Non-Standard Interaction in Radiative Neutrino Mass Models

K.S. Babu[1] **Bhupal Dev**[2] **Sudip Jana**[1] **Anil Thapa**[1]

[1] Oklahoma State University

[2]Washington University in St. Louis

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ν mass generation

- In Standard Model $M_\nu = 0$. But, ν flavor mix. $\nu_{\rm aL} \leftrightarrow \nu_{\rm bL}$

$$|\nu_\alpha\rangle = \sum U_{\alpha i}|\nu_i\rangle \Longrightarrow M_\nu \neq 0 \Longrightarrow \text{New physics beyond SM}$$

- Simplest possibility: Introduce ν_R to the SM allowing

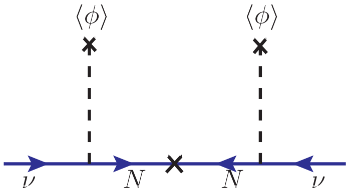
$$\mathcal{L}_Y : y_\nu \bar{\psi}_L \phi \nu_R + h.c.$$

  - $m_\nu \sim 0.1eV$, this means yukawa coupling $y_\nu \sim 10^{-12}$!!
  - Yukawa coupling likely to be same order as of quark and charged leptons. But observation shows $m_\nu << m_q$ or m_l

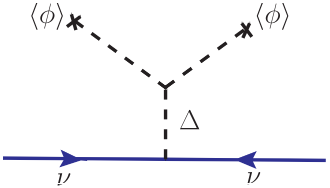
- Schemes for neutrino masses and mixings:
  - Tree-level Seesaw mechanism
  - Radiative schemes

Seesaw Paradigm

- Light neutrino mass is induced via Weingberg's dim-5 operator, $LL\phi\phi$.
- Large Majorana mass scale Λ to suppress the neutrino mass via $\frac{\langle\phi\rangle^2}{\Lambda}$.
- Different schemes:



Type I/ Type III:
ν-mass induced from fermion exchange:
$N^1 \sim (1,1,0)$ $N^3 \sim (1,3,0)$

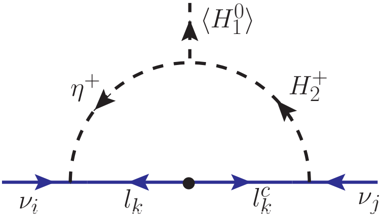


Type II:
ν-mass induced from scalar boson exchange $\Delta \sim (1,3,1)$

- The scale of new physics can be rather high

Radiative ν mass generation

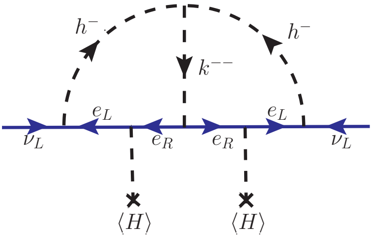
- Neutrino masses are zero at tree level as SM: ν_R may be absent.
- Small, finite Majorana masses are generated at the quantum level.
- Typically new heavy scalar fields introduced violates lepton number and lepton flavor.
- Simple realization is the Zee Model, which has a second Higgs doublet and a charged singlet.



- Smallness of neutrino mass is explained via loop and chiral suppression.
- New physics in this framework may lie at the TeV scale.

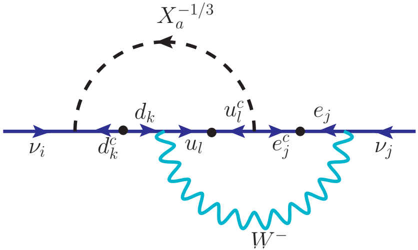
Type I radiative mechanism

- Obtained from effective d = 7, 9, 11... operators with $\Delta L = 2$ selection rule
- If the loop diagram has at least one Standard Model particle, this can be cut to generate such effective operators



$\mathcal{O}_9 = L_i L_j L_k e^c L_l e^c \epsilon^{ij} \epsilon^{kl}$

Zee, Babu



$\mathcal{O}_8 = L_i \bar{e^c} \bar{u^c} d^c H_j \epsilon^{ij}$

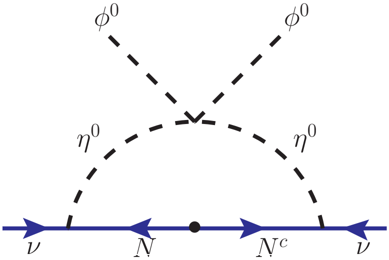
Babu, Julio (2010)

Classification: Babu, Leung (2001)

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

Type II radiative mechanism

- No Standard Model particle inside the loop
- Cannot be cut to generate d = 7, 9,... operators
- Scotogenic model is an expample



- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new phyiscs

Ma (2006)

Nonstandard neutrino interactions

- New physics near TeV scale can generate nonstandard neutrino interactions (NSI)
- Most important effect of NSI is in neutrino propagation in matter

Wolfenstein (1978)

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

- Matter potential

$$H_{\rm mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon_{e\mu}^*(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon_{e\tau}^*(x) & \varepsilon_{\mu\tau}^*(x) & \varepsilon_{\tau\tau}(x) \end{pmatrix}$$

- If $\varepsilon_{\alpha\beta} \neq 0$ for $\alpha \neq \beta$, NSI violates lepton flavor, for $\varepsilon_{\alpha\alpha} \neq \varepsilon_{\beta\beta}$, it violates lepton flavor universality.
- Presence of ε_{ij} affect mass ordering and CP violation

Esteban, Gonzalez-Garcia, Maltoni (2019)

Zee Model

- Gauge symmetry is same as Standard Model
- Zee Model has a second Higgs doublet H_2 and a charged weak singlet η^+ scalars

