Testing Neutrino Mass Models at the LHC and beyond

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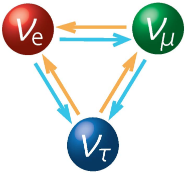
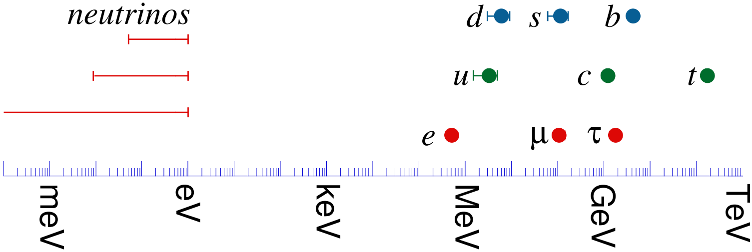
$m_\nu = m_L^T - m_D M_R^{-1} m_D$

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Harbinger of New Physics

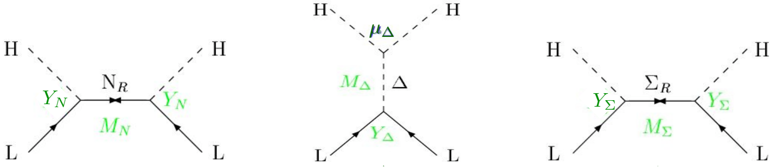


Non-zero neutrino mass $\Longrightarrow$ physics beyond the SM.



Seesaw Mechanism

- A natural way to generate neutrino masses is by breaking the $(B-L)$-symmetry of the SM.
- Parametrized by the dim-5 operator $\frac{1}{\Lambda}(LLHH)$. [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 the seesaw mechanism be tested at the LHC (and beyond)?

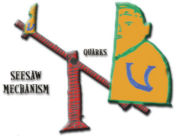
Type-I Seesaw

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

- Seesaw messenger: SM-singlet fermions (sterile neutrinos).
- In the flavor basis $\{\nu_L^C, N\}$, leads to the mass matrix

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

- In the seesaw approximation $||M_D M_N^{-1}|| \ll 1$,
  - $M_\nu^{\text{light}} \simeq -M_D M_N^{-1} M_D^\mathsf{T}$ 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.
- 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 (ongoing)]

Low-scale Type-I Seesaw

- In 'traditional' seesaw, light-heavy neutrino mixing is small at EW-scale:

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

- Strictly true only for the one generation case.
- 'Large' mixing effects possible with special structures of M_D and M_N.
  [Pilaftsis (ZPC '92); Gluza (APPB '02); de Gouvea '07; Kersten, Smirnov (PRD '07); Gavela, Hambye, Hernandez, Hernandez (JHEP '09); Ibarra, Molinaro, Petcov (JHEP '10); Mitra, Senjanović, Vissani (NPB '12); BD, Lee, Mohapatra (PRD '13)]
- Can be motivated/stabilized from symmetry arguments.
- LNV is usually suppressed due to constraints from neutrino oscillation data and $0\nu\beta\beta$, while observable LFV still possible.
- Sizable LNV possible with an extended gauge sector.

A Natural Low-scale Seesaw

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

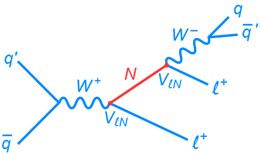
$$
\begin{aligned}
\mathcal{M}_\nu &= \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^{\mathsf{T}} & \mathbf{0} & M_N^{\mathsf{T}} \\ \mathbf{0} & M_N & \mu \end{pmatrix} \equiv \begin{pmatrix} \mathbf{0} & \mathcal{M}_D \\ \mathcal{M}_D^{\mathsf{T}} & \mathcal{M}_N \end{pmatrix} \\
M_\nu^{\text{light}} &= M_D M_N^{-1} \mu \, M_N^{-1^{\mathsf{T}}} M_D^{\mathsf{T}} + \mathcal{O}(\mu^3).
\end{aligned}
$$

- L-symmetry is restored when $\mu \to \mathbf{0}$.
- Naturally allows for large mixing:

