LHC-13 and Neutrinos

BHUPAL DEV

Washington University in St. Louis

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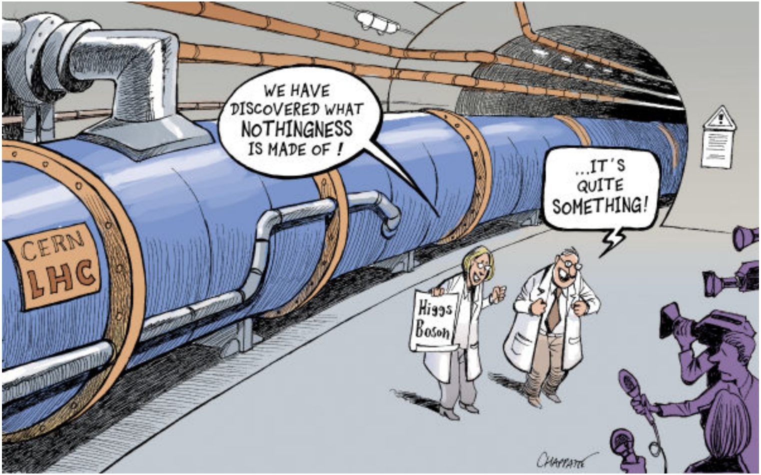
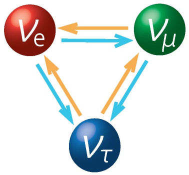
Largest Microscope

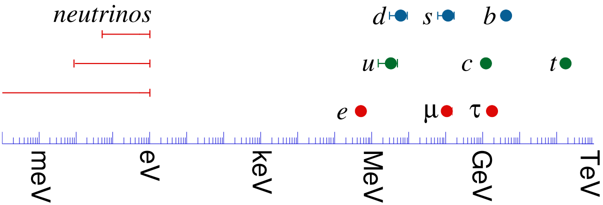


What could it tell about neutrinos?

Harbinger of New Physics



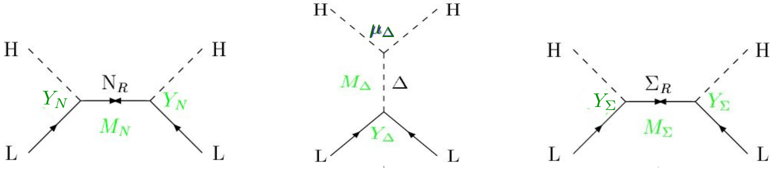
Non-zero neutrino mass $\Longrightarrow$ physics beyond the SM



Something beyond the Higgs mechanism?

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 $(LLHH)/\Lambda$. [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:

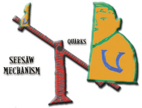
Can the seesaw mechanism be tested at the LHC (and beyond)?

Type-I Seesaw

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

- Messengers: SM-singlet **Majorana** fermions (sterile neutrinos).
- In the flavor basis $\{\nu^c, N\}$, leads to the seesaw mass matrix

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



- In the seesaw approximation ($||M_D M_N^{-1}|| \ll 1$), $M_\nu^{\rm light} \simeq -M_D M_N^{-1} M_D^\mathsf{T}$.
- Traditionally M_N is assumed to be at very high (close to GUT) scale.
- However, no definite prediction in a bottom-up approach.
- 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 '16]

Low-scale Type-I Seesaw

- In 'traditional' seesaw, active-sterile 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 valid 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); Adhikari, Raychaudhuri (PRD '11); 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.
- Possible exception: resonant enhancement of LNV signal for $\Delta M_N \sim \Gamma_N$.
  [Bray, Pilaftsis, Lee (NPB '07)]

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

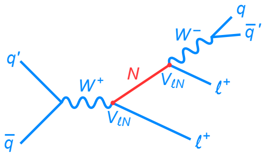
$$\begin{aligned} \mathcal{M}_\nu &= \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^\mathsf{T} & \mathbf{0} & M_N^\mathsf{T} \\ \mathbf{0} & M_N & \mu \end{pmatrix} \equiv \begin{pmatrix} \mathbf{0} & \mathcal{M}_D \\ \mathcal{M}_D^\mathsf{T} & \mathcal{M}_N \end{pmatrix} \\ M_\nu^{\text{light}}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

