Neutrino Mass Models and Nonstandard Interactions

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Oklahoma State University

Neutrino Theory Network Workshop

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Products Developed with NTN Support

- Our group at OSU was supported by NTN jointly with Washington University group of Bhupal Dev in the first two years of NTN
- Funding helped travel exchange between OSU, WashU, and Fermilab

Main Products:

1. K. S. Babu, P. S. B. Dev, S. Jana and A. Thapa, "Non-Standard Interactions in Radiative Neutrino Mass Models," JHEP **03**, 006 (2020).
2. K. S. Babu, P. S. Dev, S. Jana and Y. Sui, "Zee-Burst: A New Probe of Neutrino Nonstandard Interactions at IceCube," Phys. Rev. Lett. **124**, no.4, 041805 (2020).
3. K. S. Babu, G. Chauhan and P. S. Bhupal Dev, "Neutrino nonstandard interactions via light scalars in the Earth, Sun, supernovae, and the early Universe," Phys. Rev. D **101**, no.9, 095029 (2020).
4. K. S. Babu, D. Gonçalves, S. Jana and P. A. N. Machado, "Neutrino Non-Standard Interactions: Complementarity Between LHC and Oscillation Experiments," Phys. Lett. B **815**, 136131 (2021).
5. K. S. Babu, P. S. B. Dev, S. Jana and A. Thapa, "Unified framework for B-anomalies, muon g-2 and neutrino masses," JHEP **03**, 179 (2021).
6. K. S. Babu, S. Jana, M. Lindner and V. P. K, "Muon g-2 anomaly and neutrino magnetic moments," JHEP **10**, 240 (2021).
7. P. S. Bhupal Dev, K. S. Babu, P. B. Denton, P. A. N. Machado *et al.* "Neutrino Non-Standard Interactions: A Status Report," SciPost Phys. Proc.**2**, 001 (2019).

Students Involved in NTN Projects

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Currently at MPI, Heidelberg

Vishnu P.K (OSU)
Graduating next year

Garv Chauhan (WashU)
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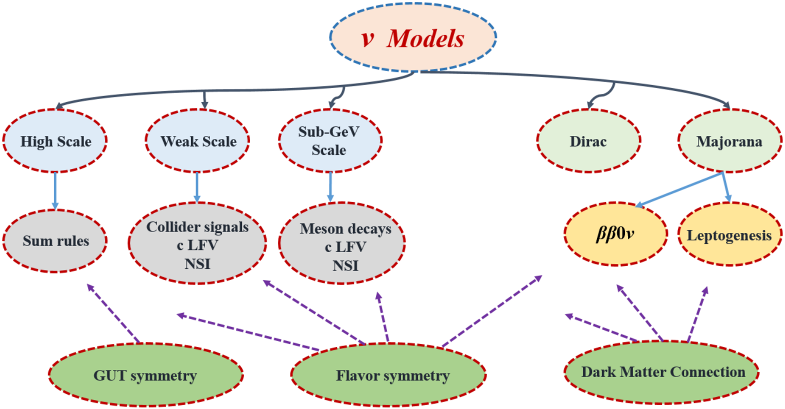
Yicong Sui (WashU)
Currently in private sector

Current knowledge of 3-neutrino oscillations

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

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

Roadmap for Neutrino Models



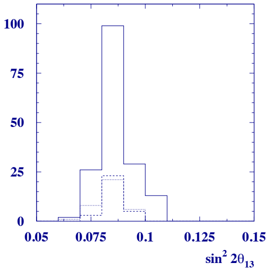
Fit to all fermion masses and mixings

Observables (masses in GeV)	**SUSY** Input			**non-SUSY** Input		
	Input	Best Fit	Pull	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)

Minimal Yukawa sector of SO(10)

- 12 parameters plus 7 phases to fit $13 + 5 = 18$ 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)

