# LHC tests of low scale neutrino mass generation

**Bhupal Dev**

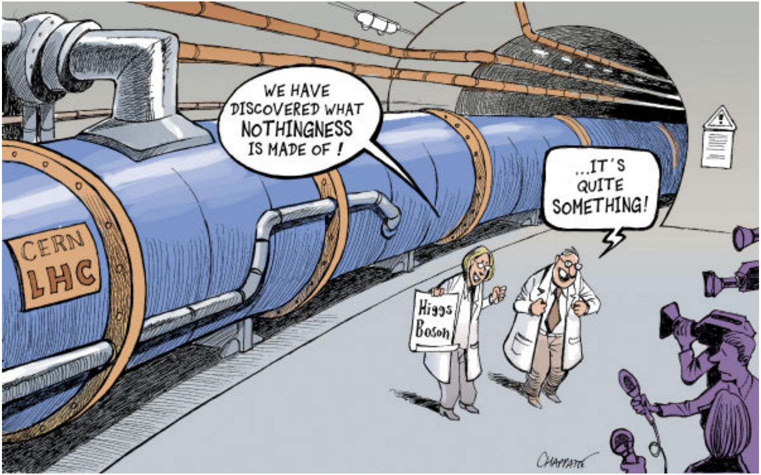
*Washington University in St. Louis*

**XXVIII International Conference on Neutrino Physics and Astrophysics**

*Heidelberg, Germany*

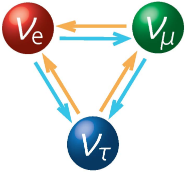
June 8, 2018

# Largest Microscope

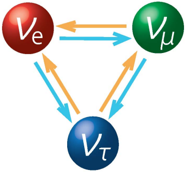



What could it tell about **neutrinos**?

# Harbinger of New Physics




**Non-zero neutrino mass $\Longrightarrow$ physics beyond the Standard Model**

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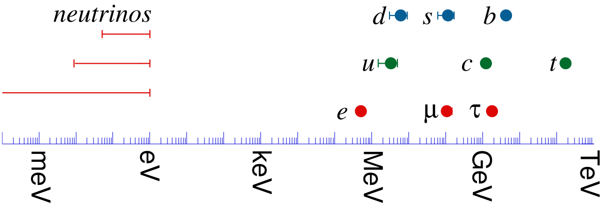


**Perhaps something beyond the standard Higgs mechanism...**

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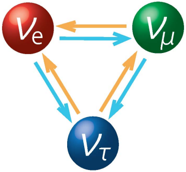


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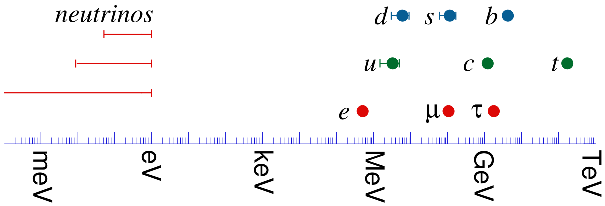


**Perhaps something beyond the standard Higgs mechanism...**

**Can the LHC test the origin of neutrino mass?**

# Neutrino Mass Models

For overview, see Tuesday talk by L. Everett

- From pheno point of view, can broadly categorize into
  - Tree-level (seesaw) vs loop-level (radiative)
  - Minimal (SM gauge group) vs gauge-extended [e.g. $U(1)_{B-L}$, Left-Right, $SO(10)$]
  - Non-supersymmetric vs Supersymmetric

