Theories of Neutrino Masses

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Pheno 2023, Pittsburgh

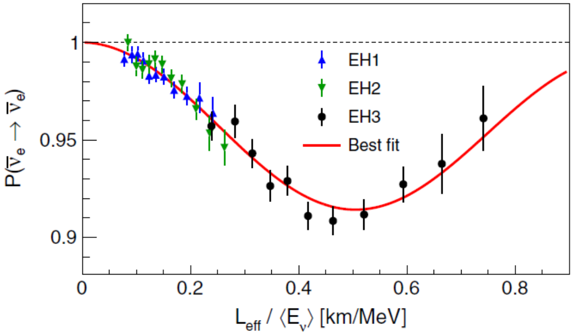
May 8 – 10, 2023

Oscillating Neutrinos

- Neutrinos oscillate among flavors:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

- Oscillatory behavior observed by Daya Bay $\overline{\nu}_e$, KamLand $\overline{\nu}_e$ and SuperKamiokande atmospheric ν_μ data



Daya Bay (2015)

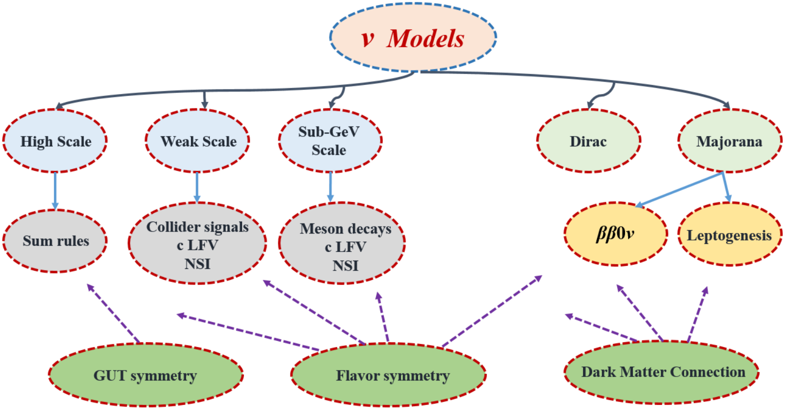
Current knowledge of 3-neutrino oscillations

NuFIT 5.1 (2021)

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

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

Roadmap for Neutrino Models



Effective Field Theory for neutrino masses

- Neutrino masses are zero in the Standard Model. Observed oscillations require new physics beyond Standard Model

- Neutrino masses and oscillations can be explained in terms of the celebrated $d = 5$ Weinberg operator

$$\mathcal{O}_1 \quad = \quad \frac{\kappa_{ab}}{2}(L^i_a L^j_b) H^k H^l \epsilon_{ik}\epsilon$$

- $\kappa^{-1} \sim (10^{14} - 10^{15})\ \mathrm{GeV}$ can explain oscillation data

- EFT description cannot be the end goal, especially when the coefficients of operators are measured. Without UV completion important phenomena would be missed (e.g. Leptogenesis)

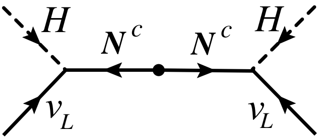
- What if neutrinos are Dirac particles? $\mathcal{O}_1$ is then the wrong description

- What if neutrino masses arose from $d = 7$ operators or $d = 9$ operators in a fundamental theory, and not through $\mathcal{O}_1$?

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:

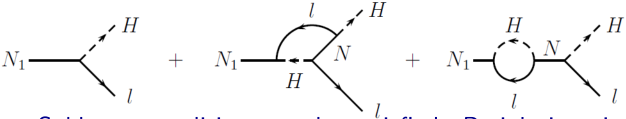
$$m_\nu \simeq f_\nu^2 \frac{v^2}{M_R}$$

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

- For $f_\nu v \simeq 100$ GeV, $M_R \simeq (10^{14} - 10^{15})$ GeV.