Yukawa Sector of Minimal $SO(10)$

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

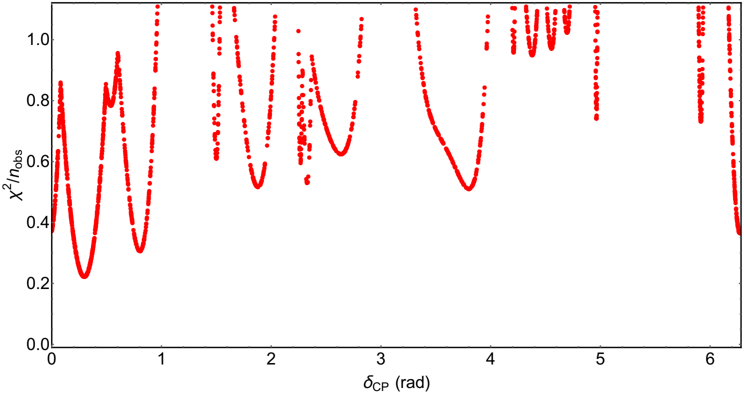
- At least two Higgs fields needed for family mixing
- Symmetric 10_H and $\overline{126}$ is the minimal model

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

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

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)

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

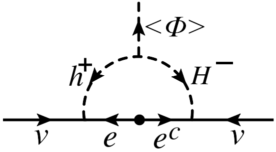
Operator $\mathcal{O}_2$ and the Zee model

- 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:

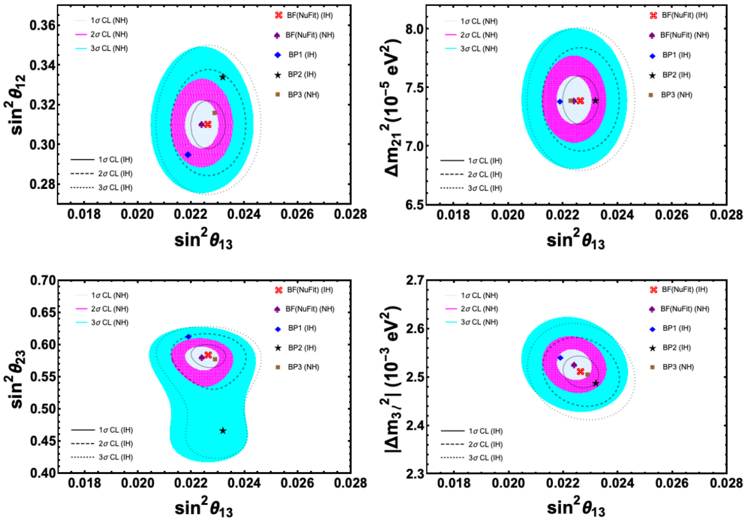
$$\text{BP I}: \; Y = \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

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

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

Babu, Dev, Jana, Thapa (2019)

Neutrino fit in the Zee model



Babu, Dev, Jana, Thapa (2019)

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:

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

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

Wolfenstein (1978)

- Effective Hamiltonian for neutrino propagation in matter is now:

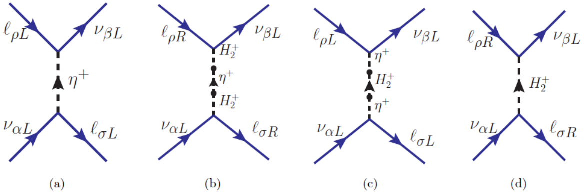
$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^\star & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\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

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

See next talk by Bhupal Dev

Neutrino NSI in the Zee model

- The two charged scalars of the Zee model mediate NSI



- The NSI parameters are given by:

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

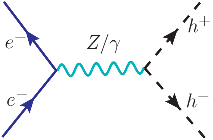
- Constrained by LHC and LEP direct limits; cLFV; precision electroweak tests; neutrino oscillation data; and theory

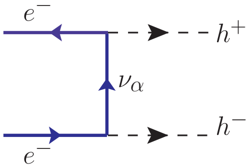
Babu, Dev, Jana, Thapa (2019)

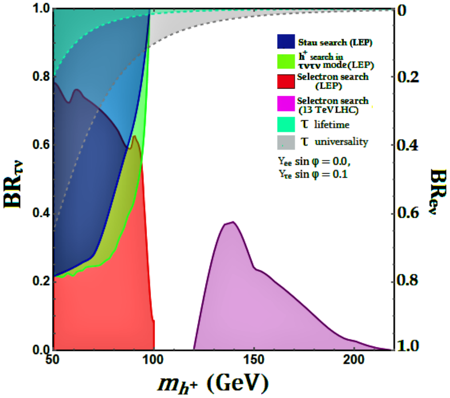
Constraints on Zee model parameters

- Electroweak T parameter sets limits on mixing $\sin\varphi$
- $\mu \to e + \gamma$ type processes limit products of couplings
- $\mu \to 3e$ type processes lead to further constraints
- τ lifetime and universality constraints
- Lepton universality in $W^{\pm}$ decays
- Theoretical constraint from avoiding charge breaking minima
- LEP direct search limits on charged scalars
- Constraints from LHC searches
- Higgs precision physics limits