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(\mathrm{v} + H_1^0 + iG^0) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(H_2^0 + iA) \end{pmatrix}$$

- Mixing between η^+ and H_2^+ :

$$\begin{pmatrix} M_2^2 & -\mu \mathrm{v}/\sqrt{2} \\ -\mu \mathrm{v}/\sqrt{2} & M_3^2 \end{pmatrix}, \qquad \sin 2\varphi = \frac{\sqrt{2}\mathrm{v}\mu}{m_{H^+}^2 - m_{h^+}^2}$$

where

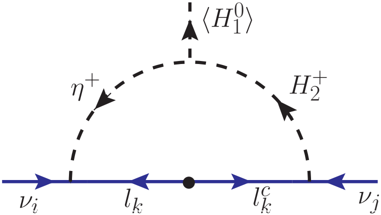
$$h^+ = \cos\varphi \eta^+ + \sin\varphi H_2^+$$
$$H^+ = -\sin\varphi \eta^+ + \cos\varphi H_2^+$$

Neutrino masses in the Zee Model

- Yukawa coupling matrices:

$$f = \begin{pmatrix} 0 & f_{e\mu} & f_{e\tau} \\ -f_{e\mu} & 0 & f_{\mu\tau} \\ -f_{e\tau} & -f_{\mu\tau} & 0 \end{pmatrix}, \qquad Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

- Neutrino mass



$$M_\nu = \kappa \left(f M_l Y^T + Y M_l f^T \right)$$
$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$

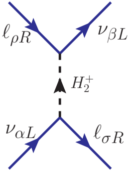
- If $Y \propto M_l$, which happens with a Z_2, then model is ruled out

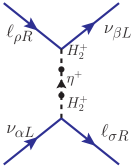
  Wolfenstein (1980)

- In general, Y is not proportional to M_l, and the model gives reasonable fit to oscillation data

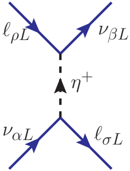
NSI in Zee Model

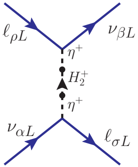
- The singly-charged scalars η^+ and H_2^+ induce NSI at tree level:





$$\sim \frac{\cos^2\varphi}{m_{H^+}^2} Y_{\alpha\beta} Y_{\sigma\rho}^* \qquad \sim \frac{\sin^2\varphi}{m_{h^+}^2} Y_{\alpha\beta} Y_{\rho\sigma}^*$$





$$\sim \frac{\cos^2\varphi}{m_{H^+}^2} f_{\alpha\beta} f_{\sigma\rho}^* \qquad \sim \frac{\sin^2\varphi}{m_{h^+}^2} f_{\alpha\beta} f_{\rho\sigma}^*$$

NSI in the Zee Model

- Considering, $y \sim \mathcal{O}(1)$, $m_\tau \sim 1.7$ GeV and $M_\nu \sim \mathcal{O}(10^{-1})$ eV demands $f \sim 10^{-8} \Longrightarrow$ NSI effect from f is heavily suppressed
- The effective NSI is:

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

- The relevant Yukawas for NSI:

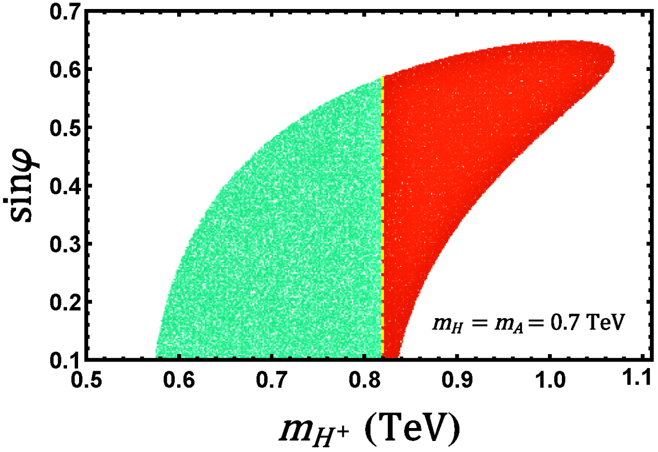
$$\begin{array}{ll} \varepsilon^m_{ee} \sim |Y_{ee}|^2 & \varepsilon^m_{e\mu} \sim Y^*_{ee} Y_{\mu e} \\ \varepsilon^m_{\mu\mu} \sim |Y_{\mu e}|^2 & \varepsilon^m_{\mu\tau} \sim Y^*_{\mu e} Y_{\tau e} \\ \varepsilon^m_{\tau\tau} \sim |Y_{\tau e}|^2 & \varepsilon^m_{e\tau} \sim Y^*_{ee} Y_{\tau e} \end{array}$$

$$\begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

- Note: $\varepsilon_{\alpha\alpha} > 0$

Bound from EW Precision Constraints

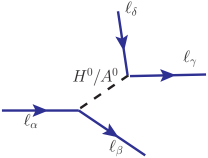
- T parameter imposes the most stringent constraint
- No mixing between the neutral $\mathcal{CP}$-even scalars h and H



- For $m_H = 0.7\,\text{TeV}$ and $m_h^+ = 100\ \text{GeV}$, the maximum mixing is 0.63.

