$ can be large.
- The textures can be stabilized by invoking discrete symmetries.
- Also possible to embed in L-R models. [BD, Lee, Mohapatra (PRD '13)]
- In the minimal seesaw, LNV is suppressed due to quasi-degeneracy of the heavy neutrinos.
- In L-R seesaw, LNV effects could be large due to additional gauge interactions. [BD, Mohapatra (Snowmass '13); BD, Lee, Mohapatra (PRD '13)]

Another Example

[Pilaftsis (ZPC '92)]

$$M_D = \begin{pmatrix} 0 & 0 \\ a & b \\ c & d \end{pmatrix} \text{ and } M_N = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}.$$

- Assuming $a \neq 0$, $M_\nu \simeq -M_D M_N^{-1} M_D^{\mathsf{T}} = 0$ if

$$d = \frac{bc}{a}, \qquad B = -\frac{b^2}{a^2} A$$

- For $b \neq a$, LNV in the μ and τ sectors can be potentially large.
- Include radiative effects and check whether all neutrino mixing angles can be reproduced. [BD (ongoing)]
- Mixing in the electron sector cannot be large due to $0\nu\beta\beta$ constraints. [Lopez-Pavon, Molinaro, Petcov '15]

A (More) Natural Low-scale Seesaw

- Inverse seesaw mechanism [Mohapatra (PRL '86); Mohapatra, Valle (PRD '86)]
- Add two sets of singlet fermions carrying opposite lepton numbers.
- Full neutrino mass matrix in the flavor basis $\{\nu^C_{L,l}\,, N_{R,\alpha}\,, S^C_{L,\beta}\}$:

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

- Light neutrino mass matrix: $M_\nu = M_D M_N^{-1} \mu_S M_N^{-1^\mathsf{T}} M_D^\mathsf{T} + \mathcal{O}(\mu_S^3)$.
- L-symmetry is restored for $\mu_S \to \mathbf{0}$.
- Can naturally allow for large mixing:

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

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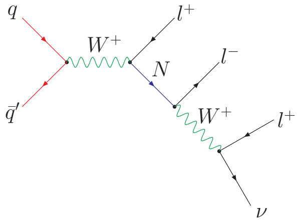
Collider Signal for Inverse Seesaw

- For small L-breaking, LNV signal of same-sign dileptons is suppressed:

$$\mathcal{A}_{\rm LNV}(\bar{s}) = -V_{lN}^2 \frac{2\Delta M_N}{\Delta M_N^2 + \Gamma_N^2} + \mathcal{O}\left(\frac{\Delta M_N}{M_N}\right)$$

  for $\Delta M_N \lesssim \Gamma_N$, where $\Delta M_N \simeq \mu_S$.
- Exception: Resonant enhancement for $\Delta M_N \simeq \Gamma_N$. [Bray, Lee, Pilaftsis (NPB '07)]
- Opposite-sign dilepton signal suffers from a large SM background.
- Golden channel is the trilepton mode: [del Aguila, Aguilar-Saavedra (NPB '09); Chen, BD (PRD '12); Das, BD, Okada (PLB '14)]

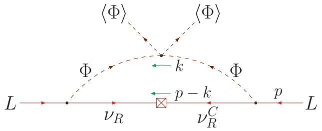


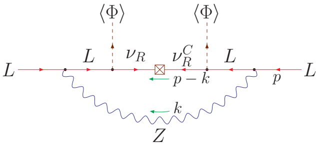
Generalized Inverse Seesaw

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

- At tree-level, μ_R does not affect the light neutrino masses.
- Only affects at loop-level through EW radiative corrections.