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

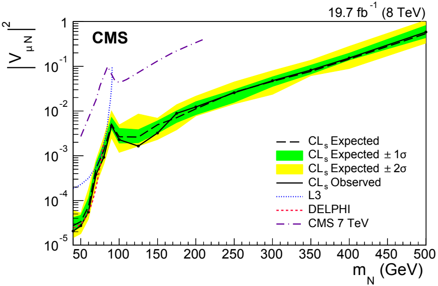
$$V_{lN} \simeq \sqrt{\frac{M_\nu}{\mu}} \approx 10^{-2}\sqrt{\frac{1\ \text{keV}}{\mu}}$$

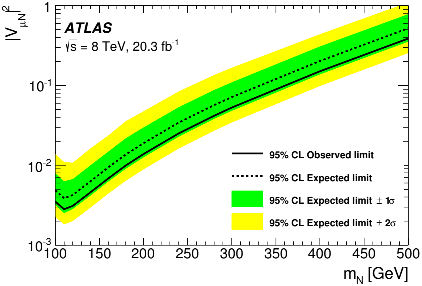
- Potentially large LFV signals at colliders, as well as in low-energy expts.

Seesaw Signals 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)]

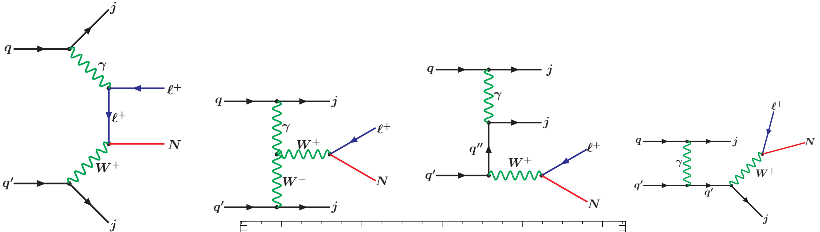


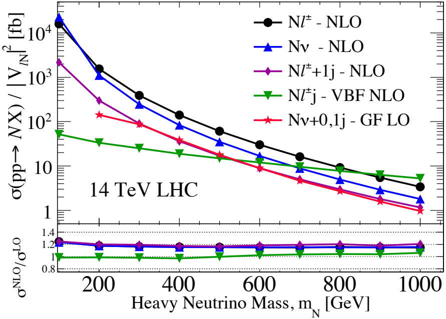


Important to also look for opposite-sign dilepton and trilepton signals.

New Contribution

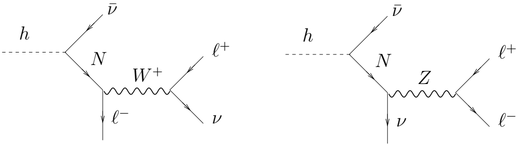
Collinear-enhancement mechanism [BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15)]

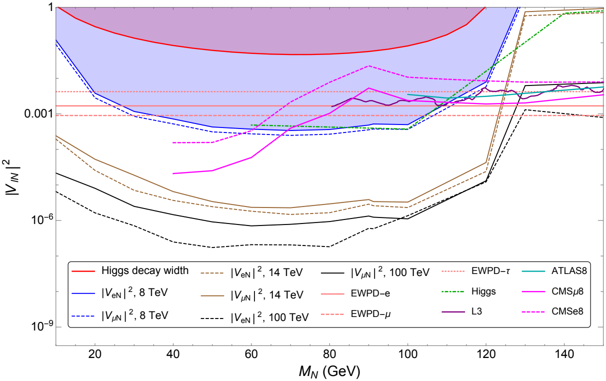




[Degrande, Mattelaer, Ruiz, Turner (PRD '16)]

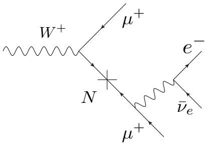
Higgs Decay

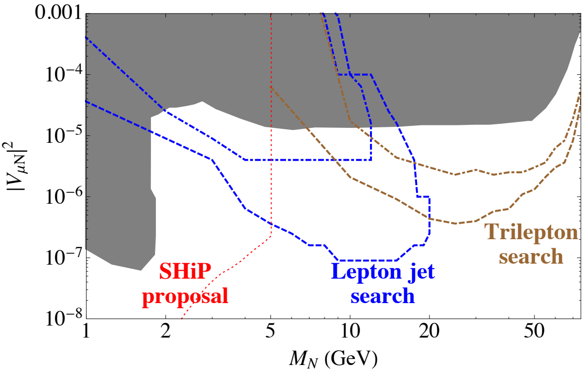




[BD, Franceschini, Mohapatra (PRD '12); Das, BD, Kim (in preparation)]