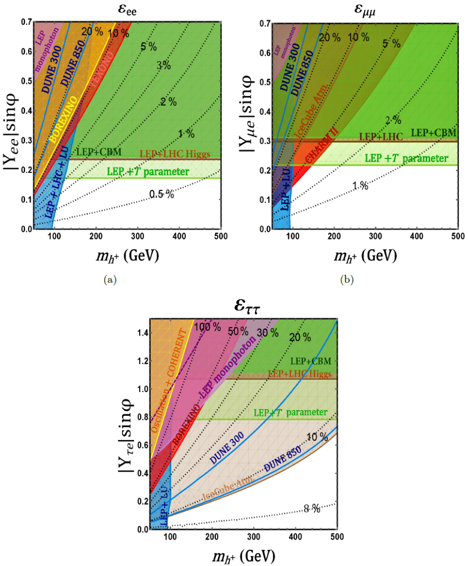
LEP and LHC constraints on Charged Scalar







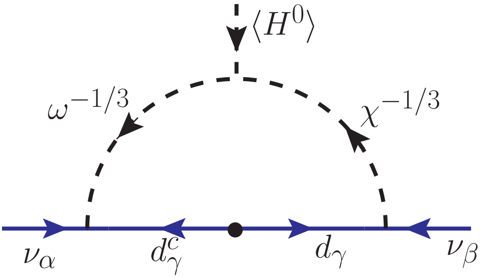
Diagonal NSI in Zee model



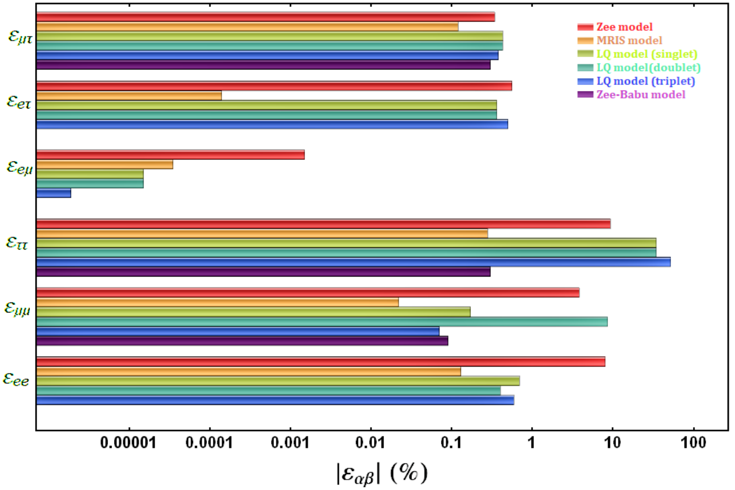
Babu, Dev, Jana, Thapa (2019)

Leptoquark models of radiative neutrino mass

- Charged lepton in Zee diagram may be replaced by quarks
- Charged scalars will then be replaced by Leptoquark scalars
- Several such models exist in literature
- More interest in context of B meson deacy anomalies



Summary of NSI in radiative models

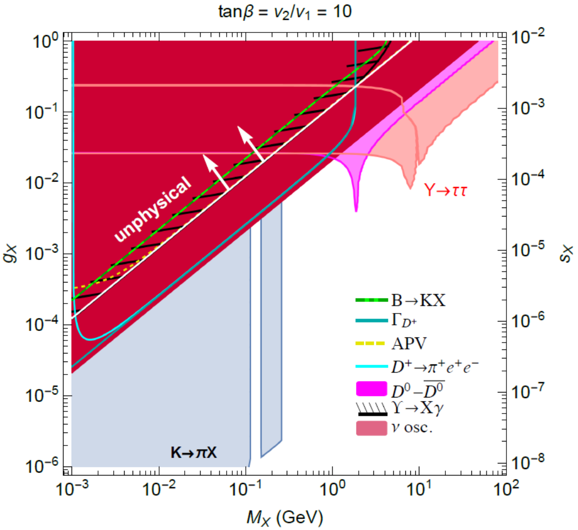


Babu, Dev, Jana, Thapa (2019)