[Pilaftsis (ZPC ’92); BD, Pilaftsis (PRD ’12)]

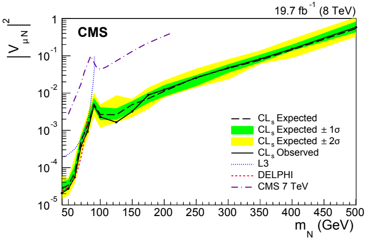




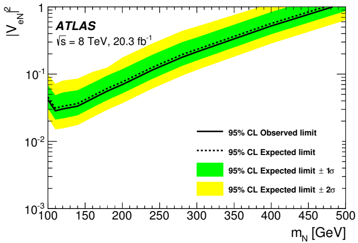
$$M_\nu^{1-\text{loop}} = \frac{\alpha_W}{16\pi M_W^2}\left[\frac{M_H^2}{M_N^2-M_H^2}\ln\left(\frac{M_N^2}{M_H^2}\right)+\frac{3M_Z^2}{M_N^2-M_Z^2}\ln\left(\frac{M_N^2}{M_Z^2}\right)\right]M_D\mu_R M_D^\mathsf{T}$$

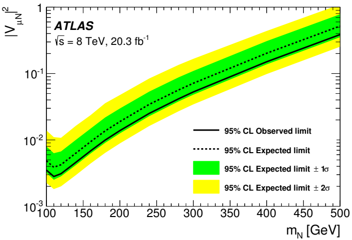
- Sizable LNV through μ_R. [BD, Pilaftsis (PRD ’12); Parida, Patra (PLB ’13); BD, Mohapatra ’15]

Direct Search Limits from LHC



[CMS Collaboration (PLB ’15)]

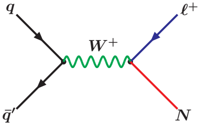




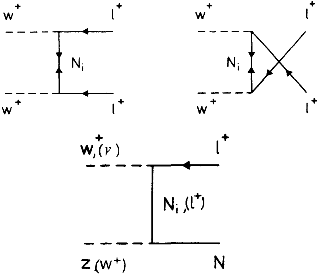
[ATLAS Collaboration ’15]

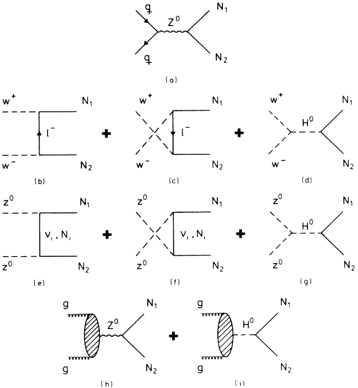
Heavy Neutrino Production at the LHC

- LHC searches so far considered only the Drell-Yan production process



- Many other production modes, but most of them are negligible.

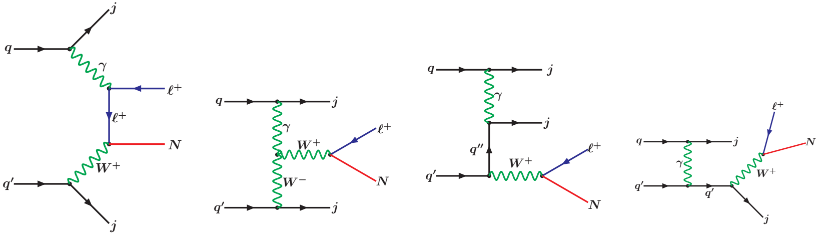


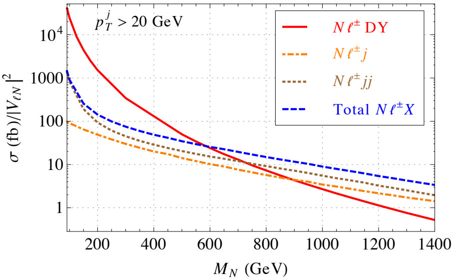


[Datta, Guchait, Pilaftsis (PRD '94)]

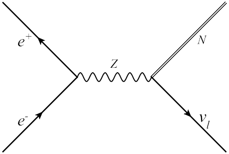
New Dominant Production Mechanism

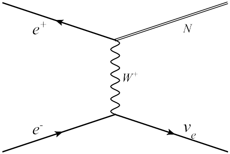
[BD, Pilaftsis, Yang (PRL '14); Das, BD, Okada (PLB '14); Alva, Han, Ruiz (JHEP '15)]

