Probing Lepton Number Violation at LHC

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Main Message

- If the process $pp \to \ell^\pm \ell^\pm +$ jets is observed at the LHC, lepton number violation by two units would be established. This would imply that neutrinos are Majorana particles.

- This collider signal can compete favorably with neutrinoless double beta decay.

- This possibility is illustrated in the context of two popular neutrino mass models: type-II seesaw model and the Zee model.

- Talk based on:

  Babu, Barman, Gonçalves, Ismail, arXiv: 2212.08025 [hep-ph]

Lepton Number Violation in Standard Model

- Lepton Number (L) and Baryon Number (B) happen to be conserved by the renormalizable Standard Model Lagrangian
- However, these apparent conservation laws are "accidental" and are expected to be broken in nature
- Weak interaction itself breaks B and L, but preserves $(B - L)$, via non-perturbative effects
- Baryon and Lepton Number currents have a chiral anomaly which leads to $B + L$ violation

$$J_B^\mu = \frac{1}{3}\left(\overline{u}\gamma^\mu u + \overline{d}\gamma^\mu d + ...\right), \qquad J_L^\mu = \left(\overline{e}\gamma^\mu e + \overline{\nu}_{eL}\gamma^\mu \nu_{eL} + ...\right)$$

$$\partial_\mu (J_B^\mu - J_L^\mu) = 0, \qquad \partial_\mu (J_B^\mu + J_L^\mu) = \frac{3\,g_2^2}{32\pi^2} F_{\mu\nu}^a \tilde{F}_a^{\mu\nu}$$

- $(B + L)$ is not conserved, and thus L is violated in Standard Model.

Strength of SM Lepton Number Violation

- B and L violation in Standard Model intrinsically nonperturbative
- At zero temperature tunneling rate between vacuua is suppressed by

$$\left(e^{-\frac{8\pi^2}{g_2^2}}\right)^2 \sim 10^{-160}$$

- $B + L$ violation effects are unobservably small at $T = 0$

  't Hooft (1976)

- At finite T, there is a nonperturbative Sphaleron configuration with energy $E_{\rm sph} \sim 10$ TeV, which allows for $B + L$ violation with tunnelling factor of $e^{-E_{\rm sph}/T}$ that is unsuppressed

  Kuzmin, Rubakov, Shaposhnikov (1985)

- Such violation of $B + L$ symmetry plays a crucial role in Baryogenesis via Leptogenesis

  Fukugita, Yanagida (1986)

- These suggest that B & L are not fundamental symmetries of nature

Quantum Gravity and Lepton Number Violation

- Quantum gravity is expected to break all global symmetries (but not gauge symmetries such as electromagnetism)
- Lepton number being a global symmetry, would suffer quantum gravitation violations. These effects would scale inversely with the Planck scale
- Leading operators that violate L are dimension-5 operators

$$\mathcal{L}_{\rm gravity} = \frac{\kappa_{ij}}{M_{\rm Pl}} \left(L_i L_j H H \right)$$

- These operators would lead to tiny Mojarana masses for the neutrinos:

$$m_\nu \sim \frac{\kappa\, v^2}{M_{\rm Pl}} \sim 10^{-6}\ {\rm eV}$$

- Although not observable in current neutrino oscillation experiments, this feature of gravity suggests L violation

L Violation in Beyond the Standard Model

- Standard Model needs to be extended to accommodate neutrino mass and also very likely for dark matter
- Many SM extensions naturally have L violation. This is especially true for theoreis that explain small neutrino masses via the seesaw mechanism
- If neutrinos are Majorana fermions, as in the seesaw framework, L must be violated by two units
- Other well motivated extesnsions, such as grand unified theories, also have L (and B) violation embedded in them, independent of the Majorana/Dirac nature of the neutrino. Eg: $p \to e^+\pi^0$ violates lepton number by one unit

Neutrino Masses & Lepton Number Violation

- Neutrino oscillations have been observed unambiguously with solar, atmospheric, accelerator and reactor neutrinos
- Neutrino oscillations require non-dgenerate neutrino masses. This is absent in the Standard Model, which therefore must be extended
- Most popular extensions have neutrinos as Majorana particles, which require lepton number violation
- If neutrinos are Majorana, neurinoless double beta decay should occur with strength determined by oscillation data
- High sensitivity searches for $\beta\beta 0\nu$ are ongoing, motivated in large part by the discovery of neutrino oscillations