Baryogenesis via leptogenesis and type-I seesaw

- In the early history of the universe, a lepton asymmetry may be dynamically generated in the decay of N Fukugita, Yanagida (1986)
- N being a Majorana fermion can decay to $L + H$ as well as $\overline{L} + H^*$



- Three Sakharov conditions can be satisfied: B violation via electroweak sphaleron, C and CP violation in Yukawa couplings of N, and out of equilibrium condition via expanding universe
- Lepton asymmetry in decay of N_1 (with $M_1 \ll M_{2,3}$):

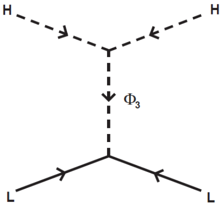
$$\varepsilon_1 \simeq \frac{3}{16\pi} \frac{1}{(f_\nu f_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(f_\nu f_\nu^\dagger)^2_{i1}\right] \frac{M_1}{M_i}$$

- $\varepsilon \sim 10^{-6}$ can explain observed baryon asymmetry of the universe
- Indirect tests in Majorana nature of ν and in CP violation in oscillations

Seesaw mechanism (cont.)

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

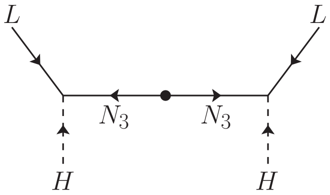
Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)



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

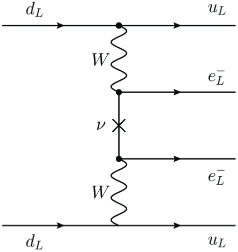
Foot, Lew, He, & Joshi (1989)

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



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

- Majorana vs Dirac neutrinos: Observation of $\beta\beta 0\nu$ will establish neutrinos are Majorana particles
- 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

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

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

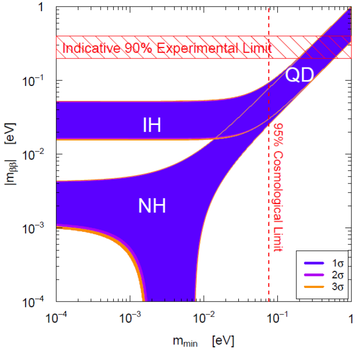
Neutrinoless Double Beta Decay (cont.)

- 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

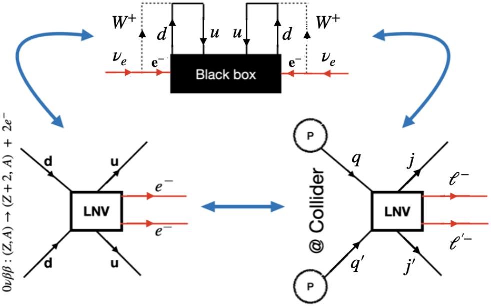
$$m_{\beta\beta} \simeq \sqrt{\Delta m_a^2} \sqrt{1 - \sin^2 2\theta_{12} \sin^2(\alpha_2 - \alpha_1)},\ \ 2\times10^{-2} \leq m_{\beta\beta} \leq 5\times10^{-2}\ \mathrm{eV}$$



Giunti, Bilenki (2014)

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)



L-violation in type-II Seesaw at LHC

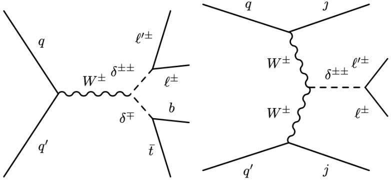
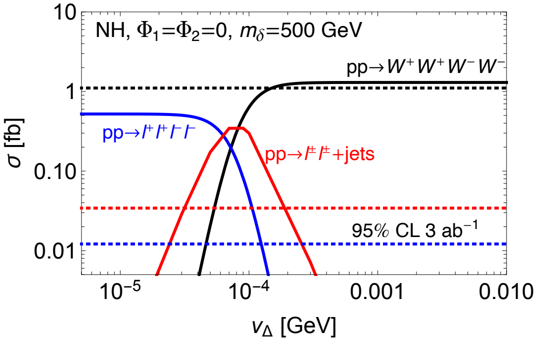