Lepton Flavor violation

- The presence of the second Higgs doublet gives rise to tree-level trilepton decays $\ell_i \to \ell_j \ell_k \ell_l$



Process	Exp. bound	Constraint
$\mu^- \to e^+ e^- e^-$	BR < 1.0×10^{-12}	$\|Y^\star_{\mu e} Y_{ee}\| < 3.28 \times 10^{-5} \left(\frac{m_H}{700 \text{ GeV}}\right)^2$
$\tau^- \to e^+ e^- e^-$	BR < 1.4×10^{-8}	$\|Y^\star_{\tau e} Y_{ee}\| < 9.05 \times 10^{-3} \left(\frac{m_H}{700 \text{ GeV}}\right)^2$
$\tau^- \to e^+ e^- \mu^-$	BR < 1.1×10^{-8}	$\|Y^\star_{\tau e} Y_{\mu e}\| < 5.68 \times 10^{-3} \left(\frac{m_H}{700 \text{ GeV}}\right)^2$

- Trilepton decays put more stringent bounds compared to the bounds from loop-level $\ell_\alpha \to \ell_\beta \gamma$ decays.

Collider Constraints on Neutral Scalar Mass

- At LEP experiment, e^+e^- collision above the Z boson mass imposes significant constraints on contact interactions involving e^+e^- and fermion pair.
- An effective Lagrangian has the form:

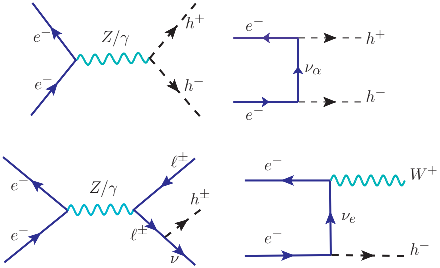
$$\mathcal{L}_{eff} = \frac{4\pi}{\Lambda^2(1+\delta_{ef})} \sum_{i,j=L,R} \eta^f_{ij} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j)$$

- In Zee model, the exchange of neutral scalars H & A from second doublet will affect $e^+e^- \to \ell^+_\alpha \ell^-_\beta$

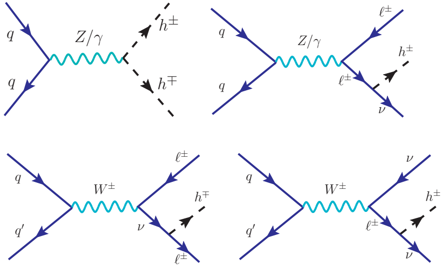
Process	LEP bound	Constraint
$e^+e^- \to e^+e^-$	$\Lambda^-_{LR/RL} > 10$ TeV	$\frac{m_H}{\lvert Y_{ee}\rvert} > 1.99$ TeV
$e^+e^- \to \mu^+\mu^-$	$\Lambda^-_{LR/RL} > 7.9$ TeV	$\frac{m_H}{\lvert Y_{\mu e}\rvert} > 1.58$ TeV
$e^+e^- \to \tau^+\tau^-$	$\Lambda^-_{LR/RL} > 2.2$ TeV	$\frac{m_H}{\lvert Y_{\tau e}\rvert} > 0.44$ TeV

Collider constraints on $h^{\pm}$ mass

- New Physics at sub-TeV scale is highly constrained from direct searches as well as indirect searches.
- Direct searches: we can put bound on h^{+} mass by looking at the final state (leptons + missing energy)
  - Some supersymmetirc searches (Stau, Selectron) exactly mimics the charged higgs searches.



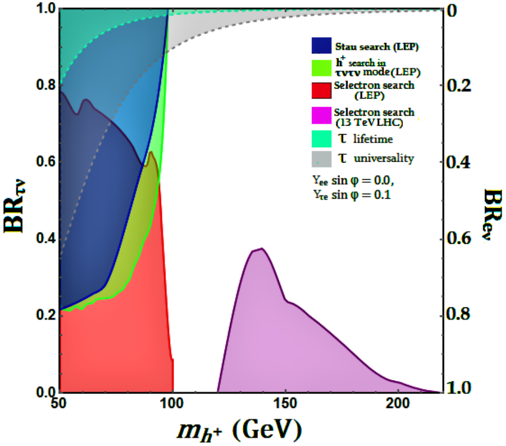
Dominant production in LEP



Dominant production in LHC

Contd.

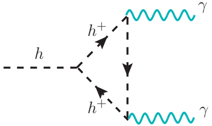
- $BR_{\tau\nu} + BR_{e\nu} = 1$ ($BR_{\mu\nu} \approx 0$) to avoid stringent limit from muon decay.
- $Y_{ee} \sin\varphi = 0 \Rightarrow$ no h^+ production with W boson $\Rightarrow$ no lepton universality in $W^\pm$ decay.

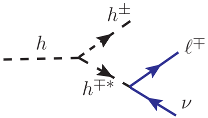


- The lowest charged higgs mass allowed is 96 GeV.

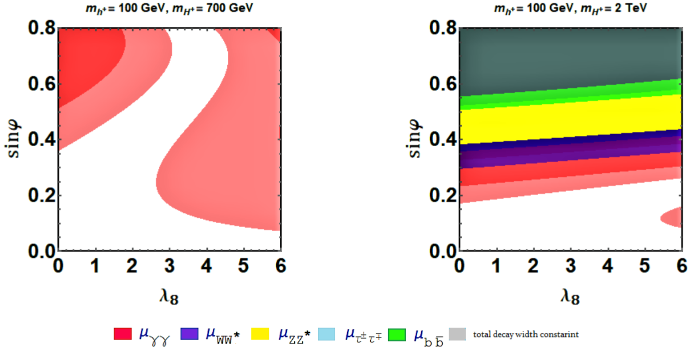
Constraints from Higgs Precision data

- Light charged scalar is leptophilic $\Rightarrow$ production rate not affected
- New contribution to loop-induced $h \to \gamma\gamma$