Neutrino Mass Models with Light Mediators

- If the mediator generating $(\overline{\nu}_\alpha \gamma_\mu \nu_\beta)(\overline{f} \gamma^\mu f)$ interactions is light, the severe charged lepton flavor violation constraints may be evaded
- Gauging $(B-L)$ for the third family is an explicit example of this
  Babu, Friedland, Machado, Mocioiu (2017)
- The model has ν_R fields, a second Higgs doublet ϕ_2 and a singlet s, both with $(B-L)$ charge of $1/3$
- ϕ_2 generates quark mixings; charged leptons remain unmixed $\Rightarrow$ No flavor violation in charged leptons
- If mass of the new gauge boson X is of order 100 MeV, with the gauge coupling $g_X \sim 10^{-3}$ all constraints are satisfied
- This explicit model generates $\epsilon_{\tau\tau} \sim 0.5$
- ν_3^c is light and may serve as the sterile neutrino relevant for short baseline anomalies Babu, Friedland, Mocioiu, Machado (to appear)

$(B-L)_3$ Model Constraints



Babu, Friedland, Machado, Mocioiu (2017)

Other Models with large NSI

- Several models have been proposed to generate observable NSI
- Main challenge is to control charged lepton flavor violation and universality constraints
- Some models use cancellations among $d = 6$ and $d = 8$ operators
  Gavela, Hernandez, Ota, Winter (2009)
- Light mediators help with satisfing such constraints Farzan, Shoemaker (2016); Farzan (2016); Denton, Farzan, Shoemaker (2018)
- Collider signals of these models have been studied, especailly for monojet signals Friedland, Graesser, Shoemaker (2012); Elahi, Martin (2019); Babu, Goncalves, Jana, Machado (2021)

Naturally Light Dirac Neutrinos from Left-Right Symmetry

- In a “universal seesaw” version of left-right symmetry, neutrinos are naturally Dirac particles
- These models provide understanding of Parity violation; some understanding of smallness of Yukawa couplings; requires right-handed neutrinos to exist; can provide a solution to the strong CP problem via Parity

  Davidson, Wali (1987); Babu, He (1989); Babu, Mohapatra (1990); Craig, Garcia Garcia, Koszegi, McCune (2020)

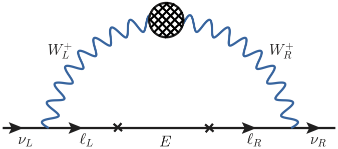
- Higgs sector is very simple; new vector-like singlet fermions (U, D, E) generate charged fermion masses via a seesaw:

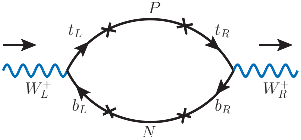
$$M_F = \begin{pmatrix} 0 & Y\kappa_L \\ Y^\dagger\kappa_R & M \end{pmatrix} \Rightarrow m_f = \frac{Y^2\kappa_L\kappa_R}{M}$$

- There is no seesaw for neutrinos, since there is no corresponding singlet fermion
- Dirac neuutrino masses arise via two-loop diagrams

Two-loop Dirac Neutrino Masses

- $W_L^+ - W_R^+$ mixing is absent at tree-level in model





- Oscillation date fits well within the model Babu, He, Su, Thapa (2022)