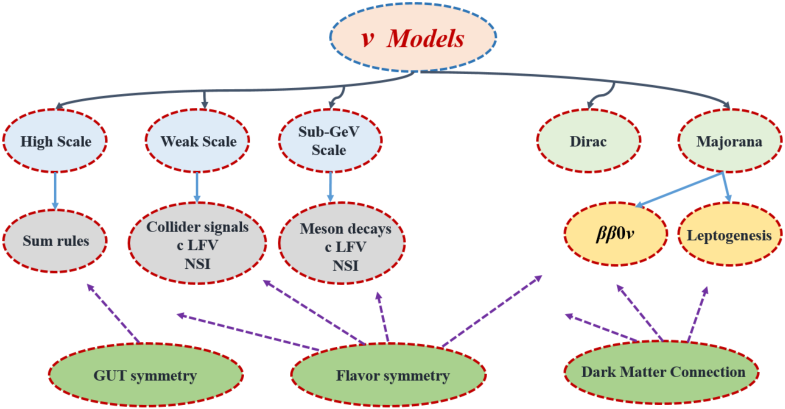
Current knowledge of 3-neutrino oscillations

NuFIT 5.1 (2021)

without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou (2020)

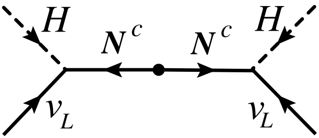
Roadmap for Neutrino Models



Origin of neutrino mass: Seesaw mechanism

- Adding right-handed neutrino N^c which transforms as singlet under $SU(2)_L$,

$$\mathcal{L} = f_\nu \, (L \cdot H) \, N^c + \tfrac{1}{2} M_R N^c N^c$$



- Integrating out the N^c, $\Delta L = 2$ operator is induced:

$$\mathcal{L}_{\rm eff} = -\frac{f_\nu^2}{2} \frac{(L \cdot H)\,(L \cdot H)}{M_R}$$

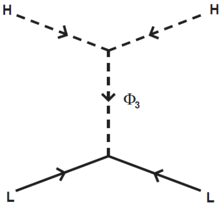
- Once H acquires VEV, neutrino mass is induced:

$$m_\nu \simeq f_\nu^2 \frac{v^2}{M_R}$$

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, Slansky (1980)
Mohapatra & Senjanovic (1980)

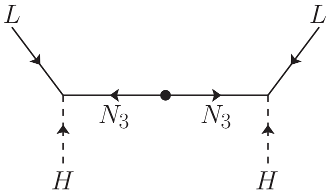
- For $f_\nu v \simeq 100$ GeV, $M_R \simeq 10^{14}$ GeV.

Seesaw mechanism (cont.)



Type II seesaw: $\Phi_3 \sim (1,3,1)$

Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)



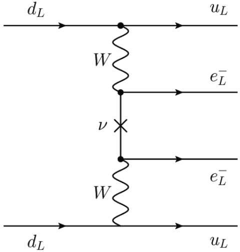
Type III seesaw: $N_3 \sim (1,3,0)$

Foot, Lew, He, & Joshi (1989)

Ma (1998)

- Φ_3 abd N_3 contain charged particles which can be looked for at LHC
- Eg: $\Phi^{++} \to \ell^+\ell^+$, $\Phi^{++} \to W^+W^+$ decays would establish lepton number violation

Neutrinoless Double Beta Decay



$$(A, Z) \to (A, Z+2) + 2e^- + Q_{\beta\beta}$$

- Kamland-Zen collaboration has a limit from ^{136}Xe:

$$T_{0\nu}^{1/2} > 1.07 \times 10^{26} \text{ yr.}$$

- Constrains effective double beta decay mass of neutrino to be

$$m_{\beta\beta} < (61 - 165) \text{ meV}$$

- Here

$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i| = |c_{12}^2 c_{13}^2 e^{2i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\alpha_2} m_2 + s_{13}^2 m_3|$$

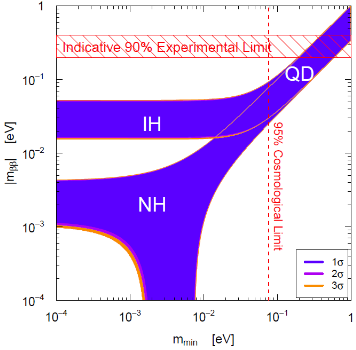
Neutrinoless Double Beta Decay (cont.)