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- Rich phenomenology.
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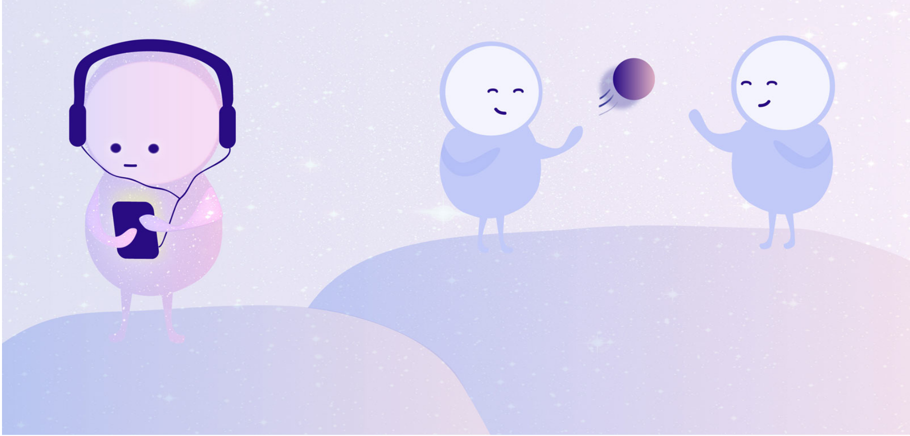
- **This talk:**
  - Tree-level [See next talk by R. Volkas for radiative models]
  - SM gauge group and two extensions [$U(1)$ and Left-Right]
  - Non-supersymmetric

# New Fermions

(aka sterile neutrinos/heavy neutrinos/heavy neutral leptons)



# Type-I Seesaw

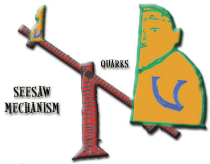
[Minkowski (PLB '77); Mohapatra, Senjanović (PRL '80); Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80; Schechter, Valle (PRD '80)]

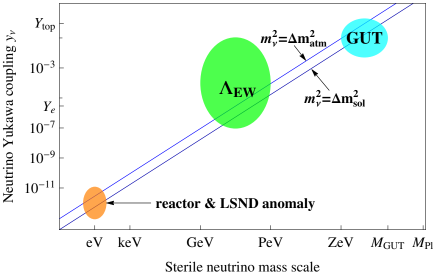
- Introduce SM-singlet **Majorana** fermions ($N$).

$$-\mathcal{L} \supset Y_\nu \bar{L}\phi^c N + \frac{1}{2} M_N \bar{N}^c N + \text{H.c.}$$

- After EWSB, $m_\nu \simeq -M_D M_N^{-1} M_D^T$, where $M_D = vY_\nu$.

[Figure from Antusch, Cazzato, Fischer (IJMPA '17)]



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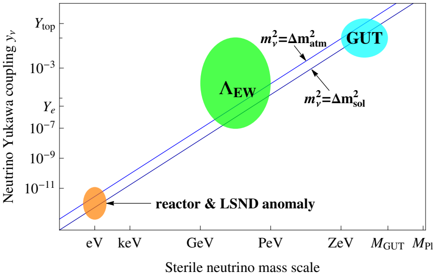


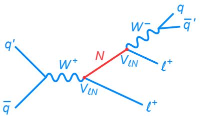

- Naturalness of Higgs mass suggests $M_N \lesssim 10^7$ GeV. [see talk by R. Volkas]

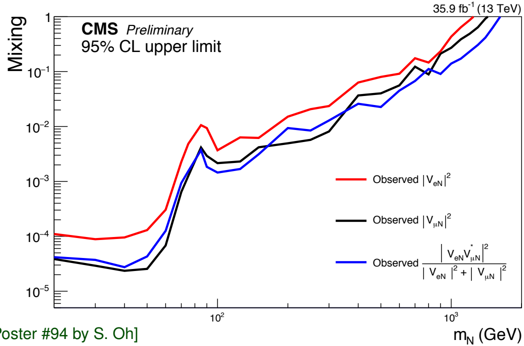
[Vissani (PRD '98); Clarke, Foot, Volkas (PRD '15); Bambhaniya, BD, Goswami, Khan, Rodejohann (PRD '17)]

# Heavy Majorana Neutrinos at the LHC

[Keung, Senjanović (PRL ’83); Datta, Guchait, Pilaftsis (PRD ’94); Panella, Cannoni, Carimalo, Srivastava (PRD ’02); Han, Zhang (PRL ’06); del Aguila, Aguilar-Saavedra, Pittau (JHEP ’07); Atre, Han, Pascoli, Zhang (JHEP ’09)]

**Same-sign dilepton plus jets without $\not{E}_T$**




[CMS PAS EXO-17-028; Poster #94 by S. Oh]

Probes (sub) TeV scale heavy Majorana neutrinos with ‘large’ active-sterile mixing.