Figure: $pp \to \ell^\pm \ell'^\pm$ + jets



(Babu, Barman, Gonçalves, Ismail, 2022)

Dirac Neutrino Models

- Neutrinos may be Dirac particles without lepton number violation
- Oscillation experiments cannot distinguish Dirac neutrinos from Majorana neutrinos
- Spin-flip transition rates (in stars, early universe) are suppressed by small neutrino mass:

$$\Gamma_{\text{spin-flip}} \approx \left(\frac{m_\nu}{E}\right)^2 \Gamma_{\text{weak}}$$

- If neutrinos are Dirac, it would be nice to understand the smallness of their mass
- Models exist which explain the smallness of Dirac m_ν
- "Dirac leptogenesis" can explain baryon asymmetry

  Dick, Lindner, Ratz, Wright (2000)

Dirac Seesaw Models

- Dirac seesaw can be achieved in Mirror Models Lee, Yang (1956); Foot, Volkas (1995); Berezhiani, Mohapatra (1995), Silagadze(1997)

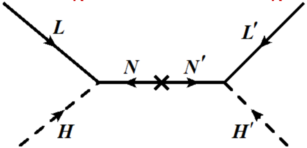
  and Left-Right Symmetric Models Mohapatra (1988); Babu, He (1989); Babu, He, Su, Thapa (2022)

- Mirror sector is a replica of Standard Model, with new particles transforming under mirror gauge symmetry:

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L ; \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} ; \quad L' = \begin{pmatrix} \nu' \\ e' \end{pmatrix}_L ; \quad H' = \begin{pmatrix} H'^+ \\ H'^0 \end{pmatrix}$$

- Effective dimension-5 operator induces small Dirac mass:

$$\frac{(LH)(L'H')}{\Lambda} \Rightarrow m_\nu = \frac{vv'}{\Lambda}$$



- $B - L$ may be gauged to suppress Planck-induced Weinberg operator $(LLHH)/M_{\rm Pl}$ that would make neutrino pseudo-Dirac particle

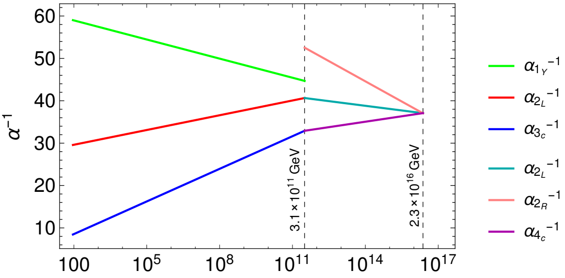
Unification of Forces & Matter in SO(10)

16 members of a family fit into a spinor of $SO(10)$

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u_r^c : \{+--\ ++\}$	$d_r^c : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u_b^c : \{-+-\ ++\}$	$d_b^c : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u_g^c : \{--+\ ++\}$	$d_g^c : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

First 3 spins refer to color, last two are weak spins

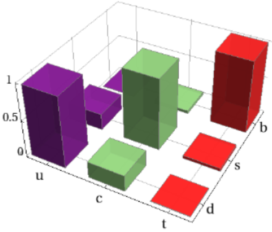
$$Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$$



Disparity in Quark & Lepton Mixings

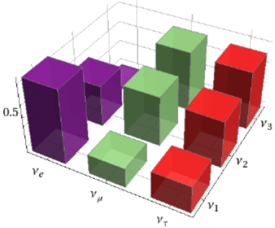
- **Quark Mixings**

$$V_{CKM} \sim \begin{bmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{bmatrix}$$



- **Leptonic Mixings**

$$U_{PMNS} \sim \begin{bmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{bmatrix}$$