- Largest uncertainty from unknown Majorana phases α_1, α_2 and θ_{23}
- For normal hierarchy cancellation possible

$$m_{\beta\beta} \simeq |c_{13}^2 s_{12}^2 \sqrt{\Delta m_s^2}\, e^{2i\alpha_2} + s_{13}^2 \sqrt{\Delta m_a^2}| < 4 \times 10^{-3}\ \mathrm{eV}$$

- For inverted hierarchy no such cancellation possible

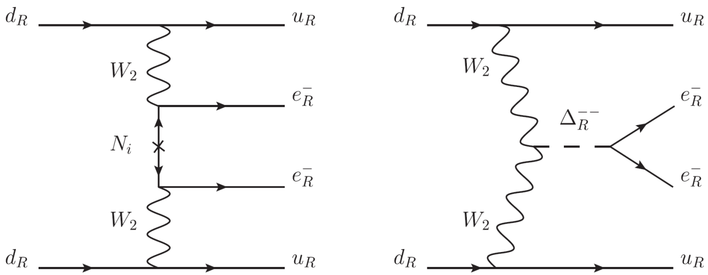
$$m_{\beta\beta} \simeq \sqrt{\Delta m_a^2}\sqrt{1 - \sin^2 2\theta_{12} \sin^2(\alpha_2 - \alpha_1)},\ 2\times10^{-2} \leq m_{\beta\beta} \leq 5\times10^{-2}\ \mathrm{eV}$$



Giunti, Bilenki (2014)

New Physics Contribution to $\beta\beta0\nu$

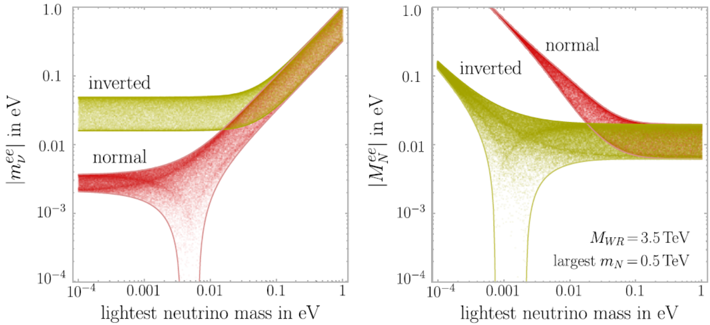
- Light neutrino exchange is not the only contribution to $\beta\beta0\nu$
- Heavy neutrino exchange in left-right symmetry; vectro-scalar exchange in supersymmetry, etc are possible
- If new physics is near TeV scale, $\beta\beta0\nu$ mediated by these heavy particles observable



Mohapatra, Vergados (1981); Li, Ramsey-Musolf, Vasquez (2009); Tello, Nemevsek, Nesti, Senjanovic (2010)

Confusion with Neutrino Mass Ordering

- $\beta\beta0\nu$ in LR model with light neutrino exchange and heavy neutrino exchange



Tello, Nemevsek, Nesti, Senjanovic (2010)

Effective Field Theory for $\beta\beta0\nu$

- 11 operators with 6 fermions
- Effects of these operators on $\beta\beta0\nu$ has been studied
- Light neutrino exchange has left-handed electrons outgoing

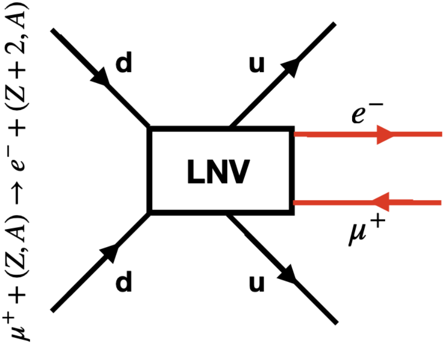
Graesser (2017); Cirigliano, Dekens, De Vries, Graesser, Mereghetti (2018)