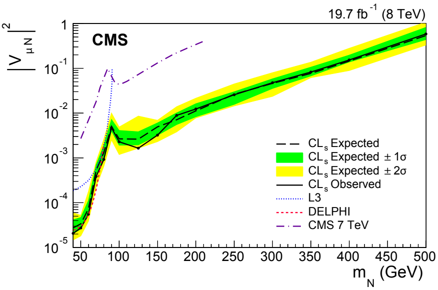
$$
V_{lN} \simeq \sqrt{\frac{M_\nu}{\mu}} \approx 10^{-2} \sqrt{\frac{1 \text{ keV}}{\mu}}
$$

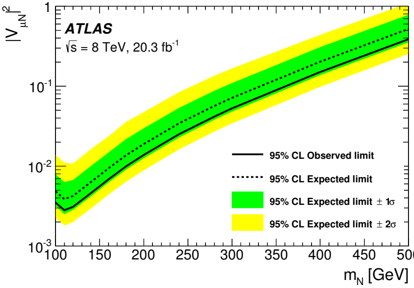
- Rich phenomenological implications.

Seesaw Signal at the LHC



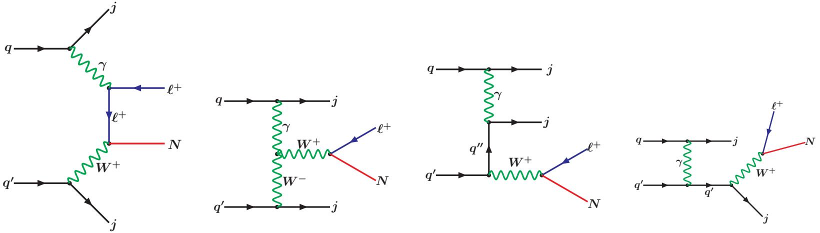
(Same-sign) dilepton plus jets without $\not{E}_T$ [Keung, Senjanović (PRL ’83); Datta, Guchait, Pilaftsis (PRD ’94); Han, Zhang (PRL ’06); Bray, Lee, Pilaftsis (NPB ’07); del Aguila, Aguilar-Saavedra, Pittau (JHEP ’07)] – talk by Un-ki Yang

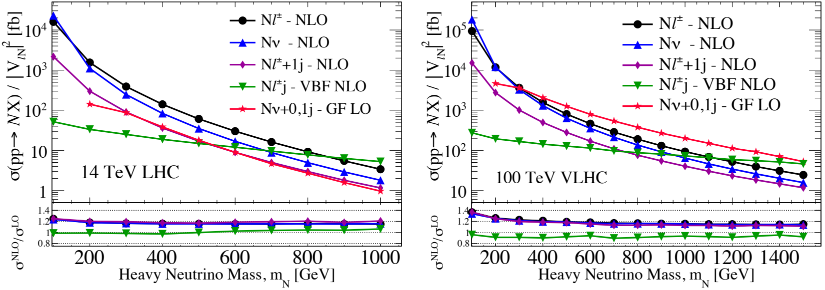




New Contribution

Collinear-enhancement mechanism [BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15)]





[Degrande, Mattelaer, Ruiz, Turner '16]

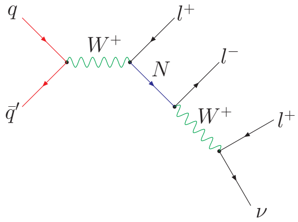
Inverse Seesaw Signal

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

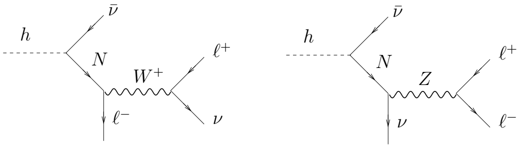
$$\mathcal{A}_{\rm LNV}(\bar{s}) = -V_{lN}^2 \frac{2\Delta M_N}{\Delta M_N^2 + \Gamma_N^2} + \mathcal{O}\left(\frac{\Delta M_N}{M_N}\right)$$