Yukawa Sector of Minimal $SO(10)$

$$16 \times 16 = 10_s + 120_a + 126_s$$

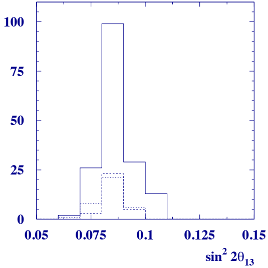
- At least two Higgs fields needed for family mixing
- Symmetric 10_H and $\overline{126}$ is the minimal model

$$W_{SO(10)} = 16^T \left(Y_{10}\, 10_H + Y_{126} \overline{126}_H \right) 16 \ .$$

$$\begin{aligned}
M_U &= v_u^{10} Y_{10} + v_u^{126} Y_{126} \\
M_D &= v_d^{10} Y_{10} + v_d^{126} Y_{126} \\
M_E &= v_d^{10} Y_{10} - 3 v_d^{126} Y_{126} \\
M_{\nu_D} &= v_u^{10} Y_{10} - 3 v_u^{126} Y_{126} \\
M_R &= Y_{126} V_R
\end{aligned}$$

Minimal Yukawa sector of SO(10)

- 12 parameters plus 7 phases to fit 18 observed quantities
- This setup fits all obsevables quite well
- Large neutrino mixings coexist with small quark mixings
- θ_{13} prediction turned out to be correct



Babu, Mohapatra (1993); Bajc, Senjanovic, Vissani (2001); (2003); Fukuyama, Okada (2002); Goh, Mohapatra, Ng (2003); Bajc, Melfo, Senjanovic, Vissani (2004); Bertolini, Malinsky, Schwetz (2006); Babu, Macesanu (2005); Dutta, Mimura, Mohapatra (2007); Aulakh et al (2004); Bajc, Dorsner, Nemevsek (2009); Joshipura, Patel (2011); Dueck, Rodejohann (2013); Ohlsson, Penrow (2019); Babu, Bajc, Saad (2018); Babu, Saad (2021)

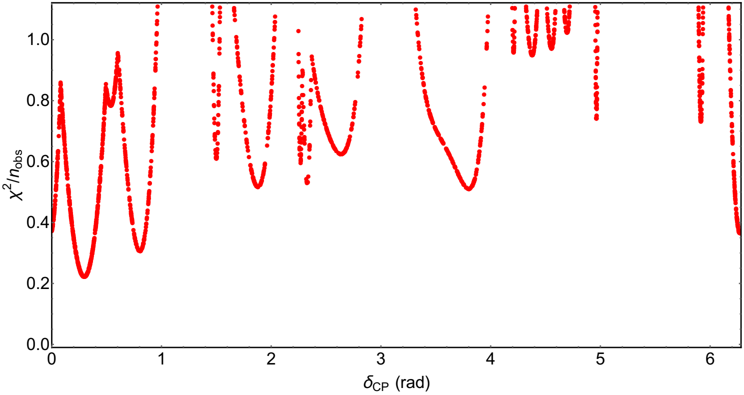
Best fit values for fermion masses and mixings