$$
\begin{aligned}
\mathrm{LM1} &= i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu Q_c)(\overline{u}_R\gamma_\mu d_R)(\bar{\ell}_b\ell^C_c) \\
\mathrm{LM2} &= i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu\lambda^A Q_c)(\overline{u}_R\gamma_\mu\lambda^A d_R)(\bar{\ell}_b\ell^C_c) \\
\mathrm{LM3} &= (\overline{u}_R Q_a)(\overline{u}_R Q_b)(\bar{\ell}_a\ell^C_b) \\
\mathrm{LM4} &= (\overline{u}_R\lambda^A Q_a)(\overline{u}_R\lambda^A Q_b)(\bar{\ell}_a\ell^C_b) \\
\mathrm{LM5} &= i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a d_R)(\overline{Q}_c d_R)(\bar{\ell}_b\ell^C_d) \\
\mathrm{LM6} &= i\sigma^{(2)}_{ab}i\sigma^{(2)}_{cd}(\overline{Q}_a\lambda^A d_R)(\overline{Q}_c\lambda^A d_R)(\bar{\ell}_b\ell^C_d) \\
\mathrm{LM7} &= (\overline{u}_R\gamma^\mu d_R)(\overline{u}_R\gamma_\mu d_R)(\bar{e}_R e^C_R) \\
\mathrm{LM8} &= (\overline{u}_R\gamma^\mu d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a d_R)(\bar{\ell}_b\gamma_\mu e^C_R) \\
\mathrm{LM9} &= (\overline{u}_R\gamma^\mu\lambda^A d_R)i\sigma^{(2)}_{ab}(\overline{Q}_a\lambda^A d_R)(\bar{\ell}_b\gamma_\mu e^C_R) \\
\mathrm{LM10} &= (\overline{u}_R\gamma^\mu d_R)(\overline{u}_R Q_a)(\bar{\ell}_a\gamma_\mu e^C_R) \\
\mathrm{LM11} &= (\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{u}_R\lambda^A Q_a)(\bar{\ell}_a\gamma_\mu e^C_R)
\end{aligned}
$$

Muon-Positron Conversion

- $\mu^- - e^+$ conversion occurs similar to $\beta\beta0\nu$ with a e^- by a μ^- swap
- Unlike $\mu^- - e^-$ conversion with is lepton flavor violating, but lepton number conserving, this process is L violating
- Mu2e experiment at Fermilab and COMET at JPARC will be sensitive to branching ratios of order 10^{-14}

Berryman, de Gouvea, Kelly, Kobach (2016)

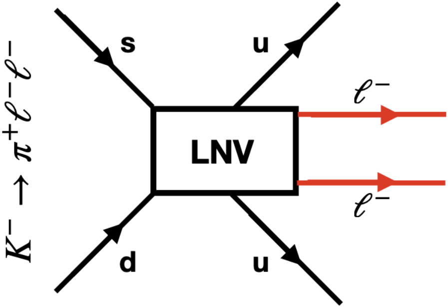


Other L-Violating Processes

- $K^+ \to \pi^- \ell^+ \ell^+$ is similar to $\beta\beta 0\nu$. Obtained by replacing one d-quark by a s-quark.

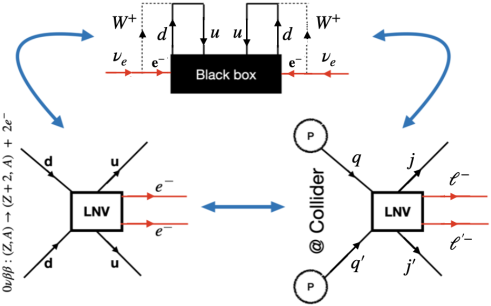
- NA62 collaboration has searched for this decay, and has obtained a limit of

$$Br(K^+ \to \pi^- e^+ e^+) \leq 2.2 \times 10^{-10}$$
$$Br(K^+ \to \pi^- \mu^+ \mu^+) \leq 4.2 \times 10^{-11}$$



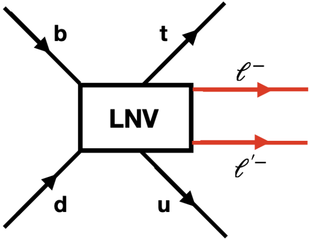
Lepton Number Violation at the LHC

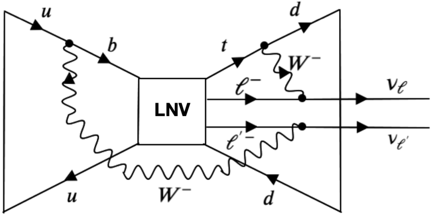
- Classic way to establish Majorana nature of neutrino is to observe neutrinoless double beta decay (Schechter, Valle, 1981)
- $pp \to \ell^{\pm}\ell^{\pm} +$ jets process can also establish L violation by two units, and hence Majorana nature of neutrino (Keung, Senjanovic, 1983)
- This is realized in type-II seesaw model (Babu, Barman, Gonçalves, Ismail, 2022; Cai, Han, Li, Ruiz, 2018)