# Low-scale Type-I Seesaw

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

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

- '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);...]

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

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

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- But the steriles with large mixing are 'quasi-Dirac' with suppressed LNV.
- Generally true in order to satisfy neutrino oscillation data and $0\nu\beta\beta$ constraints.

  [Abada, Biggio, Bonnet, Gavela, Hambye (JHEP '07); Ibarra, Molinaro, Petcov (JHEP '10); Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, Lucente (JHEP '15); Drewes, Garbrecht, Gueter, Klaric (JHEP '16)]

- Should also look for lepton number conserving channels at the LHC.

# Inverse Seesaw

- Provides a (technically) natural low-scale seesaw framework. [Mohapatra, Valle (PRD '86)]
- Two sets of SM-singlet fermions with opposite lepton numbers.

$$-\mathcal{L}_Y \supset Y_\nu \bar{L}\phi^c N + M_N \bar{S} N + \frac{1}{2}\mu_S \bar{S} S^c + \text{H.c.}$$

$$m_\nu \simeq (M_D M_N^{-1})\, \mu_S\, (M_D M_N^{-1})^{\mathsf{T}}$$

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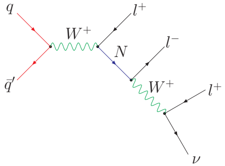
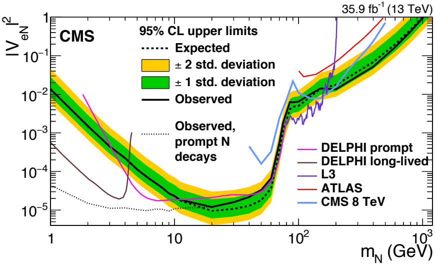
- But again quasi-Dirac heavy neutrinos.
- Should look for lepton number conserving channels at the LHC.
- Ratio of same-sign to opposite-sign dilepton signal could test the Majorana vs. Dirac nature. [Gluza, Jelinski (PLB '15); BD, Mohapatra (PRL '15); Gluza, Jelinski, Szafron (PRD '16); Anamiati, Hirsch, Nardi (JHEP '16); Das, BD, Mohapatra (PRD '17)]

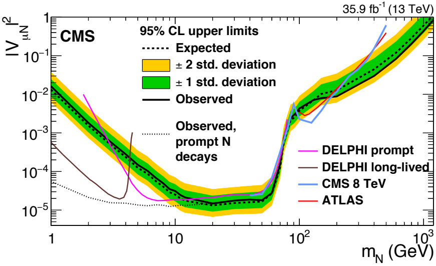
# Heavy Dirac Neutrinos at the LHC

[del Aguila, Aguilar-Saavedra (PLB ’09; NPB ’09); Chen, BD (PRD ’12); Das, Okada (PRD ’13); Das, BD, Okada (PLB ’14); Izaguirre, Shuve (PRD ’15); Dib, Kim (PRD ’15); Dib, Kim, Wang (PRD ’17; CPC ’17); Dube, Gadkari, Thalapillil (PRD ’17)]

**Trilepton plus $\not{E}_T$**

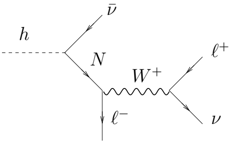


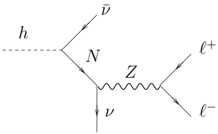



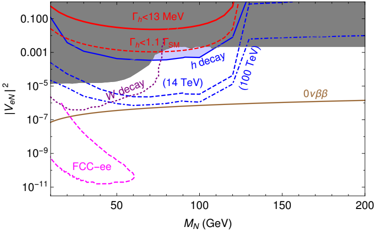



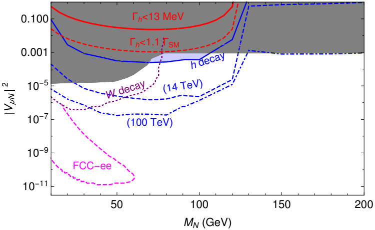

[Phys. Rev. Lett. **120**, 221801 (2018); Poster #94 by S. Oh]