Observables (masses in GeV)	**SUSY** Input	Best Fit	Pull	**non-SUSY** Input	Best Fit	Pull
$m_u/10^{-3}$	0.502±0.155	0.515	0.08	0.442±0.149	0.462	0.13
m_c	0.245±0.007	0.246	0.14	0.238±0.007	0.239	0.18
m_t	90.28±0.89	90.26	-0.02	74.51±0.65	74.47	-0.05
$m_b/10^{-3}$	0.839±0.17	0.400	-2.61	1.14±0.22	0.542	-2.62
$m_s/10^{-3}$	16.62±0.90	16.53	-0.09	21.58±1.14	22.57	0.86
m_b	0.938±0.009	0.933	-0.55	0.994±0.009	0.995	0.19
$m_e/10^{-3}$	0.3440±0.0034	0.344	0.08	0.4707±0.0047	0.470	-0.03
$m_\mu/10^{-3}$	72.625±0.726	72.58	-0.05	99.365±0.993	99.12	-0.24
m_τ	1.2403±0.0124	1.247	0.57	1.6892±0.0168	1.688	-0.05
$\|V_{us}\|/10^{-2}$	22.54±0.07	22.54	0.02	22.54±0.06	22.54	0.06
$\|V_{cb}\|/10^{-2}$	3.93±0.06	3.908	-0.42	4.856±0.06	4.863	0.13
$\|V_{ub}\|/10^{-2}$	0.341±0.012	0.341	0.003	0.420±0.013	0.421	0.10
δ°_{CKM}	69.21±3.09	69.32	0.03	69.15±3.09	70.24	0.35
$\Delta m^2_{21}/10^{-5}(eV^2)$	8.982±0.25	8.972	-0.04	12.65±0.35	12.65	-0.01
$\Delta m^2_{31}/10^{-3}(eV^2)$	3.05±0.04	3.056	0.02	4.307±0.059	4.307	0.006
$\sin^2\theta_{12}$	0.318±0.016	0.314	-0.19	0.318±0.016	0.316	-0.07
$\sin^2\theta_{23}$	0.563±0.019	0.563	0.031	0.563±0.019	0.563	0.01
$\sin^2\theta_{13}$	0.0221±0.0006	0.0221	-0.003	0.0221±0.0006	0.0220	-0.16
δ°_{CP}	224.1±33.3	240.1	0.48	224.1±33.3	225.1	0.03
χ^2	-	-	7.98	-	-	7.96

Babu, Saad (2021)

Dirac CP phase

Multiple χ^2 minima make δ_{CP} prediction difficult



Babu, Bajc, Saad (2018)

Proton decay predictions

- Proton decay branching ratios determined by neutrino oscillation fits
- Mediated by superheavy gauge bosons
- Lifetime has large uncertainties, $\tau_p \approx (10^{32} - 10^{36})$ yrs.

Prediction of branching ratios

$$\Gamma(p \to \pi^0 e^+) \to 47\%$$
$$\Gamma(p \to \pi^0 \mu^+) \to 1\%$$
$$\Gamma(p \to \eta^0 e^+) \to 0.20\%$$
$$\Gamma(p \to \eta^0 \mu^+) \to 0.00\%$$
$$\Gamma(p \to K^0 e^+) \to 0.16\%$$
$$\Gamma(p \to K^0 \mu^+) \to 3.62\%$$
$$\Gamma(p \to \pi^+ \overline{\nu}) \to 48\%$$
$$\Gamma(p \to K^+ \overline{\nu}) \to 0.22\%$$

Nemesvek, Bajc, Dorsner (2009)
Babu, Khan (2015)

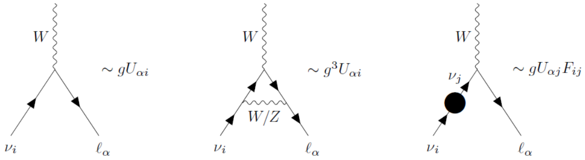
Energy-dependent oscillation parameters

- In presence of light new physics coupled to neutrinos, oscillation angles at production and detection may not coincide
- Quantum corrections can lead to observable signals in neutrino oscillations. Babu, Brdar, de Gouvea, Machado (2021); (2022)
- For neutrino produced in pion decay, $Q_p^2 = m_\pi^2$, but if detected via $\nu + n \to e^- + p$, $Q_d^2 \approx m_n E_\nu$. For two flavors,

$$P_{e\mu} = P_{\mu e} = \sin^2(\theta_p - \theta_d) + \sin 2\theta_p \sin 2\theta_d \sin^2\left(\frac{\Delta m^2 L}{4E} + \frac{\beta}{2}\right)$$

$$\theta(Q_p^2) \equiv \theta_p, \quad \theta(Q_d^2) \equiv \theta_d, \quad \text{and} \quad \tilde{\beta}(Q_d^2) - \tilde{\beta}(Q_p^2) \equiv \beta$$

- $\theta_p \neq \theta_d$ if there are light states in the mass range Q_p and Q_d



