Neutrino Models at Colliders

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SUSY2019

Corpus Christi

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Non-zero neutrino mass $\implies$ physics beyond the Standard Model
Harbinger of New Physics

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

neutrinos

d $\bullet$ s $\bullet$ b $\bullet$

u $\bullet$ c $\bullet$ t $\bullet$

e $\bullet$ $\mu$ $\bullet$ $\tau$ $\bullet$

meV ev keV MeV GeV TeV

Perhaps something beyond the standard Higgs mechanism...
Non-zero neutrino mass $\implies$ physics beyond the Standard Model

Perhaps something beyond the standard Higgs mechanism...

Can we probe the origin of neutrino mass at colliders?
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]
- **Non-supersymmetric vs Supersymmetric**
Neutrino Mass Models

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

New fermions, gauge bosons, and/or scalars – messengers of neutrino mass physics.
- Rich phenomenology.
- For messenger scale $\lesssim \mathcal{O}(\text{few TeV})$, accessible at the LHC and/or future colliders.
- Connection to other puzzles (e.g. baryogenesis, dark matter).
New Fermions
(aka sterile neutrinos/heavy neutrinos/heavy neutral leptons)
Introduce SM-singlet **Majorana** fermions \( (N) \).

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

After EWSB, \( m_\nu \sim -M_D M_N^{-1} \bar{M}_D \), where \( M_D = vY_\nu \).

[Figure from Antusch, Cazzato, Fischer (IJMPA '17)]
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-L \supset Y_\nu \overline{\phi}^c N + \frac{1}{2} M_N \overline{N}^c N + H.c.
\]

After EWSB, \(m_\nu \sim -M_D M_N^{-1} M_D^T\), where \(M_D = \nu Y_\nu\).

**Naturalness of Higgs mass suggests** \(M_N \lesssim 10^7\) GeV.

![Figure from Antusch, Cazzato, Fischer (IJMPA '17)](image-url)
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 $E_T$)

![Feynman diagram for resonant production of a Majorana neutrino (N). The observed (expected) limits are shown.]

Figure 1: The Feynman diagram for resonant production of a Majorana neutrino (N). The observed (expected) limits are shown.

| $m_N$ (GeV) | $|V_{eN}|^2$ | $|V_{\mu N}|^2$ | $|V_{eN}V_{\mu N}^*|/(|V_{eN}|^2 + |V_{\mu N}|^2)$ |
|------------|-------------|----------------|------------------------------------------------|
| 1000 GeV   | 2.1 × 10^{-3} | 2.0 × 10^{-3}  | 2.4 × 10^{-3} |
| 2000 GeV   | 2.4 × 10^{-4} | 2.4 × 10^{-4}  | 2.8 × 10^{-4} |
| 3000 GeV   | 2.7 × 10^{-5} | 2.8 × 10^{-5}  | 3.2 × 10^{-5} |

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

[ CMS PAS EXO-17-028]
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);...]

But the steriles with large mixing are ‘quasi-Dirac’ with suppressed LNV.

[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)]

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

\[
M_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \quad \text{and} \quad M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix} \quad \text{with } \epsilon_i, \delta_i \ll m_i.
\]
Low-scale Seesaw with Large Mixing

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- One example: [Kersten, Smirnov (PRD ’07)]
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  m_3 & \delta_3 & \epsilon_3
  \end{pmatrix}
  \quad \text{and} \quad
  M_N = \begin{pmatrix}
  0 & M_1 & 0 \\
  M_1 & 0 & 0 \\
  0 & 0 & M_2
  \end{pmatrix}
  \]
  with \(\epsilon_i, \delta_i \ll m_i\).

- But the steriles with large mixing are ‘quasi-Dirac’ with suppressed LNV.