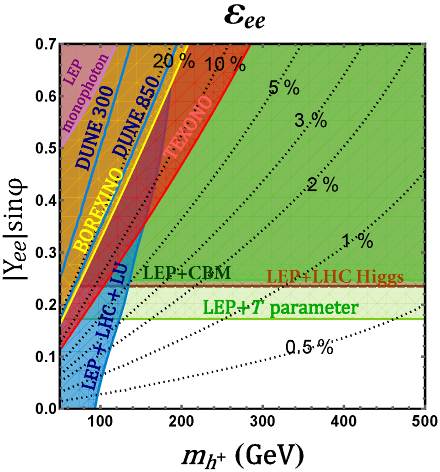


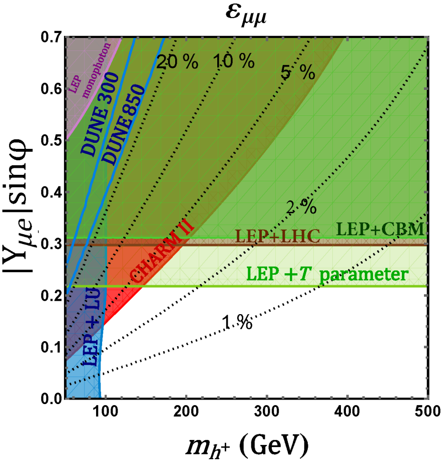


$$\lambda_{hh^+h^-} = -\sqrt{2}\mu \sin\varphi \cos\varphi + \lambda_3 v \sin^2\varphi + \lambda_8 v \cos^2\varphi$$



Numerical results for NSI

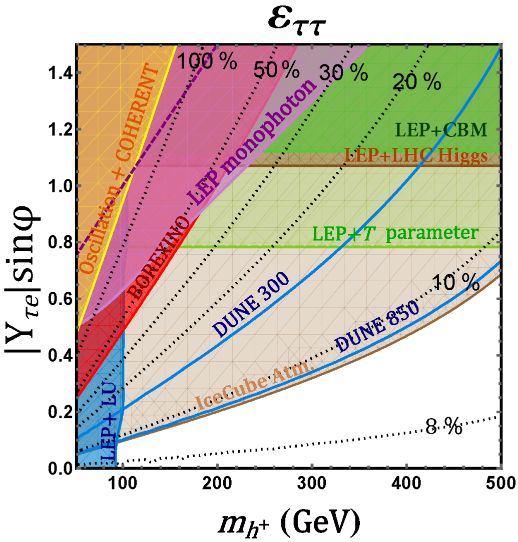




$\varepsilon_{ee}^{\max} \approx 3\%$

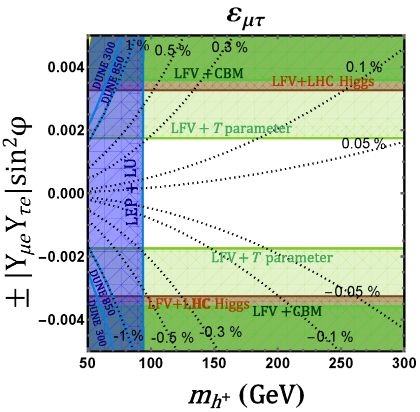
$\varepsilon_{\mu\mu}^{\max} \approx 3.8\%$

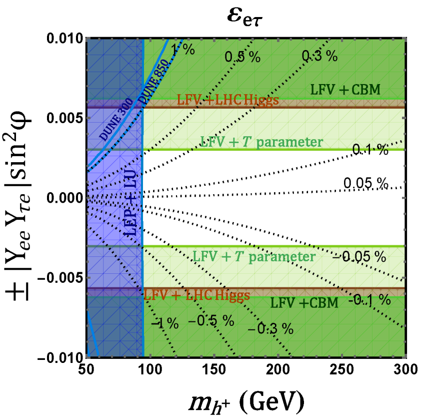
Contd.



$\varepsilon_{\tau\tau}^{\max} \approx 9.3\%$

Contd.





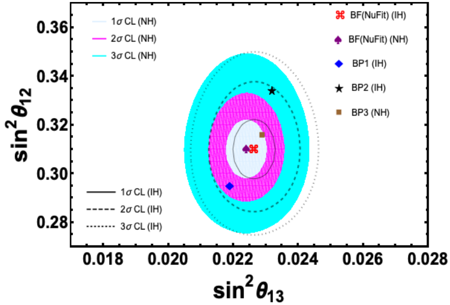
$\varepsilon_{\mu\tau}^{\max} \approx 0.34\%$

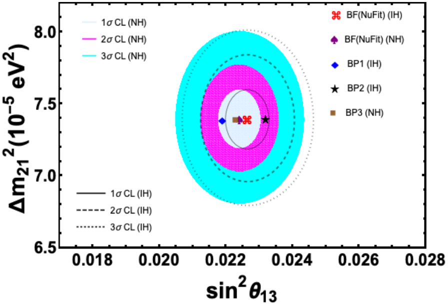
$\varepsilon_{e\tau}^{\max} \approx 0.56\%$

Consistency with Neutrino Oscillation Data

$$\begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}, \begin{pmatrix} 0 & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & 0 & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}, \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & 0 & Y_{\tau\tau} \end{pmatrix}$$

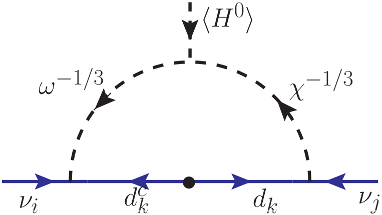
BPI BPII BPII





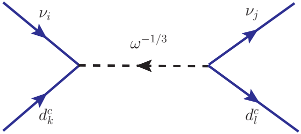
NSI in Leptoquark: Colored Zee Model

- Two $SU(3)_C$ scalar fields, $\Omega \sim (3, 2, 1/6)$ and $\chi^{-1/3} \sim (3, 1, -1/3)$, are introduced.
- Neutrino masses:



$$M_\nu = \kappa(\lambda M_d \lambda'^T + \lambda' M_d \lambda^T)$$
$$\kappa = \frac{3 \sin 2\varphi}{32\pi^2} \log \frac{M_1^2}{M_2^2}$$