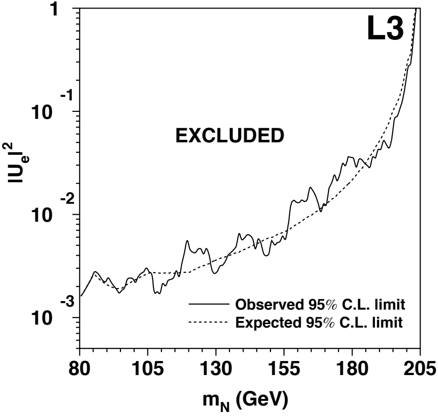




Direct Limits from LEP

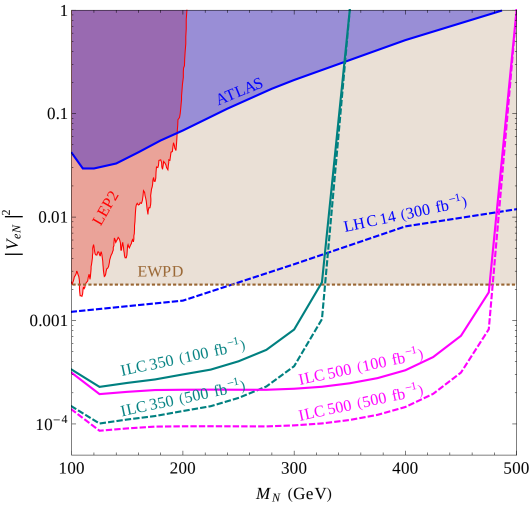






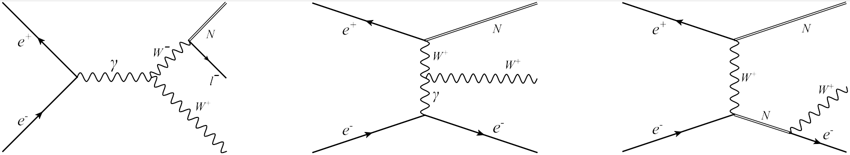
[L3 Collaboration (PLB '01)]

Sensitivity at ILC



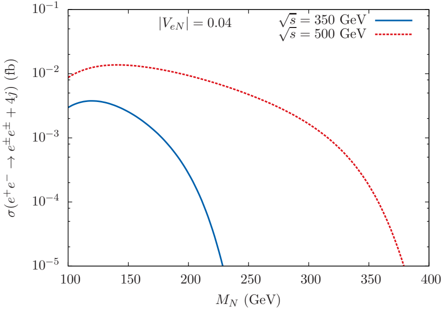
[Banerjee, BD, Ibarra, Mandal, Mitra ’15]

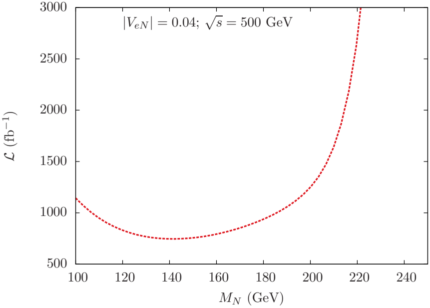
A New Production Channel



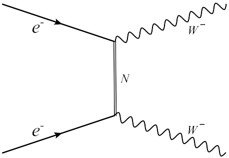
Can *directly* probe the Majorana nature of heavy neutrinos at a linear collider:

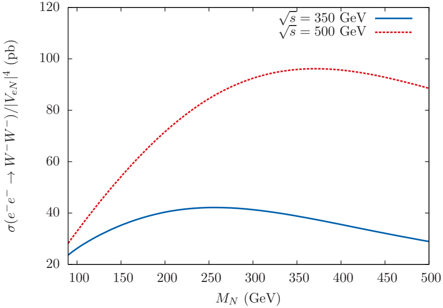
$$e^+e^- \to N\ell^\pm W^\mp \to \ell^\pm W^\mp \ell^\pm W^\mp \to \ell^\pm \ell^\pm + 4j$$