- Generic requirement 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.
- Two sets of SM-singlet fermions with opposite lepton numbers. [Mohapatra, Valle (PRD '86)]

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

\[m_\nu \simeq (M_D M_N^{-1}) \mu_S (M_D M_N^{-1})^T\]

- Naturally allows for large mixing:

\[V_{\ell N} \simeq \sqrt{\frac{m_\nu}{\mu_S}} \approx 10^{-2} \sqrt{\frac{1 \text{ keV}}{\mu_S}}\]
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- Naturally allows for large mixing:

\[ V_{\ell N} \approx \sqrt{\frac{m_\nu}{\mu_S}} \approx 10^{-2} \sqrt{\frac{1 \text{ keV}}{\mu_S}} \]

- But again quasi-Dirac heavy neutrinos.
- Should look for both lepton number conserving and violating 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 (Pseudo) 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 $\mathcal{E}_T$

![Diagram of a trilepton plus $\mathcal{E}_T$ event]

Figure 2: Exclusion region at 95% CL in the $|V_{eN}|^2$ vs. $m_N$ plane.

CMS 95% CL upper limits

- Expected
- Observed, prompt N decays
- Observed, prompt N decays

$35.9 \text{ fb}^{-1}$ (13 TeV)

[CMS Collaboration, Phys. Rev. Lett. 120, 221801 (2018)]
Neutral current production of should be summed coherently GF formally

Preliminary

Importance of VBF for Heavy Neutrino Production

is the largest rate at LHC

\[ GF_{\text{LO}} \sim O(\alpha - s) \]

with total widths that are comparable to their mass splitting \[201, 224, 254, 255\].

– 19 –

\[ \sigma_{ \text{VBF}} \]

Heavy Neutrino Mass, \( m_N \) [GeV], and indicates that na

\[ m_N = 30 (300) [3000] \text{ GeV} \]

\[ \gamma \]

\[ N \]

\[ Z^* \]

\[ h^* \]

\[ g \]

\[ (a) \]

\[ (b) \]

\[ W^* / Z^* \]

\( \ell^+/\bar{\nu}_\ell \)

\[ \gamma \]

\[ W \]

\[ N \]

\[ g \]

\[ N \rightarrow (p p 1 \pm) - NLO N \pm 0,1j - NLO N+1j - VBF NLO N+0,1j ... \]

degenerate neutrinos with total widths that are comparable to their mass splitting \[201, 224, 254, 255\].

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- 19 -
Higgs Decay

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

With more precision Higgs measurements in the near future, the limits derived from the ...

However, for specific textures for the seesaw scale in the TeV regime. However, for specific textures for the seesaw scale in the TeV regime. However, for specific textures for ...

Clear, which charged lepton appears will depend on the flavor structure of...

Clearly, which charged lepton appears will depend on the flavor structure of...

The limits derived in [Das, BD, Kim (PRD '17)] significantly, as shown in the bottom panel of Fig. 3. Here we have also included eigenstates with...

FCC-ee opens up a new mode for SM Higgs decay, i.e.,...

The limits derived in [Das, BD, Kim (PRD '17)] from neutrino-less double beta decay...
Can access the region for successful \textbf{leptogenesis} via heavy neutrino oscillations.

\textbf{Figure 8: Regions of sensitivity for sterile neutrinos as a function of mass and mixing to light neutrinos (inverted hierarchy): for $10^{12}$ Z decays (b), for $10^{13}$ Z decays occurring between 100 µm and 1 m from the interaction point (c).}

\textbf{Figure 9: Regions of sensitivity for sterile neutrinos as a function of mass and mixing to light neutrinos (normal hierarchy): for $10^{12}$ Z decays (b), for $10^{13}$ Z decays occurring between 100 µm and 1 m from the interaction point (a), same for $10^{13}$ Z decays.}

[Blondel, Graverini, Serra, Shaposhnikov, 1411.5230]
where \( j \) runs over heavy neutrino flavour states. However, the neutrinoless double beta decay process offers a greater likelihood for the discovery of a Majorana neutrino, and constrains the mixing elements. The dielectron and dineutrino modes provide the cleanest access to the Majorana mass and are therefore most sensitive to the mixing parameters. The difluorine and diquark modes are less sensitive to the mixing parameters but provide additional information about the Majorana mass.