- Choosing $\lambda\lambda' \approx 0 \Longrightarrow \lambda \sim \mathcal{O}(1)$ or $\lambda' \sim \mathcal{O}(1)$

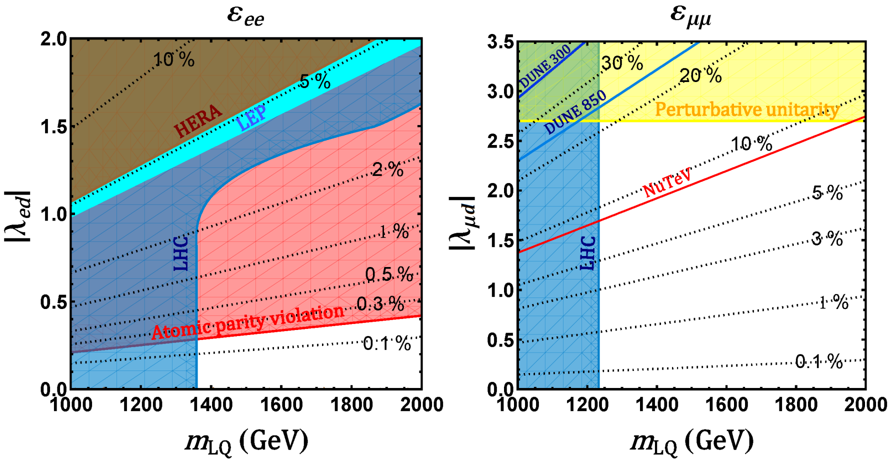


$\lambda \sim \mathcal{O}(1)$

$$\varepsilon^d_{\alpha\beta} = \frac{1}{4\sqrt{2}} \frac{\lambda^*_{\alpha 1}\lambda_{\beta 1}}{G_F M_\omega^2}$$

For $\frac{N_n(x)}{N_p(x)} = 1 \Longrightarrow \varepsilon_{\alpha\beta}(x) = 3\varepsilon^d_{\alpha\beta}$

NSI in Leptoquark: Colored Zee Model



$\varepsilon_{ee}^{\rm max} \approx 0.4\%$ $\varepsilon_{\mu\mu}^{\rm max} \approx 21.6\%$

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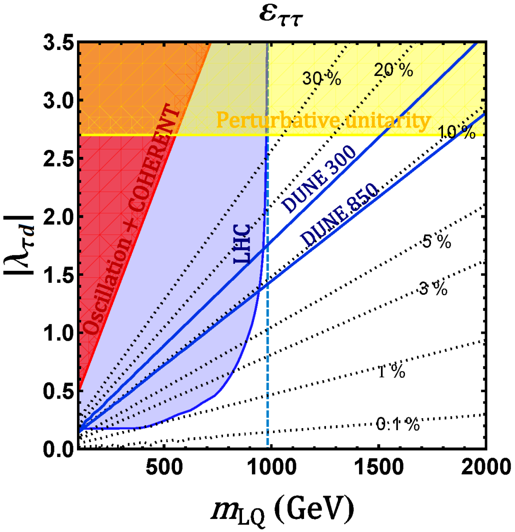
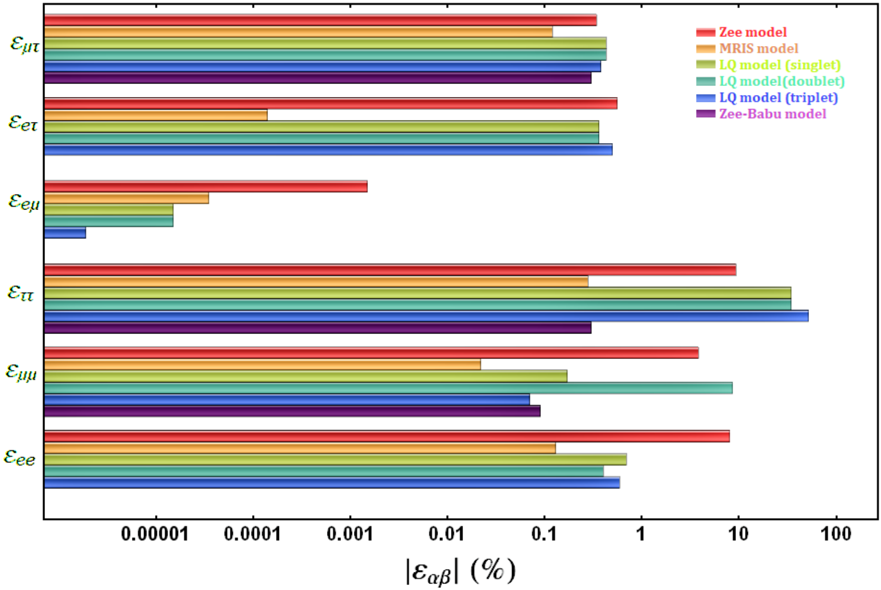