$\not{L}$ @LHC and Majorana Nature of Neutrino

$pp \to t + b + \ell^- + \ell'^-$ signal and Majorana neutrino mass:





L-violation in type-II Seesaw

- A Higgs triplet field $\Delta(1,3,1) = (\delta^{++},\, \delta^{+},\, \delta^{0})$ is introduced to SM

- It has leptonic Yukawa couplings and a cubic scalar coupling which jointly break L by two units:

$$\mathcal{L} \supset -\frac{(Y_\Delta)_{ij}}{\sqrt{2}} \ell_i^T C\, i\sigma_2\, \Delta\, \ell_j - \frac{\mu}{\sqrt{2}} \phi^T i\sigma_2 \Delta^\dagger \phi + h.c.$$

- δ^0 acquires an induced VEV v_Δ, thus leading to neutrino mass:

$$v_\Delta = \frac{\mu v^2}{\sqrt{2}\mu_\Delta^2} \Rightarrow M_\nu = \frac{Y_\Delta}{\sqrt{2}} v_\Delta$$

- When $v_\Delta = (10^{-5} - 10^{-4})$ GeV, BR for $\delta^{++} \to W^+ W^+$ and $\delta^{++} \to \ell^+ \ell'^+$ decays become comparable, consistent with neutrino oscillation data. This region is optimal for seeing L violation at LHC

- Note: If either Y_Δ or μ (equivalently v_Δ) vanishes, L becomes conserved

L-violation in type-II Seesaw at LHC

- $pp \to \ell^{\pm} + \ell'^{\pm} +$ jets can arise from:

$$
\begin{aligned}
pp &\to \delta^{\pm\pm}\delta^{\mp} \to \ell^{\pm}\ell'^{\pm}tb,\ \ell^{\pm}\ell'^{\pm}W^{\mp}Z/H \\
pp &\to \delta^{\pm\pm}\delta^{\mp\mp} \to \ell^{\pm}\ell'^{\pm}W^{\mp}W^{\mp} \\
pp &\to \delta^{\pm\pm}jj \to \ell^{\pm}\ell'^{\pm}jj
\end{aligned}
$$

- Here W, Z, H and t decay hadronically

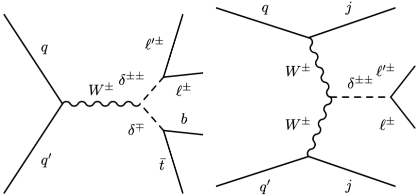
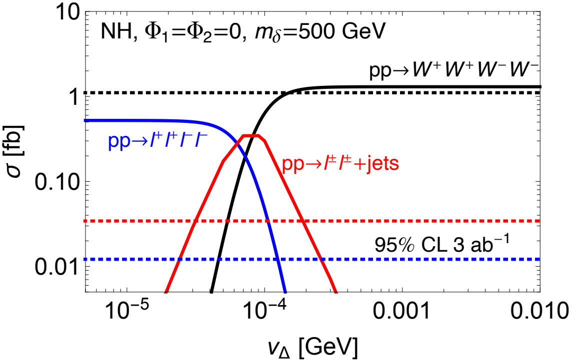


Figure: Typical diagrams for $pp \to \ell^{\pm}\ell'^{\pm}$ + jets

LHC Sensitivity for L-violation in type-II Seesaw

- Normal neutrino mass ordering assumed, along with vanishing Majorana phases and the Dirac phase. $m_1 = 0.05$ eV is assumed for the lightest neutrino mass.