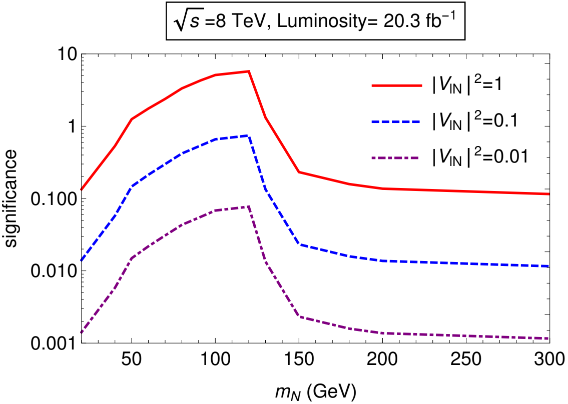
for $\Delta M_N \lesssim \Gamma_N$, where $\Delta M_N \simeq \mu$. [BD, Pilaftsis, Yang (PRL '14); Anamiati, Hirsch, Nardi '16]

- Exception: Resonant enhancement for $\Delta M_N \simeq \Gamma_N$. [Bray, Lee, Pilaftsis (NPB '07)]
- Look for opposite-sign dilepton signal (large SM background).
- Or trilepton channel. [del Aguila, Aguilar-Saavedra (NPB '09); Chen, BD (PRD '12); Das, Okada (PRD '14); Das, BD, Okada (PLB '14)]



Constraints from LHC Higgs Data

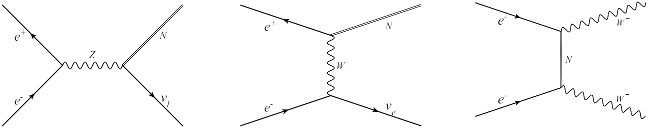


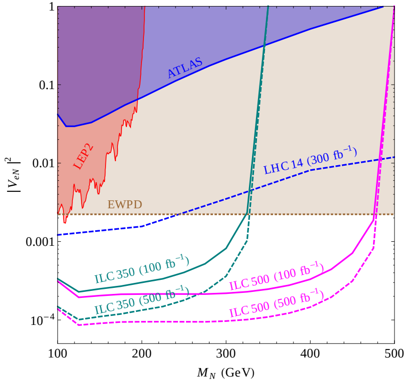


[BD, Franceschini, Mohapatra (PRD ’12); Das, BD, Kim (in preparation)]

Lepton Collider Searches

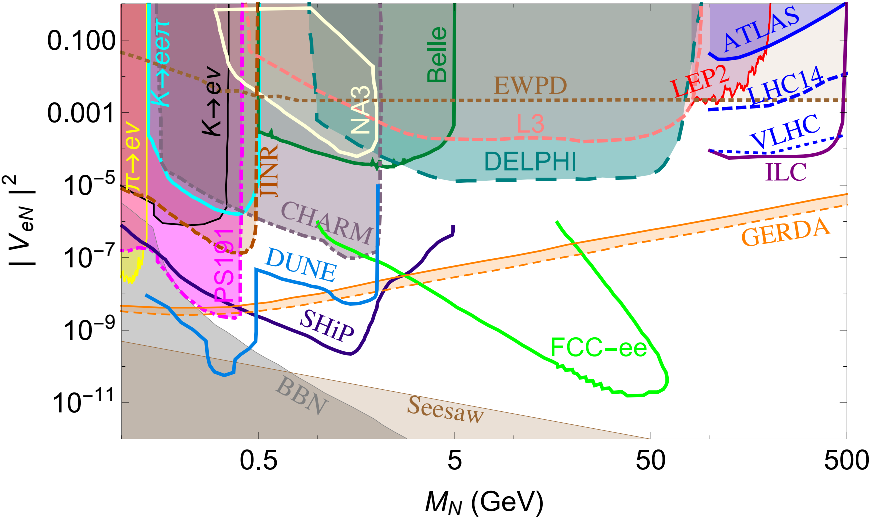
[Buchmuller, Greub (NPB ’91); Azuelos, Djouadi (ZPC ’94); Ananthanarayan, Minkowski (PLB ’96); Gluza, Zralek (PLB ’96); Gluza, Maalampi, Raidal, Zralek (PLB ’97); Rodejohann (PRD ’10); Asaka, Tsuyuki (PRD ’15)]