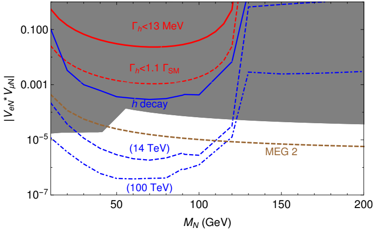
[BD, Franceschini, Mohapatra (PRD ’12); Cely, Ibarra, Molinaro, Petcov (PLB ’13)]



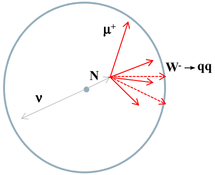



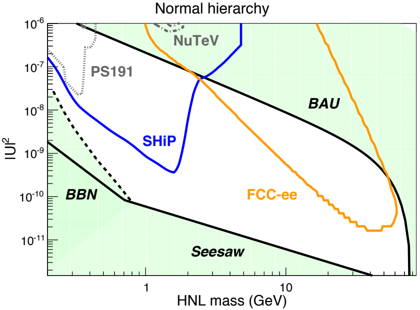



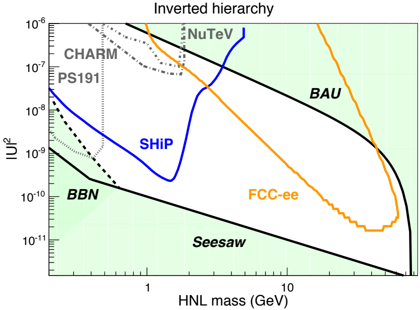

[Das, BD, Kim (PRD ’17)]

# $Z$ Decay




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

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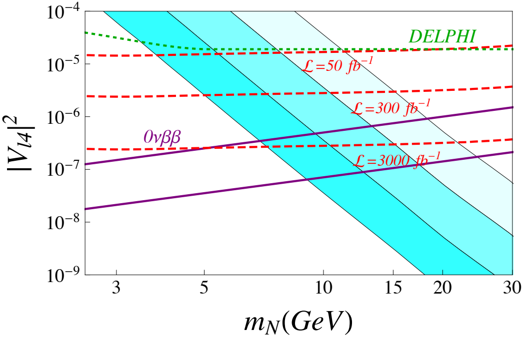
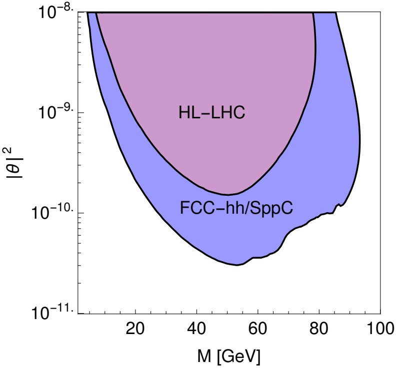
[Blondel, Graverini, Serra, Shaposhnikov ’14]

# Displaced Vertex



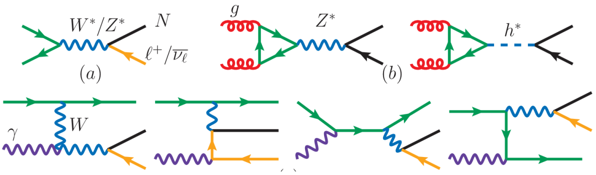

[Helo, Kovalenko, Hirsch (PRD '14)]

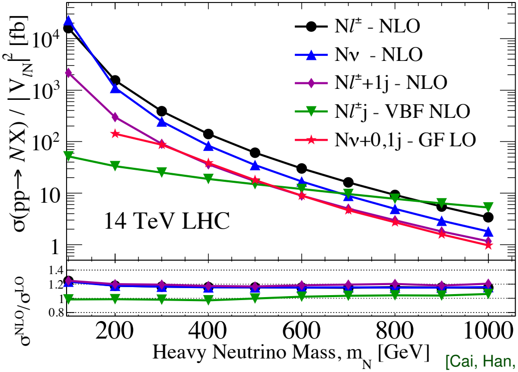



[Antusch, Cazzato, Fischer (IJMPA '17)]