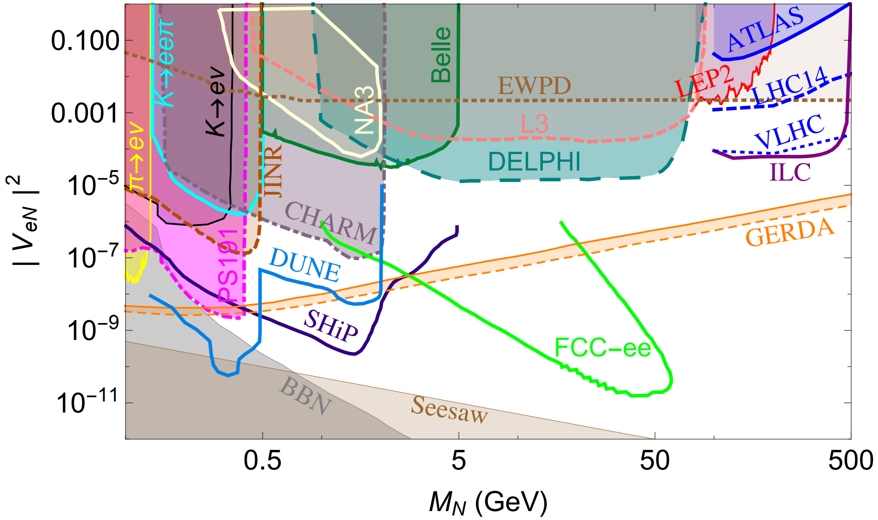
W Decay





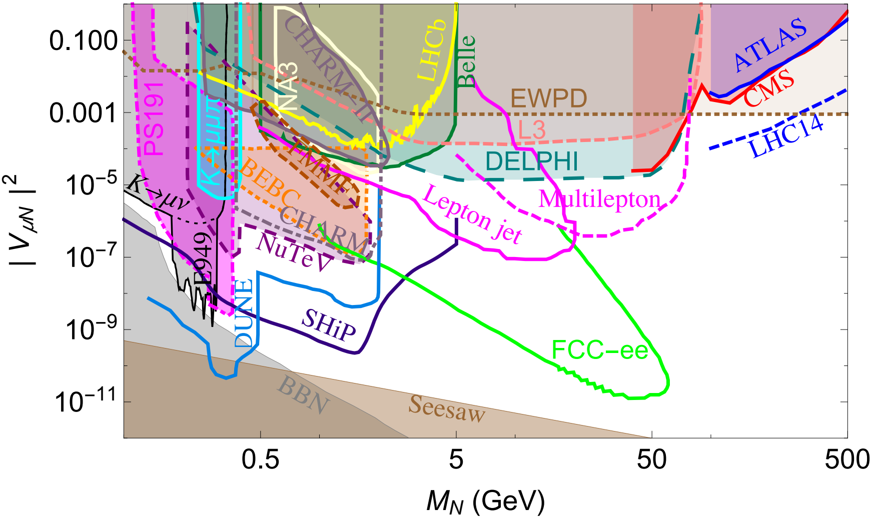
[Izaguirre, Shuve (PRD '15); Dib, Kim (PRD '15); Dib, Kim, Wang, Zhang (PRD '16)]

Summary Plot (Electron Sector)



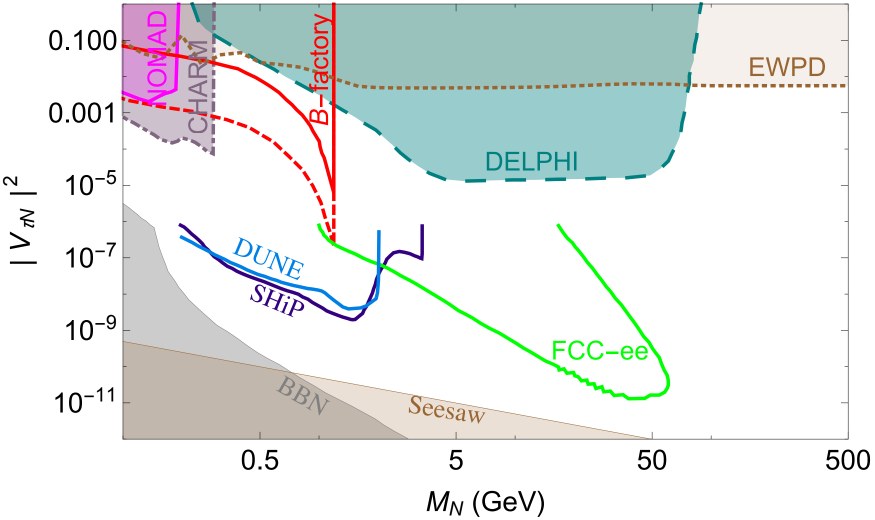
[Atre, Han, Pascoli, Zhang (JHEP ’09); Deppisch, BD, Pilaftsis (NJP ’15)]