$\varepsilon_{\tau\tau}^{\max} \approx 34.3\%$

Summary of type-I Models

Term	$\mathcal{O}$	Model	Loop level	$\mathcal{S}/\mathcal{F}$	New particles	Max NSI @ tree-level $\lvert\varepsilon_{ee}\rvert$	$\lvert\varepsilon_{\mu\mu}\rvert$	$\lvert\varepsilon_{\tau\tau}\rvert$	$\lvert\varepsilon_{e\mu}\rvert$	$\lvert\varepsilon_{e\tau}\rvert$	$\lvert\varepsilon_{\mu\tau}\rvert$
$L\ell^c\Phi^\star$	$\mathcal{O}_2^2$	Zee [14]	1	$\mathcal{S}$	$\eta^+(1,1,1)$, $\Phi_2(1,2,1/2)$	0.08	0.038	0.43	$\mathcal{O}(10^{-5})$	0.0056	0.0034
	$\mathcal{O}_9$	Zee-Babu [15, 16]	2	$\mathcal{S}$	$h^+(1,1,1)$, $k^{++}(1,1,2)$						
	$\mathcal{O}_9$	KNT [36]	3	$\mathcal{S}$ $\mathcal{F}$	$\eta_1^+(1,1,1)$, $\eta_2^+(1,1,1)$ $N(1,1,0)$	0	0.0009	0.003	0	0	0.003
$LL\eta$	$\mathcal{O}_9$	1S-1S-1F [200]	3	$\mathcal{S}$ $\mathcal{F}$	$\eta_1(1,1,1)$, $\eta_2(1,1,3)$ $F(1,1,2)$						
	$\mathcal{O}_2^1$	1S-2VLL [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\eta(1,1,1)$ $\Psi(1,2,-3/2)$						
$Le^c\phi$	$\mathcal{O}_3'$	AKS [38]	3	$\mathcal{S}$ $\mathcal{F}$	$\Phi_2(1,2,1/2)$, $\eta^+(1,1,1)$, $\eta^0(1,1,0)$ $N(1,1,0)$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$
	$\mathcal{O}_9$	Cocktail [39]	3	$\mathcal{S}$	$\eta^+(1,1,1)$, $k^{++}(1,1,2)$, $\Phi_2(1,2,1/2)$	0	0	0	0	0	0
W/Z	$\mathcal{O}_2'$	MRIS [43]	1	$\mathcal{F}$	$N(1,1,0)$, $S(1,1,0)$	0.024	0.022	0.10	0.0013	0.0035	0.012
$L\Omega d^c$	$\mathcal{O}_3^8$	LQ variant of Zee [30]	1	$\mathcal{S}$	$\Omega(3,2,1/6)$, $\chi(3,1,-1/3)$	0.004	0.216	0.343	$\mathcal{O}(10^{-7})$	0.0036	0.0043
$(LQ\chi^\star)$	$\mathcal{O}_8^4$	2LQ-1LQ [33]	2	$\mathcal{S}$	$\Omega(3,2,1/6)$, $\chi(3,1,-1/3)$	(0.0069)	(0.0086)				
	$\mathcal{O}_3^3$	2LQ-1VLQ [34]	2	$\mathcal{S}$ $\mathcal{F}$	$\Omega(3,2,1/6)$ $U(3,1,2/3)$						
$L\Omega d^c$	$\mathcal{O}_3^6$	2LQ-3VLQ [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\Omega(3,2,1/6)$ $\Sigma(3,3,2/3)$	0.004	0.216	0.343	$\mathcal{O}(10^{-7})$	0.0036	0.0043
	$\mathcal{O}_8^2$	2LQ-2VLL [31]	2	$\mathcal{S}$ $\mathcal{F}$	$\Omega(3,2,1/6)$ $\psi(1,2,-1/2)$						
	$\mathcal{O}_8^3$	2LQ-2VLQ [31]	2	$\mathcal{S}$ $\mathcal{F}$	$\Omega(3,2,1/6)$ $\xi(3,2,7/6)$						
$L\Omega d^c$ $(LQ\bar{\rho})$	$\mathcal{O}_3^9$	Triplet-Doublet LQ [31]	1	$\mathcal{S}$	$\rho(3,3,-1/3)$, $\Omega(3,2,1/6)$	0.0059	0.0249	0.517	$\mathcal{O}(10^{-8})$	0.0050	0.0038
	$\mathcal{O}_{11}$	LQ/DQ variant Zee-Babu [32]	2	$\mathcal{S}$	$\chi(3,1,-1/3)$, $\Delta(6,1,-2/3)$						
	$\mathcal{O}_{11}$	Angelic [35]	2	$\mathcal{S}$ $\mathcal{F}$	$\chi(3,1,1/3)$ $F(8,1,0)$						
$LQ\chi^\star$	$\mathcal{O}_{11}$	LQ variant of KNT [37]	3	$\mathcal{S}$ $\mathcal{F}$	$\chi(3,1,-1/3)$, $\chi_2(3,1,-1/3)$ $N(1,1,0)$	0.0069	0.0086	0.343	$\mathcal{O}(10^{-7})$	0.0036	0.0043
	$\mathcal{O}_3^4$	1LQ-2VLQ [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\chi(3,1,-1/3)$ $\mathcal{Q}(3,2,-5/6)$						
$Lu^c\delta$ $(LQ\bar{\rho})$	$\bar{\mathcal{O}}_1$	**3LQ-2LQ-1LQ (New)**	1	$\mathcal{S}$	$\bar{\rho}(\bar{3},3,1/3)$, $\delta(3,2,7/6)$, $\xi(3,1,2/3)$	0.004 (0.0059)	0.216 (0.007)	0.343 (0.517)	$\mathcal{O}(10^{-7})$	0.0036 (0.005)	0.0043 (0.0038)
$Lu^c\delta$	$\mathcal{O}_{d=13}$	**3LQ-2LQ-2LQ(New)**	2	$\mathcal{S}$	$\delta(3,2,7/6)$, $\Omega(3,2,1/6)$,$\hat{\Delta}(6^\star,3,-1/3)$	0.004	0.216	0.343	$\mathcal{O}(10^{-7})$	0.0036	0.0043
$LQ\bar{\rho}$	$\mathcal{O}_3^5$	3LQ-2VLQ [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\bar{\rho}(\bar{3},3,-1/3)$ $\mathcal{Q}(3,2,-5/6)$	0.0059	0.0007	0.517	$\mathcal{O}(10^{-7})$	0.005	0.0038
	All Type-II Radiative models					0	0	0	0	0	0