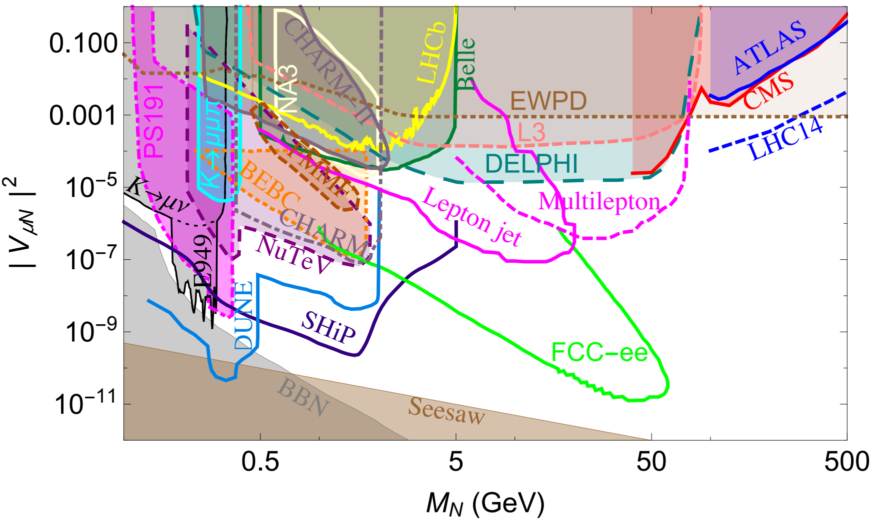
[Banerjee, BD, Ibarra, Mandal, Mitra (PRD ’15)]

Summary Plot (Electron Sector)



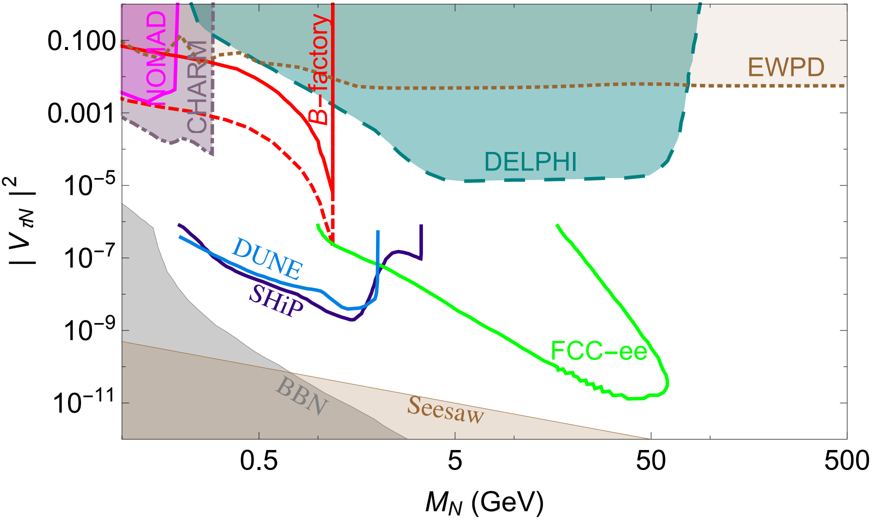
[Deppisch, BD, Pilaftsis (NJP '15)]

Summary Plot (Muon Sector)



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

Summary Plot (Tau Sector)



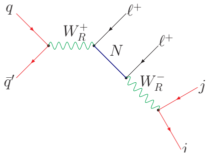
[Deppisch, BD, Pilaftsis (NJP '15)]