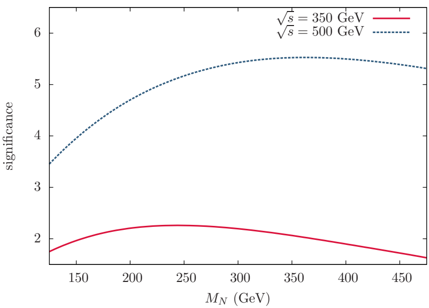




Another probe of LNV: $e^- e^- \to 4j$

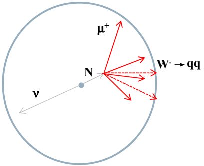


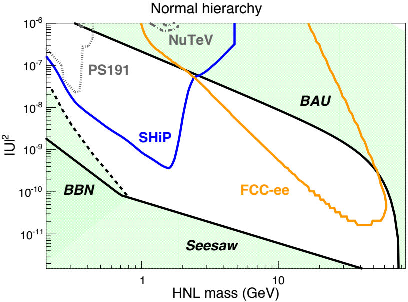




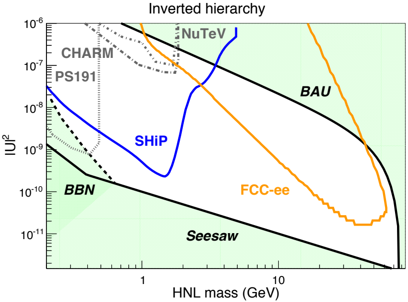
[Banerjee, BD, Ibarra, Mandal, Mitra ’15]

Heavy Neutrinos at FCC-ee





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



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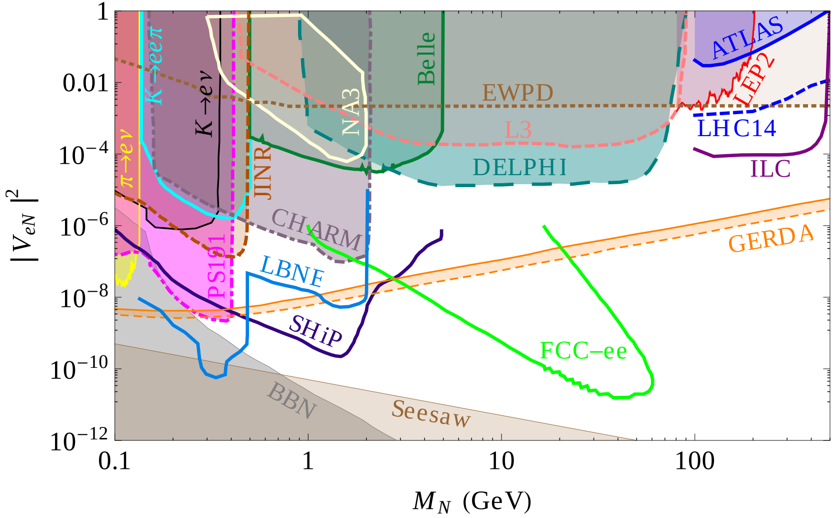
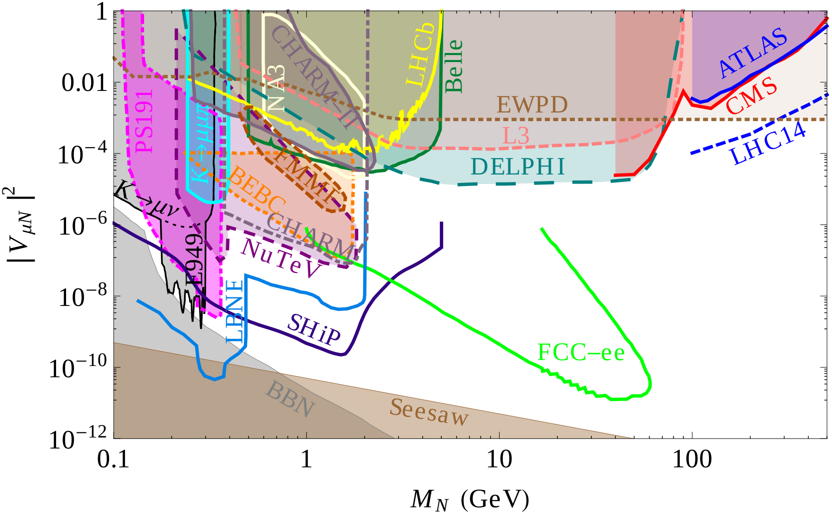
[Blondel, Graverini, Serra, Shaposhnikov ’14]