Summary Plot (Muon Sector)



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

Summary Plot (Tau Sector)



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

Left-Right Seesaw

- Provides a natural framework for type-I seesaw embedding.
- Based on the gauge group $\mathcal{G}_{\rm LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

  [Pati, Salam (PRD '74); Mohapatra, Pati (PRD '75); Senjanović, Mohapatra (PRD '75)]

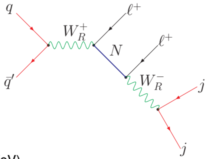
$$Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i : \left(\mathbf{3}, \mathbf{2}, \mathbf{1}, \frac{1}{3}\right), \qquad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i : \left(\mathbf{3}, \mathbf{1}, \mathbf{2}, \frac{1}{3}\right),$$

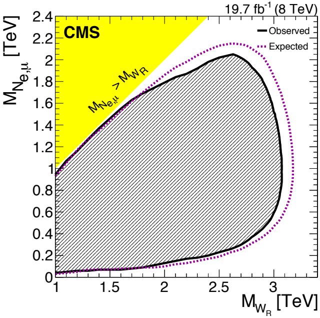
$$\psi_{L,i} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i : (\mathbf{1}, \mathbf{2}, \mathbf{1}, -1), \qquad \psi_{R,i} = \begin{pmatrix} N_R \\ e_R \end{pmatrix}_i : (\mathbf{1}, \mathbf{1}, \mathbf{2}, -1).$$

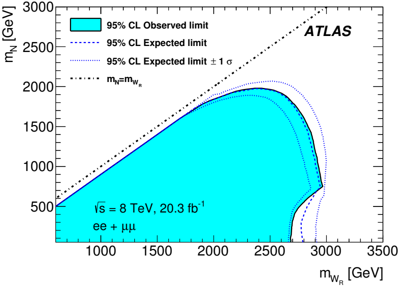
- RH neutrinos are an essential part of the theory (not put in 'by hand').
- Seesaw scale intimately connected with the $U(1)_{B-L}$ symmetry breaking.
- Can be realized at $v_R \gtrsim 5$ TeV scale, with many observable effects.

Collider Signal

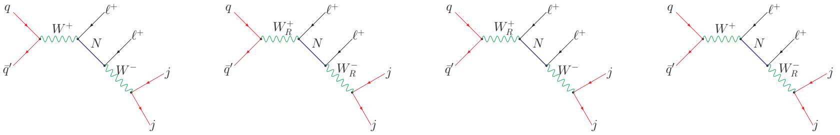
New contribution to Drell-Yan process via W_R exchange. [Keung, Senjanović (PRL '83); Ferrari *et al* (PRD '00); Nemevsek, Nesti, Senjanović, Zhang (PRD '11); Das, Deppisch, Kittel, Valle (PRD '12); Lindner, Queiroz, Rodejohann, Yaguna (JHEP '16); Mitra, Ruiz, Scott, Spannowsky (PRD '16)]