# New Contributions to Heavy Neutrino Production

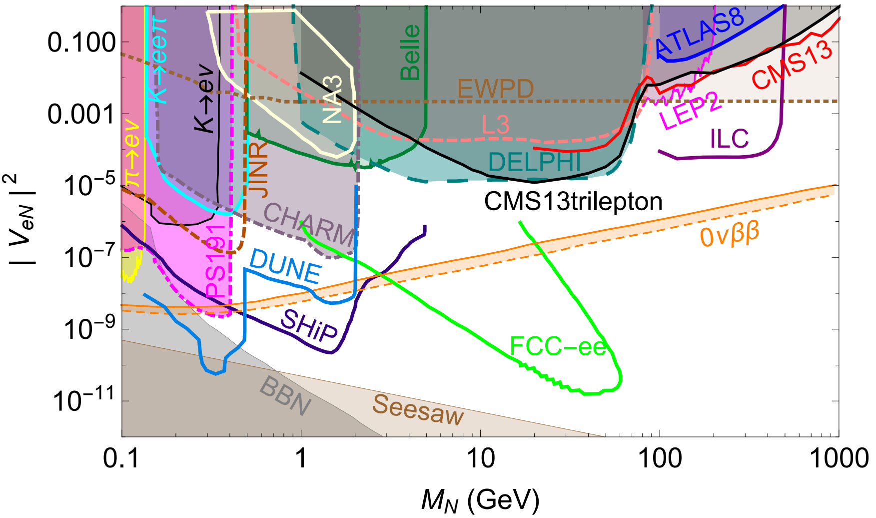
[BD, Pilaftsis, Yang (PRL '14); Alva, Han, Ruiz (JHEP '15); Degrande, Mattelaer, Ruiz, Turner (PRD '16); Das, Okada (PRD '16)]




[Cai, Han, Li, Ruiz (Front. in Phys. '18)]

# Summary of Constraints and Prospects




[updated from Deppisch, BD, Pilaftsis (New J. Phys. '15)]

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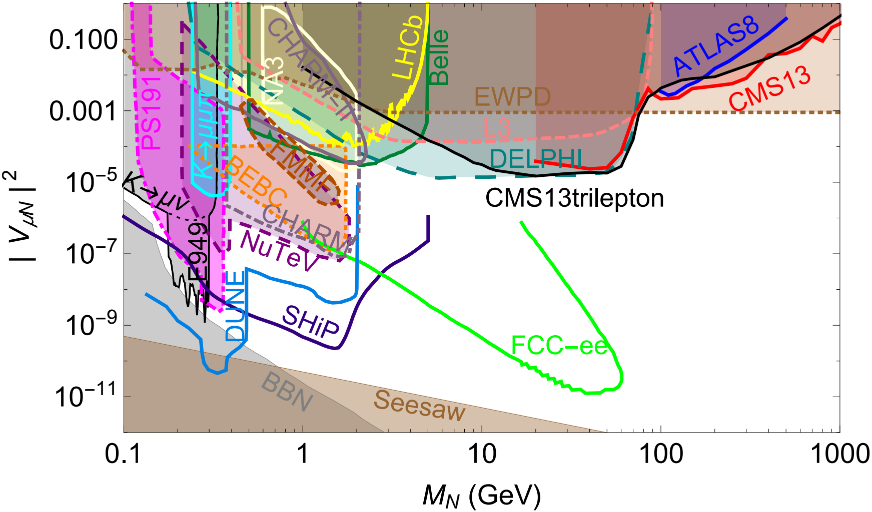


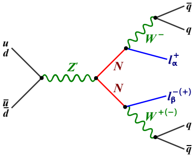

[updated from Deppisch, BD, Pilaftsis (New J. Phys. '15)]