Summary Plot (Electron Sector)



[Deppisch, BD, Pilaftsis (NJP '15)]

Summary Plot (Muon Sector)



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Conclusion

- Neutrino oscillations: first conclusive experimental evidence of BSM.
- Important to explore the experimental signatures of neutrino mass models to understand the underlying new physics.

- Low-scale neutrino mass models can lead to observable signals at the Energy Frontier.
- Future colliders provide a clean test of the seesaw mechanism.

- Complementary tests in low-energy experiments at the Intensity Frontier.
- Also important consequences at the Cosmic Frontier, e.g. baryon asymmetry via leptogenesis and Dark Matter.

THANK YOU.

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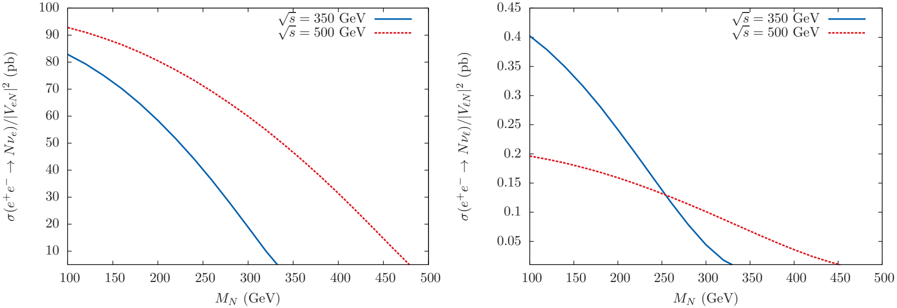
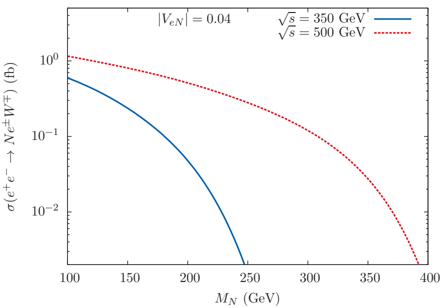
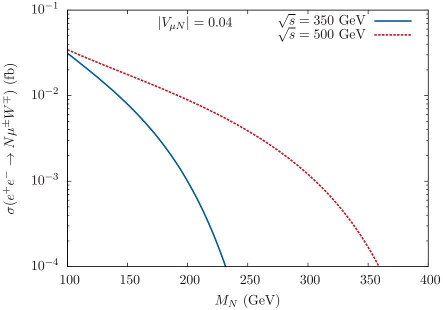
BACKUP

Cross Section for $e^+e^- \to N\nu_\ell$

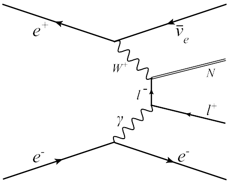


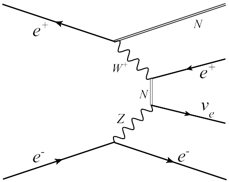
Cross Section for $e^+e^- \to N\ell^\pm W^\mp$