Addressing MiniBoone Anomaly

- Active neutrinos assumed to mix with two sterile neutrinos:

$$M_\nu = \begin{pmatrix} x & x & x & \mu_e & 0 \\ x & x & x & \mu_\mu & 0 \\ x & x & x & \mu_\tau & 0 \\ \mu_e & \mu_\mu & \mu_\tau & 0 & M \\ 0 & 0 & 0 & M & 0 \end{pmatrix}$$

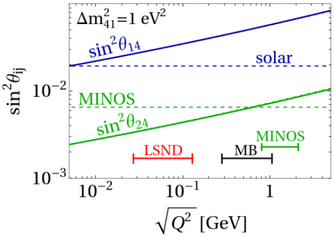
$$\tan\theta_{14} \simeq \frac{\mu_e}{M}, \qquad \tan\theta_{24} \simeq \frac{\mu_\mu}{M}$$

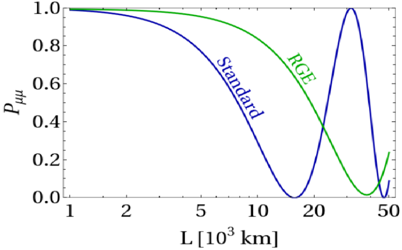
- If N_i couple to a light gauge boson, M will decrease with energy, and thus θ_{14} and θ_{24} will decrease

$$M(\mu) = M(\mu_0)\left(1 - \frac{5g'(\mu_0)^2}{24\pi^2}\ln(\frac{\mu}{\mu_0})\right)^{9/4}$$

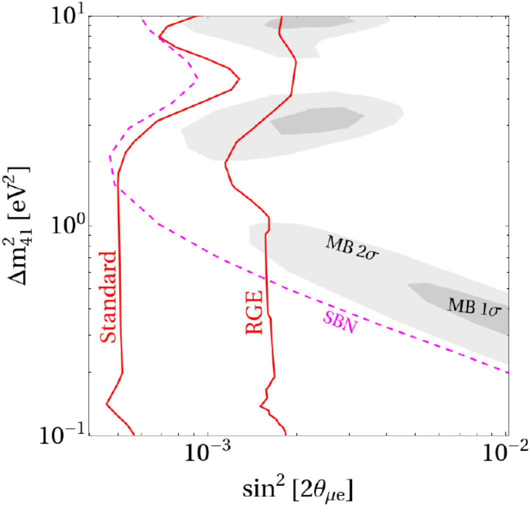
- Tension between appearance and disappearance experiments can be relaxed by this running effect

Addressing MiniBoone Anomaly: Results





MiniBoone Results



Babu, Brdar, de Gouvea, Machado (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

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

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:

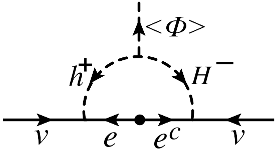
$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + \mu H^a \Phi^b h^- \epsilon_{ab} + \text{h.c.}$$

$$\Downarrow$$

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

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

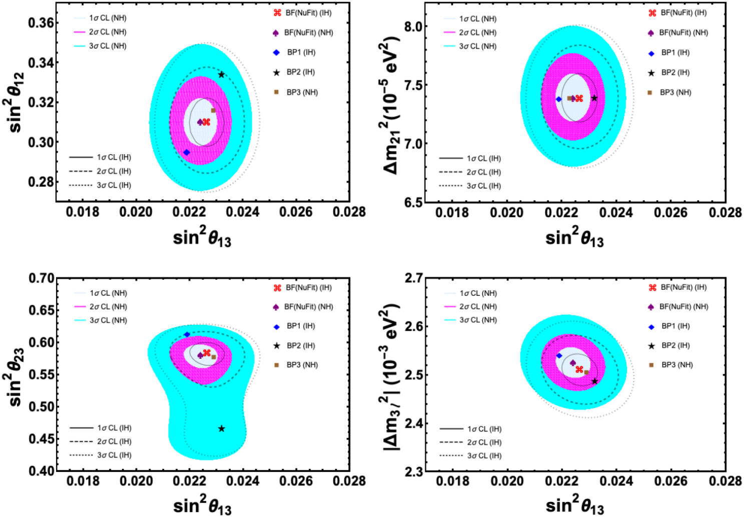
- Neutrino oscillation data can be fit to the Zee model consistently without the Z_2 symmetry