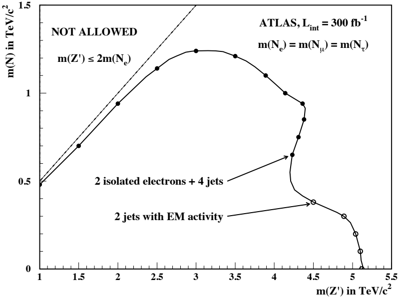
## New Gauge Bosons

$(W', Z')$

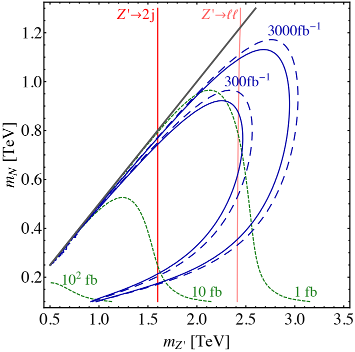
# $U(1)_{B-L}$ Extension

[Buchmuller, Greub (NPB '91); Fileviez Perez, Han, Li (PRD '09); Kang, Ko, Li (PRD '15); Heeck, Teresi (PRD '16); BD, Mohapatra, Zhang (JHEP '17); Das, Okada, Raut '17; Cox, Han, Yanagida (JHEP '18); ...]



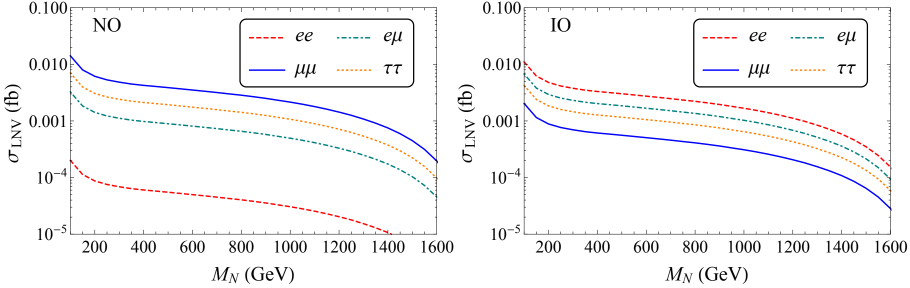

[Ferrari, Collot '00]




[Deppisch, Desai, Valle (PRD '14)]

# Probing Neutrino Mass Hierarchy at the LHC

- In a symmetry-based scenario, Dirac Yukawa couplings can be directly related to the PMNS mixing matrix (á la Casas-Ibarra).
- Could give rise to either prompt or displaced vertex signals at the LHC.
- LNV cross section is sensitive to the light neutrino mass hierarchy.

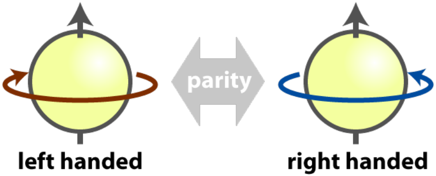



[BD, Hagedorn, Molinaro (in prep.)]

# Left-Right Symmetric Extension

- Based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

  [Pati, Salam (PRD '74); Mohapatra, Pati (PRD '75); Senjanović, Mohapatra (PRD '75)]
- Parity restoration at high energy.

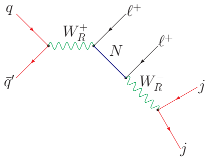


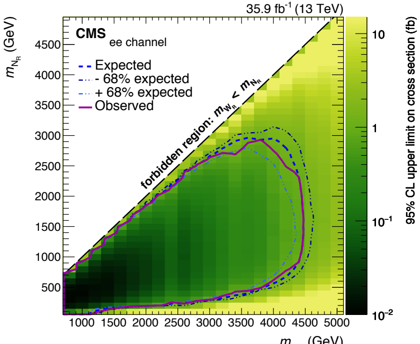

- Provides a natural framework for type-I (and type-II) seesaw embedding.
- RH neutrinos are an essential part of the theory (not put in 'by hand').
- Seesaw scale intimately connected with the $U(1)_{B-L}$ symmetry breaking.
- Can be realized at $v_R \gtrsim 5$ TeV scale, with many observable effects.