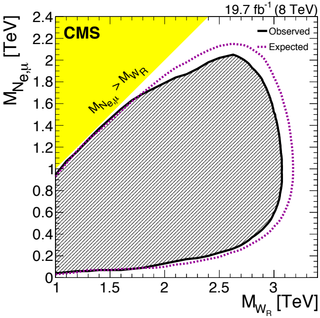
Left-Right Seesaw

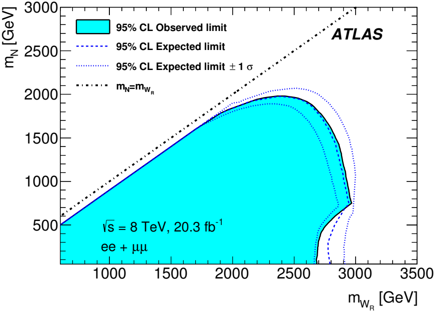
- Provides a natural framework for type-I seesaw (at TeV scale).

  [Pati, Salam (PRD ’74); Mohapatra, Pati (PRD ’75); Senjanović, Mohapatra (PRD ’75)]
- New contribution to Drell-Yan process via W_R exchange.

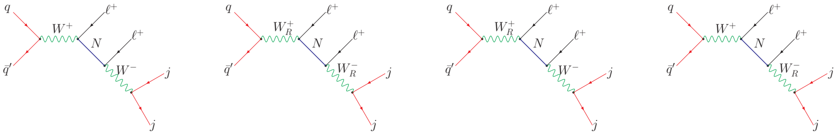
  [Keung, Senjanović (PRL ’83)]



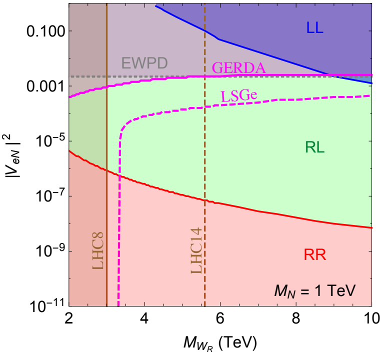




L-R Seesaw Phase Diagram

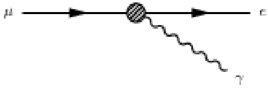


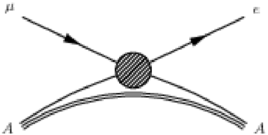
(a) LL (b) RR (c) RL (d) LR

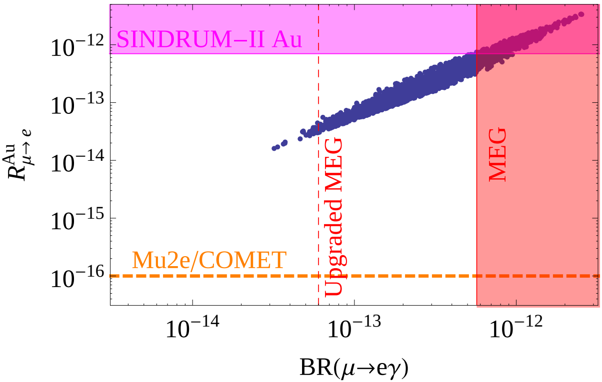


[Chen, BD, Mohapatra (PRD ’13); BD, Kim, Mohapatra (JHEP ’16)]