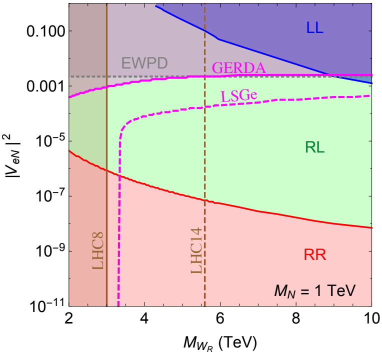




L-R Seesaw Phase Diagram

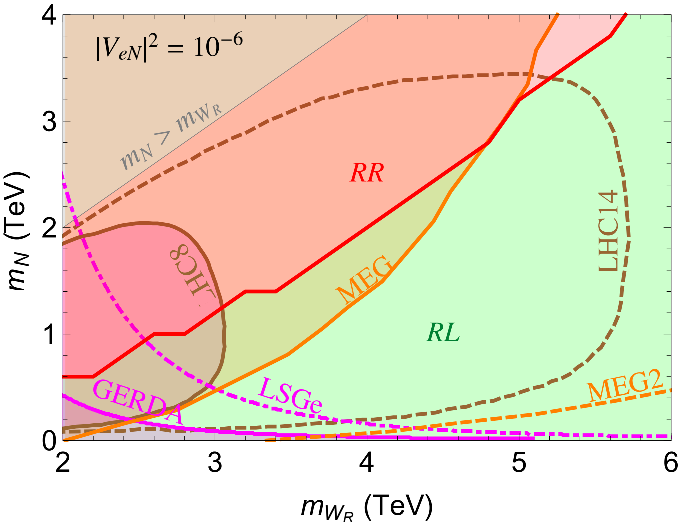


(a) LL (b) RR (c) RL (d) LR



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

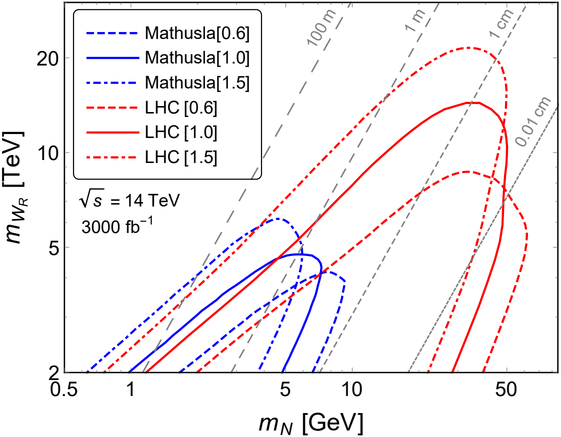
Complementarity with Low-energy Experiments



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

Displaced Vertex Signal

Applicable if the RH neutrino is light and/or the active-sterile mixing is very small. [Helo, Hirsch, Kovalenko (PRD '14); Deppisch, Desai, Valle (PRD '14); Castillo-Felisola, Dib, Helo, Kovalenko, Ortiz (PRD '15)]



[BD, Mohapatra, Zhang '17]

Extended Higgs Sector

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

- $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ by $\langle \Delta_R^0 \rangle \equiv v_R$.
- $SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$ by $\langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$.
- Fermion masses arise from the Lagrangian

$$\mathcal{L}_Y = h^a_{q,ij} \bar{Q}_{L,i} \Phi_a Q_{R,j} + \tilde{h}^a_{q,ij} \bar{Q}_{L,i} \tilde{\Phi}_a Q_{R,j} + h^a_{\ell,ij} \bar{\psi}_{L,i} \Phi_a \psi_{R,j} + \tilde{h}^a_{\ell,ij} \bar{\psi}_{L,i} \tilde{\Phi}_a \psi_{R,j} + f_{ij} \psi^{\mathsf{T}}_{R,i} C i \tau_2 \Delta_R \psi_{R,j} + \text{H.c.}$$

- Including the Δ_L field could give rise to a type-II seesaw contribution.
- The triplet scalar fields are *hadrophobic*.

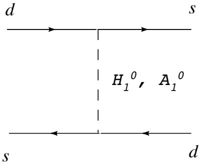
Physical Higgs Bosons

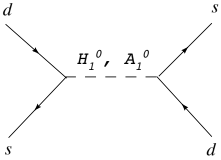
$$\begin{aligned}
\phi_1^0 &= \kappa + \frac{1}{\sqrt{2}}\phi_1^{0\,\mathrm{Re}} + \frac{i}{\sqrt{2}}\phi_1^{0\,\mathrm{Im}}\,, \\
\phi_2^0 &= \kappa' + \frac{1}{\sqrt{2}}\phi_2^{0\,\mathrm{Re}} + \frac{i}{\sqrt{2}}\phi_2^{0\,\mathrm{Im}}\,, \\
\Delta_R^0 &= v_R + \frac{1}{\sqrt{2}}\Delta_R^{0\,\mathrm{Re}} + \frac{i}{\sqrt{2}}\Delta_R^{0\,\mathrm{Im}}\,.
\end{aligned}$$

- 14 scalar fields:
  $\{\phi_1^{0\,\mathrm{Re}},\ \phi_2^{0\,\mathrm{Re}},\ \Delta_R^{0\,\mathrm{Re}},\ \phi_1^{0\,\mathrm{Im}},\ \phi_2^{0\,\mathrm{Im}},\ \Delta_R^{0\,\mathrm{Im}}\}\,,\quad \{\phi_1^{\pm},\ \phi_2^{\pm},\ \Delta_R^{\pm}\}\,,\quad \{\Delta_R^{\pm\pm}\}$.
- 6 Goldstone modes eaten by $(W^{\pm}, Z, W_R^{\pm}, Z_R)$.
- 8 remaining physical fields, denoted by $\{h,\ H_1^0,\ A_1^0,\ H_3^0,\ H_1^{\pm},\ H_2^{\pm\pm}\}$.