![Diagram](image-url)

**Figure 11: First look at the sensitivity reach of FASER to HNLs mixing with the electron neutrino in the (\( u \rightarrow e \)) channel.**

The sensitivity reach of FASER to HNLs mixing with the electron neutrino in the (\( u \rightarrow e \)) channel is shown in the figure. The reach is compared to that of other proposed experiments such as the HL-LHC, FCC-hh, and SppC. The sensitivity is shown for different mass limits and mixing strengths. The figure also shows the sensitivity reach for the proposed MATHUSLA FCC-hh (Forward) and SHiP experiments.

[Antusch, Cazzato, Fischer (IJMPA ’17)]
Displaced Vertex Search

\[ \begin{align*}
q' &\rightarrow W^+ N \nu_{\ln} t'^- \\
\bar{q} &\rightarrow W^- \nu_{\ln} \bar{t}'^-
\end{align*} \]

\( |\theta|^2 \)

\[ \begin{align*}
|\theta|^2 &< 10^{-11} \\
|\theta|^2 &> 10^{-12} & \text{HL-LHC} \\
|\theta|^2 &< 10^{-10} & \text{FCC-hh/SppC}
\end{align*} \]

\[ \begin{align*}
M [\text{GeV}] &\leq 100 \\
|U_{eN}| &< 10^{-4} & \text{SHIP} \\
|U_{eN}| &< 10^{-5} & \text{DUNE} \\
|U_{eN}| &> 10^{-6} & \text{NA62}
\end{align*} \]

[Antusch, Cazzato, Fischer (IJMPA '17)]
where $j$ runs over heavy neutrino flavour states. However, the neutrinoless double beta decay from a combined analysis of the phase-I and phase-II data acquired by the KamLAND-Zen experiment [55] is brought into collision with the 50 TeV proton beam from the FCC-hh. This would result in center-of-mass energies up to 200 GeV. It is in turn possible to explore this energy range with a Lorentz factor of 40 and 100 from proton-proton collisions at hadron colliders, which consist of a hadron ring with an intersecting storage ring. In a previous publication [30], the Lorentz factor $\gamma$ of the heavy neutrinos we assume an average value of $\gamma = 450$ GeV that are compatible with present constraints on active-sterile mixing. The FCC-hh/SppC en-...
Summary of Constraints and Prospects

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

[Hernandez, Jones-Perez, Suarez-Navarro (EPJC ’19); Bolton, Deppisch, BD (to appear)]
New Gauge Bosons

\((W', Z')\)
$U(1)_X$ 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 (EPJC '18); Cox, Han, Yanagida (JHEP '18); ...]

![Feynman diagram for heavy Majorana neutrino production](image-url)
within the standard minimal seesaw sector by choosing specific flavour textures in the mass matrix of the heavy neutrinos. We find that LFV can potentially be discovered from dilepton searches reported by CMS [26] (assuming SO(10) de- nistic SO(10) or E(6) extensions. An introduction and extensive list of references can be found in Ref. [16]. Elec-

Various physics scenarios beyond the Standard Model give the required luminosity at the LHC for a 5

One of the RHNs can be made a candidate.
Within the standard minimal seesaw sector by choosing specific flavour textures in the mass matrix of the type-I seesaw, see for example [12–14]. One of the RHNs can be made a dark matter candidate. [see parallel talk by S. Okada]
[Keung, Senjanović (PRL ’83); Ferrari et al (PRD ’00); Nemevsek, Nesti, Senjanović, Zhang (PRD ’11); Das, Deppisch, Kittel, Valle (PRD ’12); Mitra, Ruiz, Scott, Spannowsky (PRD ’16);…]; see Tuesday plenary talk by G. Senjanović

New contribution to same-sign dilepton signal (independent of mixing)
Left-Right Symmetric Extension