Summary of Maximum NSI



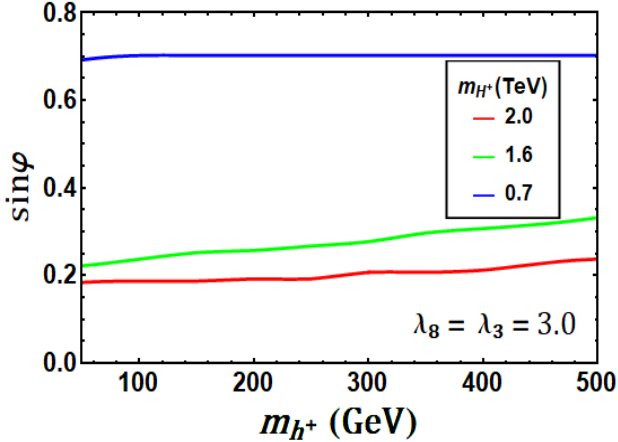
Conclusion

- Matter NSI in the radiative mass models has been studied.
- Mass as low as 96 GeV for the charged scalar is shown to be consistent with direct and indirect limits from LEP and LHC.
- Diagonal NSI in Zee Model are allowed to be as large as (8 $\%$, 3.8 $\%$, 9.3 $\%$) for $(\varepsilon_{ee}, \varepsilon_{\mu\mu}, \varepsilon_{\tau\tau})$, while off-diagonal NSIs are allowed to be (-, 0.56 $\%$, 0.34 $\%$) for $(\varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{\mu\tau})$.
- NSI in leptoquark models are studied which allows diagonal NSI $\varepsilon_{\tau\tau}$ as large as 51.7$\%$

Thank You

Charge Breaking Minima

- To have sizable NSI $\Rightarrow$ large mixing φ $\Rightarrow$ large μ $(\mu\epsilon_{ij}H_1^i H_2^j \eta^-)$
- Need to ensure CCM is deeper than CBM



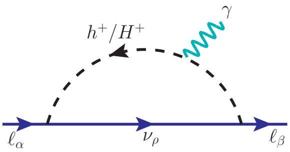
$\sin\varphi < 0.23$ for $m_{H^+} = 2$ TeV

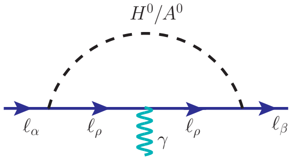
$\sin\varphi \sim 0.707$ for $m_{H^+} = 0.7$ TeV

- Max. value of μ is found to be 4.1 times the heavier mass m_{H^+}

Lepton Flavor Violation

- Detection of LFV signals $\Longrightarrow$ clear evidence for BSM
- Safely ignore cLFV processes involving the $f_{\alpha\beta}(\sim 10^{-8})$ couplings
- $\ell_i \to \ell_j \gamma$ arises at one loop level

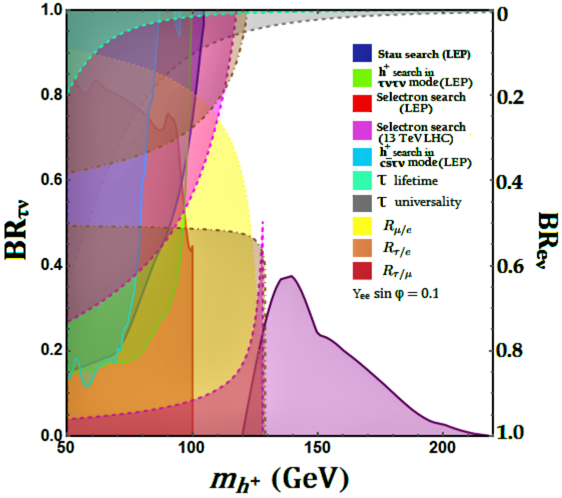




Process	Exp. bound	Constraint
$\mu \to e\gamma$	BR < 4.2×10^{-13}	$\lvert Y^\star_{\mu e} Y_{ee} \rvert < 1.05 \times 10^{-3} \left(\frac{m_H}{700\text{ GeV}}\right)^2$
$\tau \to e\gamma$	BR < 3.3×10^{-8}	$\lvert Y^\star_{\tau e} Y_{ee} \rvert < 0.69 \left(\frac{m_H}{700\text{ GeV}}\right)^2$
$\tau \to \mu\gamma$	BR < 4.4×10^{-8}	$\lvert Y^\star_{\tau e} Y_{\mu e} \rvert < 0.79 \left(\frac{m_H}{700\text{ GeV}}\right)^2$