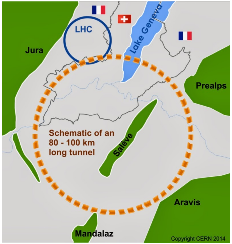
Heavy Neutral Higgs Bosons

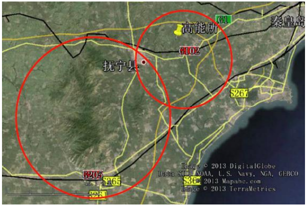
- FCNC constraints require the bidoublet scalars (H_1^0, A_1^0, $H_1^\pm$) to be very heavy $\gtrsim 10 - 20$ TeV. [An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14)]



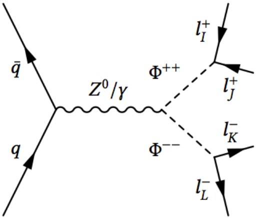


- No hope for them at the LHC. Need a 100 TeV collider! [BD, Mohapatra, Zhang (JHEP '16)]

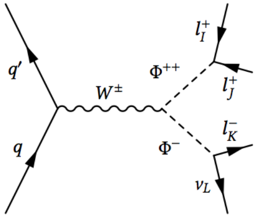




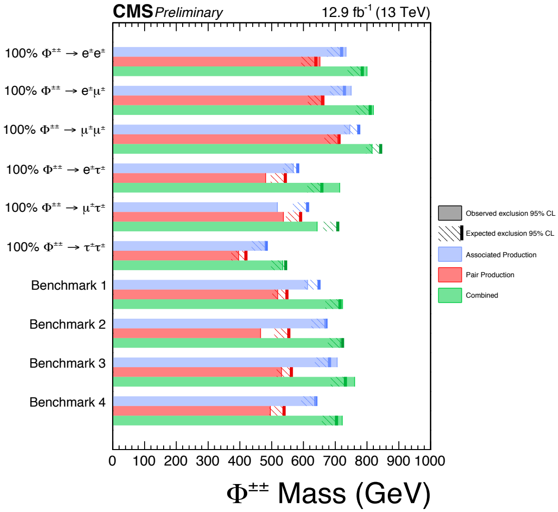
Charged Higgs (also in Type-II Seesaw)



(a) 4ℓ

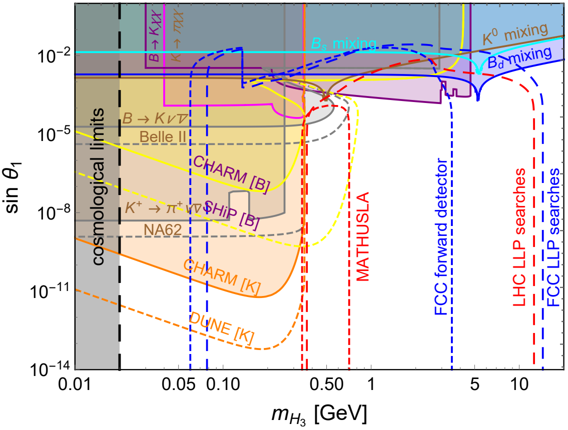


(b) 3ℓ



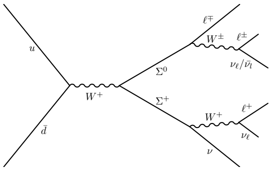
A Light Neutral Higgs as a Probe of Seesaw

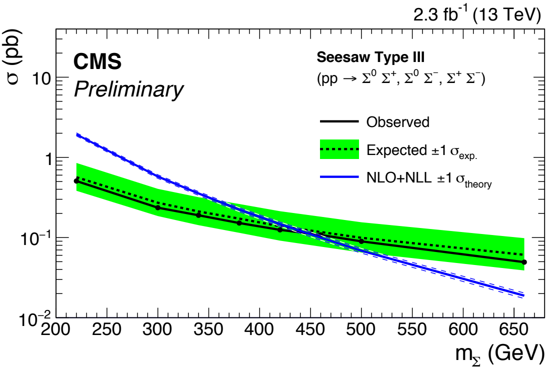
- The CP-even neutral triplet component can be light (GeV-scale).
- Suppressed coupling to SM particles (either loop-level or small mixing).
- Necessarily long-lived at the LHC, with displaced vertex signals.



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

Type-III Seesaw Signal





Conclusion

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