- Some benchmark points for Yukawa couplings of second doublet:

$$
\begin{aligned}
\text{BP I}: \; Y \; &= \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix} \\
\text{BP II}: \; Y \; &= \begin{pmatrix} 0 & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & 0 & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix} \\
\text{BP III}: \; Y \; &= \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & 0 & Y_{\tau\tau} \end{pmatrix}
\end{aligned}
$$

Babu, Dev, Jana, Thapa (2019)

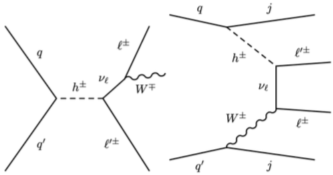
Neutrino fit in the Zee model

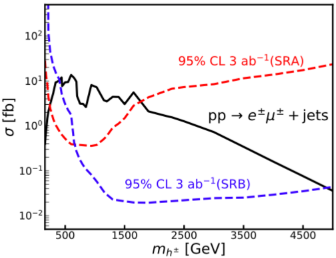


Babu, Dev, Jana, Thapa (2019)

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





Neutrino Non-Standard Interactions (NSI)

- Neutrino oscillation picture would change if there are non-standard interactions
- Modification of matter effects most important
- EFT for neutrino NSI:

$$\mathcal{L}_{\mathrm{NSI}}^{\mathrm{NC}} = -2\sqrt{2}G_F \sum_{f,X,\alpha,\beta} \varepsilon_{\alpha\beta}^{fX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f}\gamma_\mu P_X f\right) ,$$

$$\mathcal{L}_{\mathrm{NSI}}^{\mathrm{CC}} = -2\sqrt{2}G_F \sum_{f,f',X,\alpha,\beta} \varepsilon_{\alpha\beta}^{ff'X} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta\right) \left(\bar{f}'\gamma_\mu P_X f\right)$$

Wolfenstein (1978)

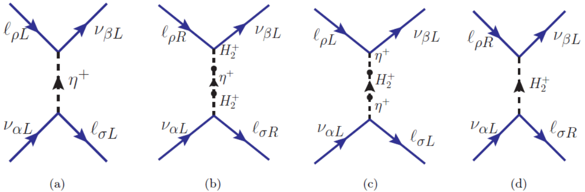
- Effective Hamiltonian for neutrino propagation in matter is now:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^\star & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^\star & \varepsilon_{\mu\tau}^\star & \varepsilon_{\tau\tau} \end{pmatrix}$$

- $\epsilon_{\alpha\beta}$ measure of NSI normalized to weak interaction strength

Neutrino NSI in the Zee model

- The two charged scalars of the Zee model mediate NSI



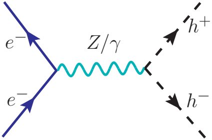
- The NSI parameters are given by:

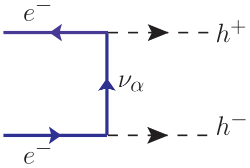
$$\varepsilon_{\alpha\beta} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y^*_{\beta e} \left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}} \right)$$

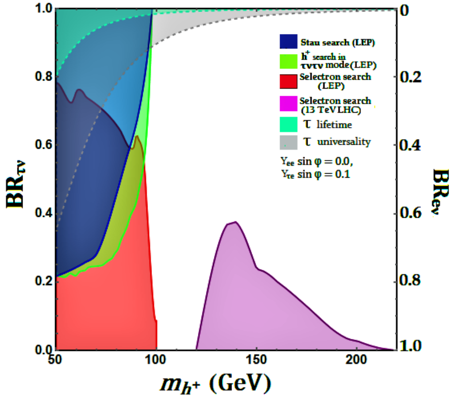
- Constrained by LHC and LEP direct limits; cLFV; precision electroweak tests; neutrino oscillation data; and theory