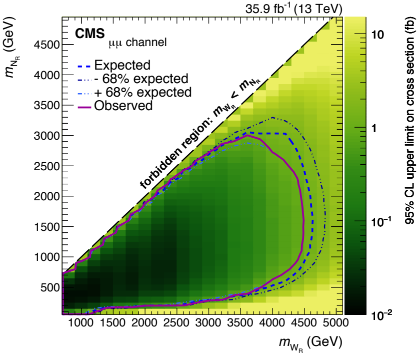
# LHC Signal

[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);...]

**New contribution to same-sign dilepton signal (independent of mixing)**

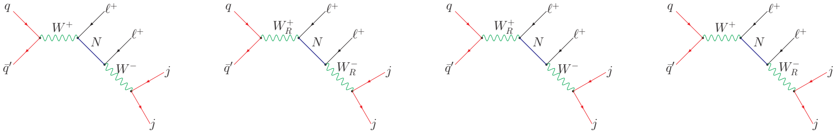


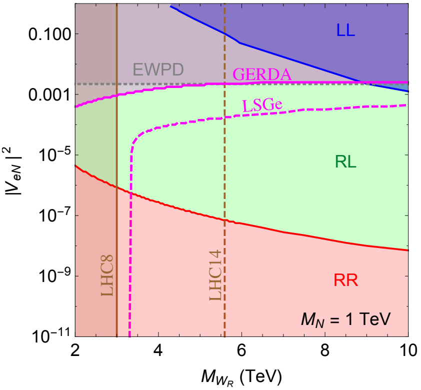




[JHEP **1805**, 148 (2018)]

# L-R Seesaw Phase Diagram

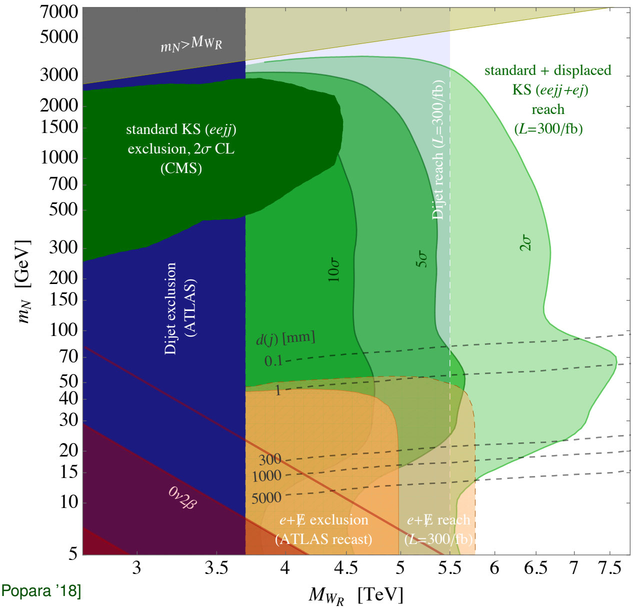



(a) LL (b) RR (c) RL (d) LR




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

# Future Prospects




[Nemevsek, Nesti, Popara '18]

## New Scalars

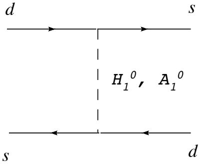
# L-R Seesaw Higgs Sector

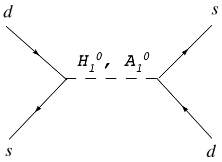
$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \Delta_R = \begin{pmatrix} \frac{\Delta_R^+}{\sqrt{2}} & \Delta_R^{++} \\ \Delta_R^0 & -\frac{\Delta_R^+}{\sqrt{2}} \end{pmatrix}, \quad \Delta_L = \begin{pmatrix} \frac{\Delta_L^+}{\sqrt{2}} & \Delta_L^{++} \\ \Delta_L^0 & -\frac{\Delta_L^+}{\sqrt{2}} \end{pmatrix}$$

- $\langle \Delta_R^0 \rangle \equiv v_R$ gives rise to RH Majorana neutrino masses, and hence, type-I seesaw.
- $\langle \Delta_L^0 \rangle \equiv v_L$ gives rise to a type-II seesaw contribution.
- 14 physical scalar fields (compared to just 1 in the SM).
- Very rich phenomenology.