Lepton Flavor Violation

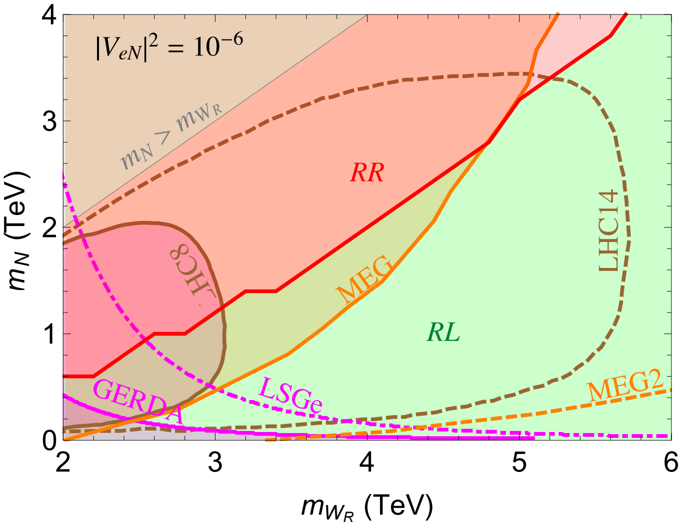






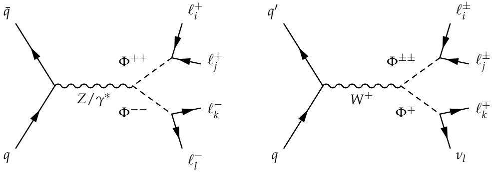
[BD, Lee, Mohapatra (PRD '13)]

Complementarity with the LHC

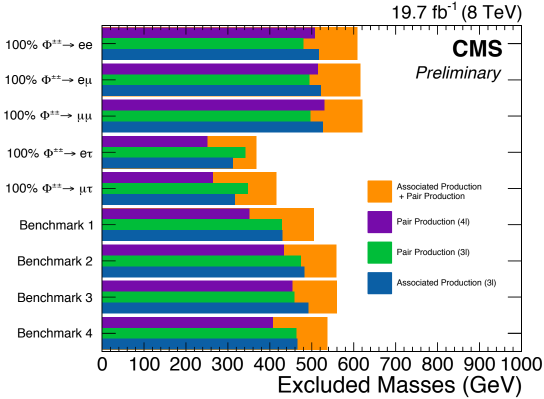


[BD, Kim, Mohapatra (JHEP '16)]

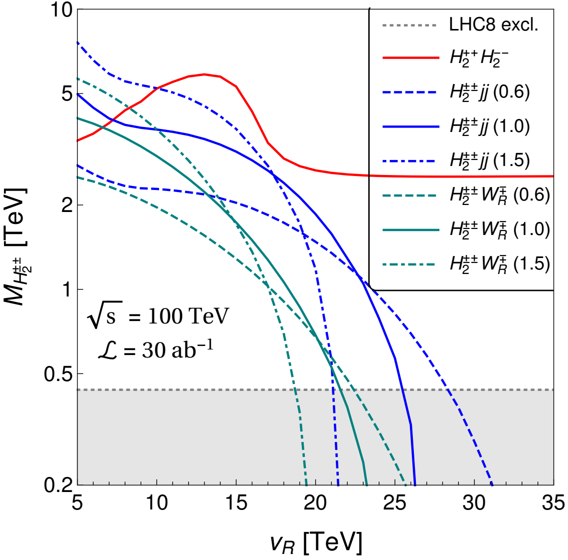
Type-II Seesaw Signal



(a) 4ℓ (b) 3ℓ

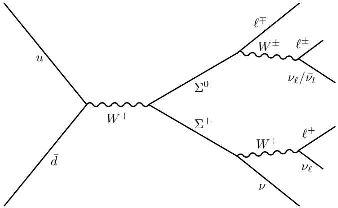


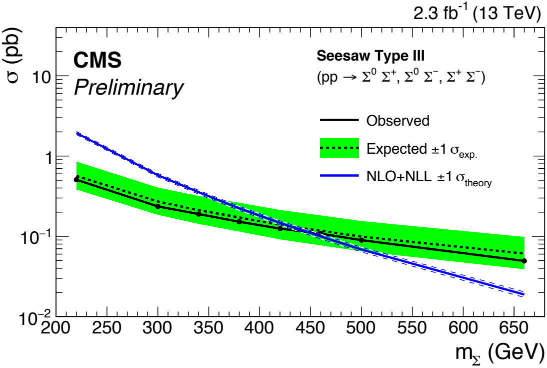
Prospects at 100 TeV



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

Type-III Seesaw Signal





Conclusion

- Understanding the neutrino mass mechanism will provide important insights into the BSM world.
- Might also shed light on other puzzles (e.g., baryon asymmetry and dark matter).
- Colliders provide a ripe testing ground for low-scale neutrino mass models.
- Healthy complementarity at the intensity and cosmic frontiers.