[Keung, Senjanović (PRL '83); Ferrari et al (PRD '00); Nemevsek, Nesti, Senjanović, Zhang (PRD '11); Das, Deppisch, Kittel, Valle (PRD '12); Mitra, Ruiz, Scott, Spannowsky (PRD '16);...]; see Tuesday plenary talk by G. Senjanović

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

\[ q \bar{q}' W^+ + R \ell^+ + N \ell^+ + W^- j j \]

\[ m_{N_R} \text{[TeV]} \]

\[ m_{W_R} \text{[TeV]} \]

(a) [ATLAS Collaboration, JHEP 1901, 016 (2019)]

(b) [ATLAS Collaboration, JHEP 1901, 016 (2019)]
FIG. 9. Summary plot collecting all searches involving the KS process at LHC, in the electron channel. The green shaded areas represent the LH sensitivity to the KS process at $300/\text{fb}$, according to the present work. The rightmost reaching contour represents the enhancement obtained by considering jet displacement.

Discovering the RH gauge boson $W_R$ in connection with the RH neutrino $N$ is the so-called Keung-Senjanović (KS) process [16], $\text{pp} \rightarrow W_R \rightarrow \nu \rightarrow \nu jj$. The constraints from direct searches [37,38], from flavour changing processes [11,14] and model perturbativity [12] point to a scale of the new RH interaction which is now at the fringe of the LHC reach, so the residual kinematically accessible range will be probed in the next year of two.

In this work we reconsidered this process and addressed the regime of light $N$ ($m_N < 100 \text{ GeV}$) which leads to long-lived RH neutrinos and thus to displaced vertices from its decay to a lepton and jets. This complements previous studies and gives a comprehensive overview of the collider reach covering the full parametric space.

To this aim, we classified the signatures resulting from the KS process, depending on the RH neutrino mass, in four regions: 1) a standard region where the final state is $\nu jj$, with half of the cases featuring same-sign leptons, testifying the lepton number violation. 2) a merged region, with lighter and more boosted $N$, in which its decay products are typically merged in a single jet including the secondary lepton, resulting in a lepton and associated neutrino jet. 3) a displaced region, for $m_N \approx 10-100 \text{ GeV}$, in which the merged jet $\nu j$ is originated from the $N$ decay at some appreciable displacement from the primary vertex, typically from mm to 30 cm where the silicon tracking ends and detection of displaced tracks becomes unfeasible. 4) an invisible region, for $m_N > 40 \text{ GeV}$, in which $N$ can decay outside the tracking chambers of even the full detector, leading thus to a signature of a lepton plus missing energy, $E_T$.

We assessed the reach in all these regions by scanning the $m_N, M_{WR}$ parameter space, up to $O(10) \text{ TeV}$. For $W_R$ masses beyond $\approx 5 \text{ TeV}$ the process is dominated by the off-shell $W_R^* \nu$ production, and we noted that, by this mechanism, for $m_N > 500 \text{ GeV}$ the final cross section...
L-R Seesaw Phase Diagram

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

[Chen, BD, Mohapatra (PRD '13); BD, Kim, Mohapatra (JHEP '16)]
\[
\begin{pmatrix}
N_e \\
N_\mu
\end{pmatrix} = \begin{pmatrix}
\cos \theta_R & \sin \theta_R e^{-i\delta_R} \\
-\sin \theta_R e^{i\delta_R} & \cos \theta_R
\end{pmatrix}
\begin{pmatrix}
N_1 \\
N_2
\end{pmatrix}.
\]

**Same sign charge asymmetry** : \[A_{\alpha\beta} \equiv \frac{\mathcal{N}(l_\alpha^+ l_\beta^+) - \mathcal{N}(l_\alpha^- l_\beta^-)}{\mathcal{N}(l_\alpha^+ l_\beta^+) + \mathcal{N}(l_\alpha^- l_\beta^-)}.\]
\( \begin{pmatrix} N_e \\ N_{\mu} \end{pmatrix} = \begin{pmatrix} \cos \theta_R & \sin \theta_R e^{-i\delta_R} \\ -\sin \theta_R e^{i\delta_R} & \cos \theta_R \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}. \)