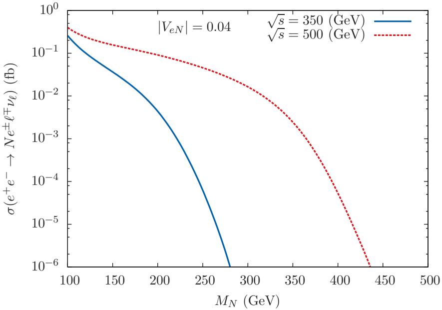


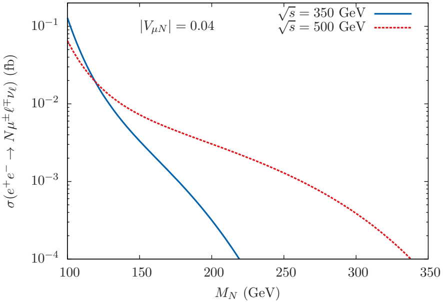


Cross Section for $e^+e^- \to N\ell^\pm\ell'^\mp\nu$

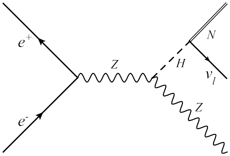


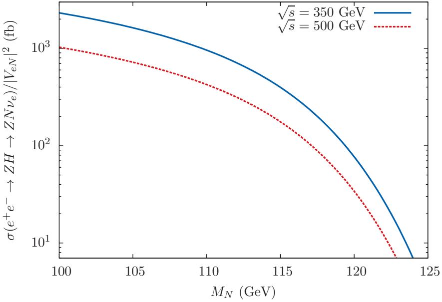




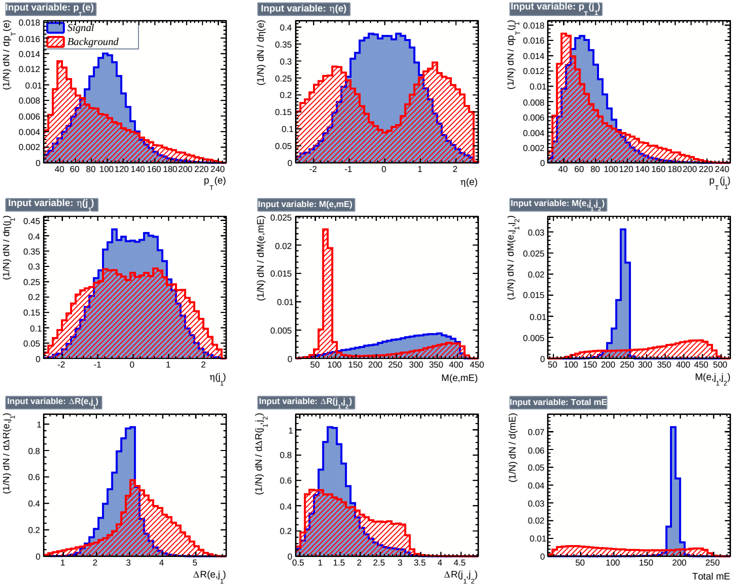


Cross Section for $e^+e^- \to ZH \to ZN\nu$

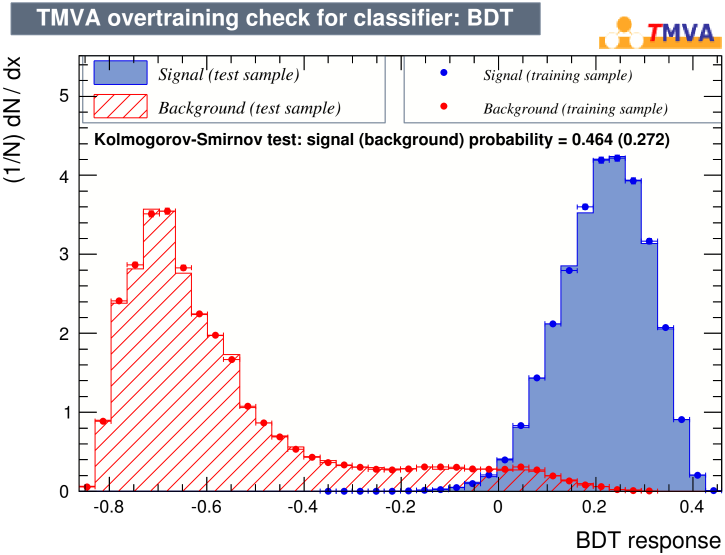




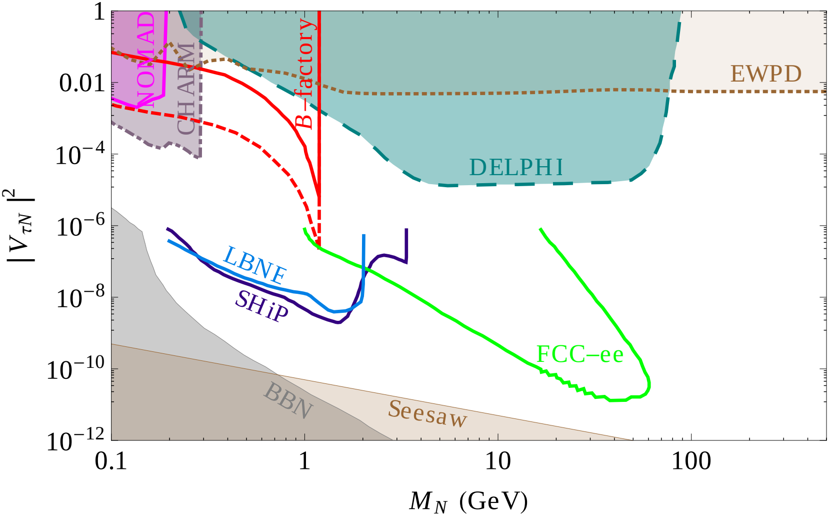
Signal vs Background Distributions



MVA

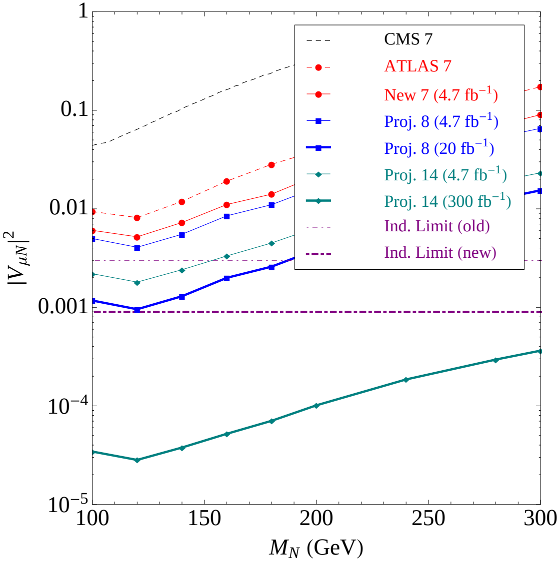

TMVA overtraining check for classifier: BDT