  Babu, Dev, Jana, Thapa (2019)

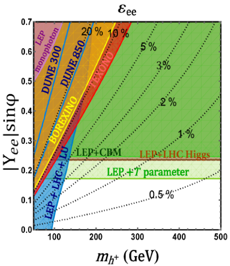
LEP and LHC constraints on Charged Scalar



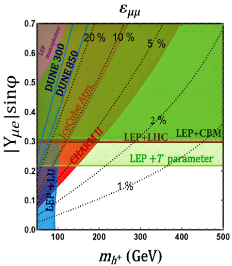




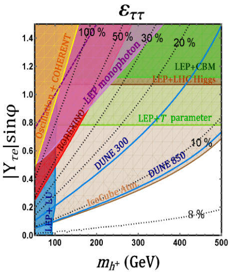
Diagonal NSI in Zee model



(a)

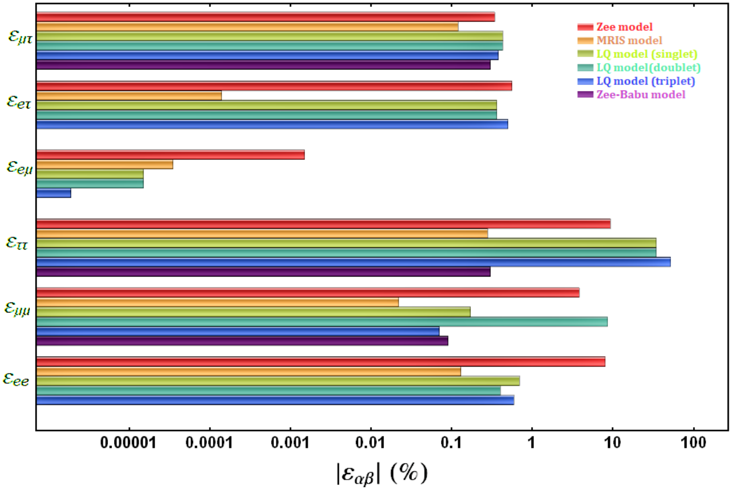


(b)



Babu, Dev, Jana, Thapa (2019)

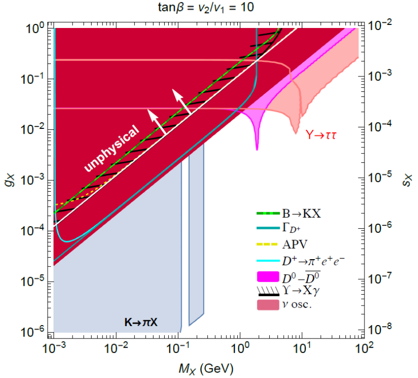
Summary of NSI in radiative models



Babu, Dev, Jana, Thapa (2019)

NSI from Light Mediators

- With light mediators NSI induced may be more compatible with charged lepton flavor violation
- Several models have been proposed Gavela, Hernandez, Ota, Winter (2009); Farzan, Heeck (2016); Babu, Friedland, Machado, Mocioiu (2017); Denton, Farzan, Shoemaker (2018)



$(B-L)_3$ Model: Babu, Friedland, Machado, Mocioiu (2017)

Conclusions

- EFT description alone in neutrino sector is inadequate; we may miss important phenomena such as leptogenesis

- Grand Unification provides powerful tools to interconnect neutrino sector with quark sector

- Neutrino may very well be Dirac particles; interesting models of Dirac neutrino exist

- Lepton number violation by two units is accessible at the LHC, which would imply Majorana nature of neutrino

- Energy-dependent oscillation angles can arise in presence of light fields coupled to neutrinos

- Various $d = 7$ and $d = 9$ lepton number violating EFT operators can lead to interesting neutrino mass models