**Same sign charge asymmetry** : \( A_{\alpha\beta} \equiv \frac{N(\ell^+_{\alpha} \ell^+_{\beta}) - N(\ell^-_{\alpha} \ell^-_{\beta})}{N(\ell^+_{\alpha} \ell^+_{\beta}) + N(\ell^-_{\alpha} \ell^-_{\beta})}. \)

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The diagrams show the evolution of \( \mathcal{R}_{\alpha\beta} \) as the \( W_R \) mass changes, with and without CPV, and across different collider scenarios: LHC14, HE-LHC, and FCC-hh. The current LHC limit is also plotted for comparison.
The matrix representation of the RHN sector with CPV is given by:

\[
\begin{pmatrix}
N_e \\
N_\mu
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_R & \sin \theta_R e^{-i\delta_R} \\
-\sin \theta_R e^{i\delta_R} & \cos \theta_R
\end{pmatrix}
\begin{pmatrix}
N_1 \\
N_2
\end{pmatrix}.
\]

The same sign charge asymmetry is defined as:

\[
A_{\alpha\beta} \equiv \frac{N(\ell_\alpha^+ \ell_\beta^+) - N(\ell_\alpha^- \ell_\beta^-)}{N(\ell_\alpha^+ \ell_\beta^+) + N(\ell_\alpha^- \ell_\beta^-)}.
\]
New Scalars
L-R Seesaw Higgs Sector

\[
\begin{pmatrix}
\phi^0_1 & \phi^+_2 \\
\phi^-_1 & \phi^0_2
\end{pmatrix},
\begin{pmatrix}
\frac{\phi^+_R}{\sqrt{2}} & \phi^{++}_R \\
\phi^0_R & \frac{\phi^+_R}{\sqrt{2}}
\end{pmatrix},
\begin{pmatrix}
\frac{\phi^+_L}{\sqrt{2}} & \phi^{++}_L \\
\phi^0_L & \frac{\phi^+_L}{\sqrt{2}}
\end{pmatrix}
\]

\[\langle \phi^0_R \rangle \equiv \nu_R \text{ gives rise to RH Majorana neutrino masses, and hence, type-I seesaw.} \]

\[\langle \phi^0_L \rangle \equiv \nu_L \text{ gives rise to a type-II seesaw contribution.} \]

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);...]
Bidoublet Sector

- 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!** [see Monday plenary talk by T. Han]
Neutral Triplet Sector

- Hadrophobic and allowed to be light (down to sub-GeV scale) by current constraints.
- Suppressed coupling to SM particles (either loop-level or small mixing).
- Necessarily long-lived at the LHC, with displaced vertex signals.
- Clean LFV signals at future lepton colliders.

![Diagram showing the search for neutral Higgs triplet resonances at CEPC and ILC, with excluded regions and expected sensitivities plotted against Higgs triplet mass and mixing strength.]

[BD, Mohapatra, Zhang (PRD '17; NPB '17)]

[BD, Mohapatra, Zhang (PRL '18; PRD '18)]
Figure 9: Summary of expected and observed limits for each production mode and the combined limit. The shaded region represents the excluded mass points and the thick solid line represents the expected exclusion with the hashed region indicating the direction.
Prospects at $e^- p$ Collider

$\nu$
Prospects at $e^- p$ Collider

$\nu$
Radiative neutrino mass generation

At tree level, neutrino masses are zero – $R$ may be absent.

Small, finite Majorana masses are induced at the quantum level.

Typically involves exchange of scalars that violate lepton number.

Simple realization is the Zee model, which has a second Higgs doublet and a charged singlet.

$$h_0 \quad H^0_i$$

Smallness of neutrino mass explained via loop and chiral suppression.