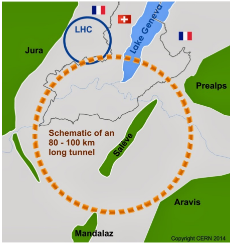
  [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Polak, Zralek (PLB '92); Akeroyd, Aoki (PRD '05); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP '14); Dutta, Eusebi, Gao, Ghosh, Kamon (PRD '14); Maiezza, Nemevsek, Nesti (PRL '15); BD, Mohapatra, Zhang (JHEP '16);...]
- The triplet scalar fields are *hadrophobic*.

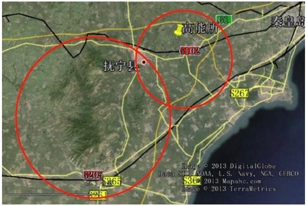
- FCNC constraints require the bidoublet scalars ($H_1^0$, $A_1^0$, $H_1^\pm$) to be very heavy $\gtrsim$ 15 TeV. [An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14)]



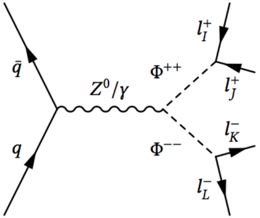




- No hope for them at the LHC. **Need a 100 TeV collider!**

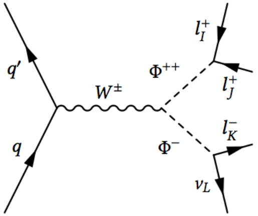


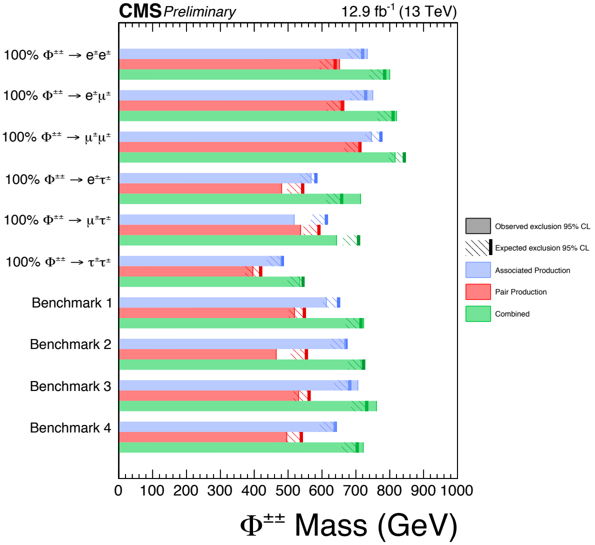
# Charged Triplet Sector




(a) $4\ell$



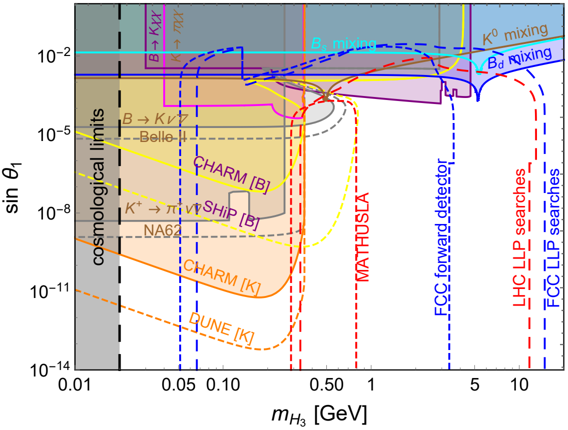

(b) $3\ell$




[CMS-PAS-HIG-16-036]

# Neutral Triplet Sector

- Can be very 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 (PRD '17; NPB '17)]

# Conclusion

- 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.
- Can probe the messenger particles (new fermions/gauge bosons/scalars) in a wide range of parameter space.
- Healthy complementarity at the intensity frontier.
- Might be directly relevant for other outstanding puzzles, such as the matter-antimatter asymmetry (leptogenesis). [see afternoon talk by M. Drewes]

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*Thank You!*