TMVA
Signal (test sample)
Background (test sample)
Signal (training sample)
Background (training sample)
Kolmogorov-Smirnov test: signal (background) probability = 0.464 (0.272)
(1/N) dN / dx
5
4
3
2
1
0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
BDT response

Summary Plot (Tau Sector)

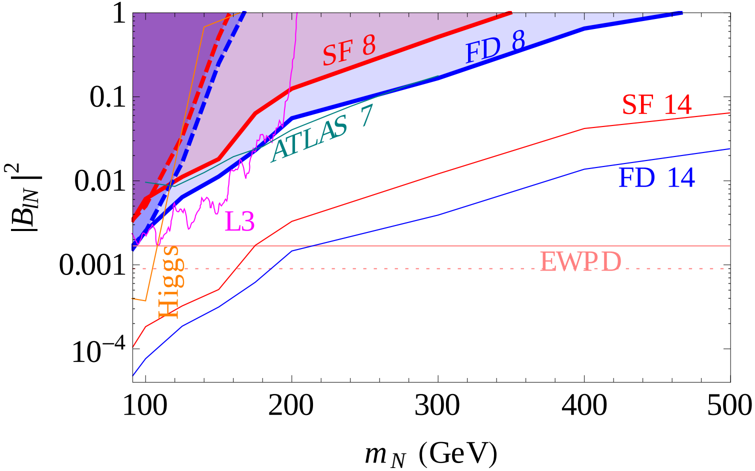


[Deppisch, BD, Pilaftsis (NJP ’15)]

Improved Upper Limit on Mixing



Direct Limit for Dirac Neutrinos



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