Oscillation parameters	3σ range NuFit5.1	Model prediction			
		BP I (NH)	BP II (NH)	BP III (IH)	BP IV (IH)
$\Delta m^2_{21}(10^{-5}\ \mathrm{eV}^2)$	6.82 - 8.04	7.42	7.32	7.35	7.30
$\Delta m^2_{23}(10^{-3}\ \mathrm{eV}^2)$(IH)	2.410 - 2.574	-	-	2.48	2.52
$\Delta m^2_{31}(10^{-3}\ \mathrm{eV}^2)$(NH)	2.43 - 2.593	2.49	2.46	-	-
$\sin^2\theta_{12}$	0.269 - 0.343	0.324	0.315	0.303	0.321
$\sin^2\theta_{23}$ (IH)	0.410 - 0.613	-	-	0.542	0.475
$\sin^2\theta_{23}$ (NH)	0.408 - 0.603	0.491	0.452	-	-
$\sin^2\theta_{13}$ (IH)	0.02055 - 0.02457	-	-	0.0230	0.0234
$\sin^2\theta_{13}$(NH)	0.02060 - 0.02435	0.0234	0.0223	-	-
δ_{CP} (IH)	192 - 361	-	-	271°	296°
δ_{CP} (NH)	105 - 405	199°	200°	-	-
m_{light} (10^{-3}) eV		0.66	0.17	0.078	4.95
M_{E_1}/M_{W_R}		917	321.3	639	3595
M_{E_2}/M_{W_R}		0.650	19.3	1.54	5.03
M_{E_3}/M_{W_R}		0.019	1.26	0.054	2.94

Tests with $N_{\rm eff}$ in Cosmology

- Dirac neutrino models of this type will modify $N_{\rm eff}$ by about 0.14

$$\Delta N_{\rm eff} \simeq 0.027 \left(\frac{106.75}{g_\star\left(T_{\rm dec}\right)}\right)^{4/3} g_{\rm eff}$$

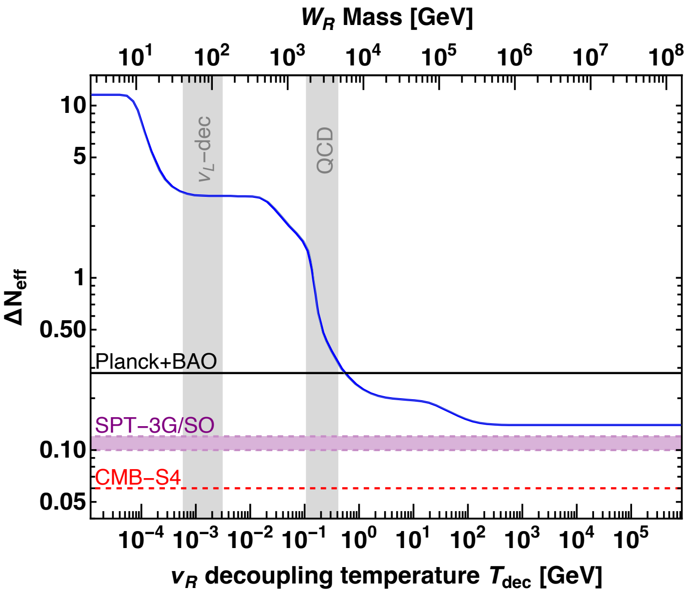
$$g_{\rm eff} = (7/8) \times (2) \times (3) = 21/4$$

- Can be tested in CMB measurements: $N_{\rm eff} = 2.99 \pm 0.17$ (Planck+BAO)

$$G_F^2 \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 T_{\rm dec}^5 \approx \sqrt{g^*(T_{\rm dec})}\,\frac{T_{\rm dec}^2}{M_{\rm Pl}}$$

$$T_{\rm dec} \simeq 400 \text{ MeV} \left(\frac{g_*\left(T_{\rm dec}\right)}{70}\right)^{1/6} \left(\frac{M_{W_R}}{5 \text{ TeV}}\right)^{4/3}$$

- Present data sets a lower limit of 7 TeV on W_R mass



W_R Mass [GeV]
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8
ΔN_{eff}
10
5
1
0.50
0.10
0.05
ν_L−dec
QCD
Planck+BAO
SPT−3G/SO
CMB−S4
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5
ν_R decoupling temperature T_{dec} [GeV]

Conclusions

- The scale of neutrino mass generation can be of order GUT scale, weak scale, or sub-GeV scale
- Grand Unification provides powerful tools to interconnect neutrino sector with quark sector
- Various $d = 7$ and $d = 9$ lepton number violating EFT operators can lead to interesting neutrino mass models.
- These models may be realized near the TeV scale, with potential signals for NSI, cFLV and direct detection at colliders
- Neutrino may very well be Dirac particles; interesting models of Dirac neutrino exist. $\Delta N_{\rm eff}$ in cosmology could test this scenario

Thank You!

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