New physics in this framework may lie at the TeV scale.

Collider constraints on $h^\pm$ mass

Direct searches: One can put bounds on $h^+$ mass by looking at final states (leptons + missing energy).

Some supersymmetric searches (like Stau, Selectron ..) can be used to set limits on $h^+$ mass.

Dominant production mechanisms in LEP are:

1. $$e^+ e^- h^+$$
2. $$Z/\gamma \nu e h^-$$
3. $$e^- h^+$$
4. $$W^+ h^+$$

Constraints on light charged scalar

The lowest charged higgs mass allowed is 82 GeV with $y^{\tau e} = 0$.

The lowest charged higgs mass allowed is 94 GeV with $y^{\tau e} = 1$.

(Babu, BD, Jana, Thapa (to appear); see Tuesday parallel talk by K. S. Babu)
At tree level, neutrino masses are zero – $\tilde{R}$ may be absent. Small, finite Majorana masses are induced at the quantum level, typically involving exchange of scalars that violate lepton number. A simple realization is the Zee model, which has a second Higgs doublet and a charged singlet.

The lowest charged Higgs mass allowed is $82$ GeV with $\alpha \epsilon = 0$. (K.S. Babu, BD, Jana, Thapa (to appear); see Tuesday parallel talk by K. S. Babu).
Zee Model

At tree level, neutrino masses are zero – $\Delta R$ may be absent.
Small, finite Majorana masses are induced at the quantum level.
Typically involves exchange of scalars that violate lepton number.

A simple realization is the Zee model, which has a second Higgs doublet and a charged singlet.

$$H_1^0 + H_2^+ \quad \eta^+ \quad H_2^+$$

Smallness of neutrino mass explained via loop and chiral suppression.

New physics in this framework may lie at the TeV scale.

Collider constraints on $h^{\pm}$ mass:
Direct searches: One can put bounds on $h^{\pm}$ mass by looking at final states (leptons + missing energy).
Some supersymmetric searches (like Stau, Selectron, ...) can be used to set limits on $h^{\pm}$ mass.

Dominant production mechanisms in LEP are:

$$e^+ e^- \rightarrow h^{\pm} h^0$$

Constraints on light charged scalar $h^{\pm}$:
The lowest charged higgs mass allowed is 82 GeV with $y^{\pm e} = 0$.
The lowest charged higgs mass allowed is 94 GeV with $y^{\pm e} = 1$.

[Babu, BD, Jana, Thapa (to appear); see Tuesday parallel talk by K. S. Babu]
\[ W_{\text{RPV}} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \]

(a) \hspace{1cm} (b)

[Hall, Suzuki (NPB '84); Babu, Mohapatra (PRL '90)]
$$W_{\text{RPV}} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \chi'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda'_{ijk} U_i^c D_j D^c_k$$

\[\begin{array}{c}
\text{Figure 5.1: One-loop contributions to neutrino masses and mixings induced by the trilinear couplings } \lambda_{ijk} (a) \text{ and } \lambda_{ijk}' (b) \text{.}
\end{array}\]

[Hall, Suzuki (NPB '84); Babu, Mohapatra (PRL '90)]
$W_{RPV} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c$

**Recent interest in light of the $B$-anomalies.** [Deshpande, He (EPJC ’17); Altmannshofer, BD, Soni (PRD ’17); Das, Hati, Kumar, Mahajan (PRD ’17); Earl, Gregoire (JHEP ’18); Trifinopoulos (EPJC ’18)] – see Friday plenary talk by X.-G. He

**Can also address the ANITA anomalous events.** [Collins, BD, Sui (PRD ’19); see Tuesday parallel talk by Y. Sui]
Conclusion

- Understanding the neutrino mass mechanism will provide important insights into the BSM world.

- Current and future colliders provide 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.

- Could shed light on other outstanding puzzles, such as the matter-antimatter asymmetry and dark matter.
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