Babu, Barman, Gonçalves, Ismail, 2022

Radiative neutrino mass generation

- An alternative to seesaw is radiative neutrino mass generation, where neutrino mass is absent at tree level, but arises via quantum loop corrections
- The smallness of neutrino mass is explained by loop and chiral suppressions
- Loop diagrams may arise at 1-loop, 2-loop or 3-loop levels
- New physics scale typically near TeV and thus accessible to LHC
- Further tests in observable LFV processes and as nonstandard neutrino interaction (NSI) in oscillations

Effective $\Delta L = 2$ Operators

$$
\begin{aligned}
\mathcal{O}_1 &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \\
\mathcal{O}_2 &= L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_3 &= \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_4 &= \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\} \\
\mathcal{O}_5 &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km} \\
\mathcal{O}_6 &= L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl} \\
\mathcal{O}_7 &= L^i Q^j \bar{e^c} \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm} \\
\mathcal{O}_8 &= L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij} \\
\mathcal{O}_9 &= L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_1' &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} H^{*m} H_m
\end{aligned}
$$

Babu & Leung (2001)

de Gouvea & Jenkins (2008)

Angel & Volkas (2012)

Cai, Herrero-Garcia, Schmidt, Vicente, Volkas (2017)

Lehman (2014) – all $d = 7$ operators

Li, Ren, Xiao, Yu, Zheng (2020); Liao, Ma (2020) – all $d = 9$ operators

Operator $\mathcal{O}_2$ and the Zee model

- Introduce a singly charged scalar and a second Higgs doublet to standard model:

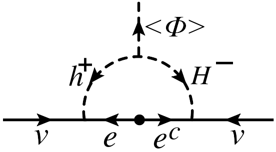
$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + \mu H^a \Phi^b h^- \epsilon_{ab} + \text{h.c.}$$

$$\Downarrow$$

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$$

Zee (1980)

- Neutrino mass arises at one-loop.



- A minimal version of this model in which only one Higgs doublet couples to a given fermion sector with a Z_2 symmetry yields: Wolfenstein (1980)

$$m_\nu = \begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix}, \quad m_{ij} \simeq \frac{f_{ij}}{16\pi^2} \frac{(m_i^2 - m_j^2)}{\Lambda}$$

It requires $\theta_{12} \simeq \pi/4 \rightarrow$ ruled out by solar + KamLAND data.

Koide (2001); Frampton *et al.* (2002); He (2004)

Neutrino oscillations in the Zee model

- Neutrino oscillation data can be fit to the Zee model consistently without the Z_2 symmetry
- The second Higgs doublet has Yukawa couplings to leptons and quarks, and the η^- scalar has leptonic Yukawa coupling:

$$\begin{aligned} -\mathcal{L}_Y &\supset f_{\alpha\beta} L^i_\alpha L^j_\beta \epsilon_{ij} \eta^+ + Y_{\alpha\beta} \tilde{H}^i_2 L^j_\alpha \ell^c_\beta \epsilon_{ij} \\ &+ \tilde{Y}_{u\,\alpha\beta} H^i_2 Q^j_\alpha u^c_\beta \epsilon_{ij} + Y_{d\,\alpha\beta} \tilde{H}^i_2 Q^j_\alpha d^c_\beta \epsilon_{ij} + h.c. \end{aligned}$$

- In addition, there is a cubic scalar coupling that ensures L violation:

$$V \supset \mu H^i_1 H^j_2 \eta^- \epsilon_{ij} + h.c.$$

- Neutrino mass given by:

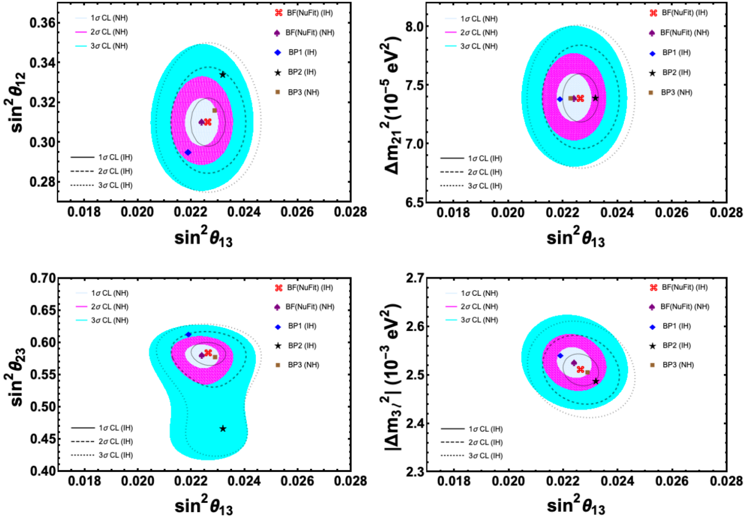
$$m_\nu = \kappa (f\, M_\ell Y + Y^T M_\ell f^T)$$

where $\kappa = (1/16\pi^2) \sin 2\varphi \, \log(m^2_{h^+}/m^2_{H^+})$

- Oscillation data can be accommodated easily

Babu, Dev, Jana, Thapa (2019)

Neutrino fit in the Zee model



Babu, Dev, Jana, Thapa (2019)

Constraints on Zee Model Parameters

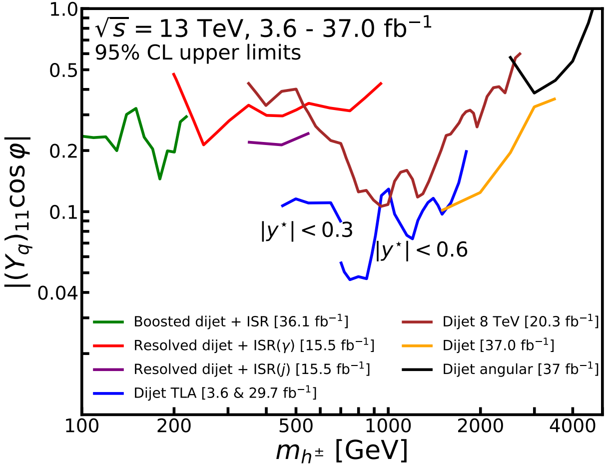
- The product $Y \times f$ has to be rather small to accommodate small neutrino masses
- This allows for large f and small Y which we explore
- Muon decay receives new contributions from η^- exchange. This interferes with SM amplitude, leadint to the limit

$$|f_{e\mu} \sin\varphi|^2 \leq 0.02\,(m_{h^+}/\mathrm{TeV})^2$$

- Neutron beta decay is also modified by charged scalar exchange, but due to flavor antisymmetry of f, the antineutrino is $\overline{\nu}_\mu$. Since there is no interference with SM contributions, the limits are weaker
- A pseudoscalar coupling of $h^\pm$ of the form $y_p \cos\phi\,(\overline{u}\gamma_5 d)\,h^+$ would lead a constraint of $|y_p\, f_{e\mu} \cos\phi \sin\phi| \leq 5 \times 10^{-4}\,(m_{h^\pm}/\mathrm{TeV})^2$ from $\Gamma(\pi \to e\nu_\mu)/\Gamma(\pi \to \mu\nu_\mu)$. This can be satisfied by choosing $(Y_d)_{11} = (\tilde{Y}_u)_{11} \equiv (Y_q)_{11}$, so that $y_p = 0$

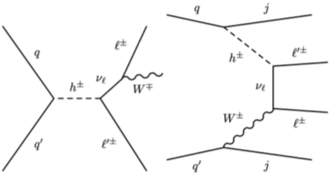
LHC Constraints on Zee Model Parameters

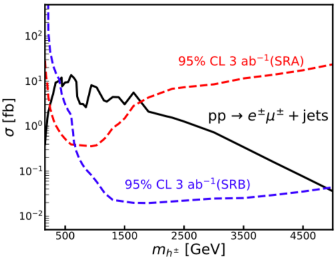
- Since the charged scalar couples to quarks, the model is constrained by dijet searches at LHC
- We have interpreted dijet resonance searches within the Zee model



Measuring L-violation in the Zee Model at LHC

- L violation in Zee model occurs via mixing of two charged scalars which carry different lepton number
- $pp \to e^+\mu^+ +$ jets occurs: Babu. Barman. Goncalves, Ismail, 2022





Conclusions

- Lepton number is very likely to be broken in nature
- Standard Model already has L-violation; most scenarios of neutrino mass predict Majorana neutrino and thereby L violation
- Neutrinoless double beta decay is the best way to test L violation at low energies. Other related processes such as $\mu^- - e^+$ conversion are promising
- Interesting ways of testing L violation at the LHC via $pp \to \ell^+\ell^+ + \text{jets}$ are studied
- Two popular models, the type-II seesaw model and the Zee model, are shown to be able to provide signals of L violation by two units, and thus the Majorana nature of the neutrino