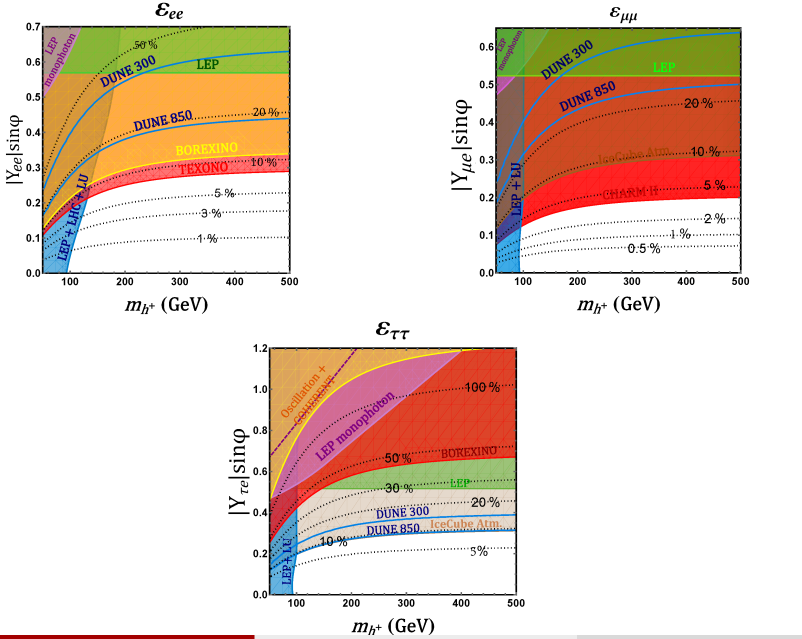
Constraints on Light Charged Scalar

- $\mathrm{BR}_{\tau\nu} + \mathrm{BR}_{e\nu} = 1$ ($\mathrm{BR}_{\mu\nu} \approx 0$) to avoid stringent limit from muon decay.



- The lowest charged higgs mass allowed is 110 GeV.

Zee Model NSI for light neutral scalar



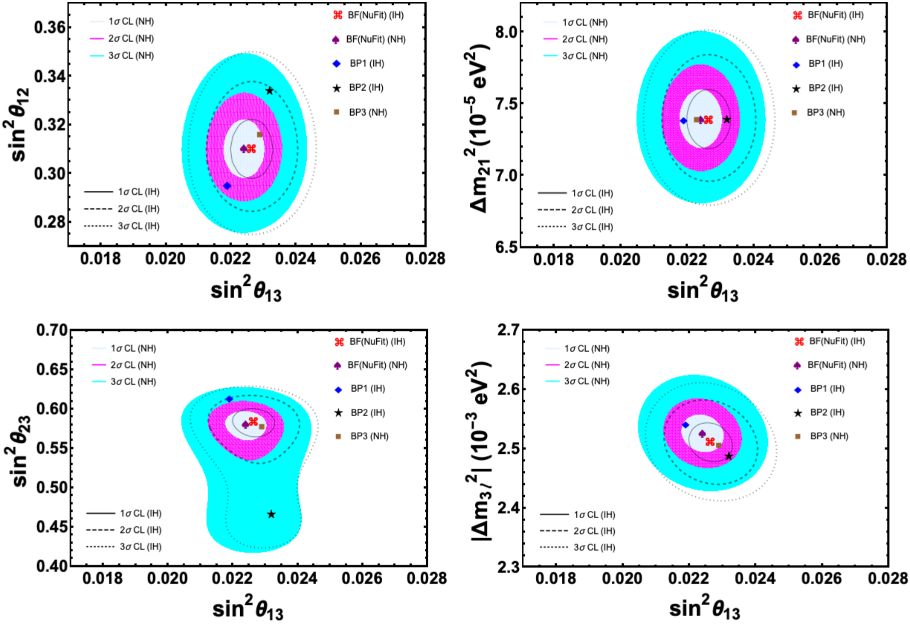
Consistency with Neutrino Oscillation Data

$$\begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}, \begin{pmatrix} 0 & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & 0 & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}, \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & 0 & Y_{\tau\tau} \end{pmatrix}$$

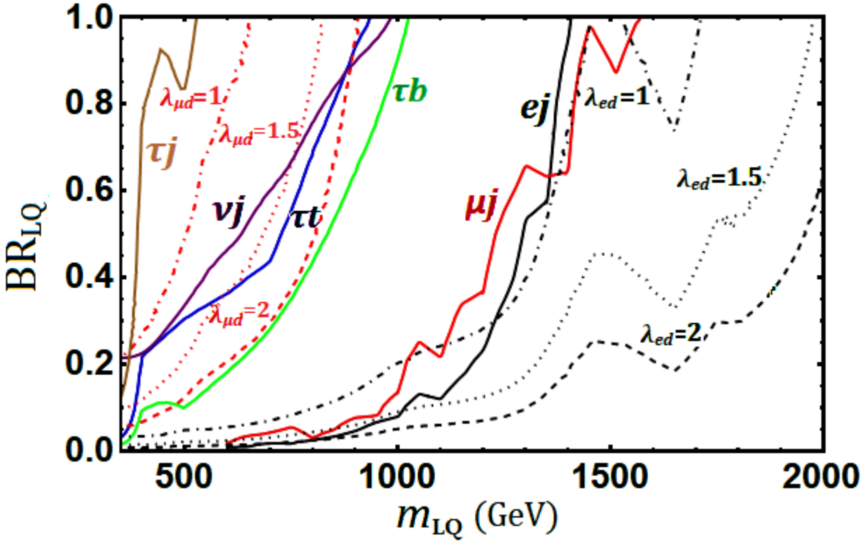
BPI BPII BPII

Oscillation parameters	**3σ allowed range from `NuFit4`**	**Model prediction**		
		BP I (IH)	BP II (IH)	BP III (NH)
$\Delta m^2_{21}(10^{-5}\ \text{eV}^2)$	6.79 - 8.01	7.388	7.392	7.390
$\Delta m^2_{23}(10^{-3}\ \text{eV}^2)$(IH)	2.412 - 2.611	2.541	2.488	-
$\Delta m^2_{31}(10^{-3}\ \text{eV}^2)$(NH)	2.427 - 2.625	-	-	2.505
$\sin^2\theta_{12}$	0.275 - 0.350	0.295	0.334	0.316
$\sin^2\theta_{23}$ (IH)	0.423 - 0.629	0.614	0.467	-
$\sin^2\theta_{23}$ (NH)	0.418 - 0.627	-	-	0.577
$\sin^2\theta_{13}$ (IH)	0.02068 - 0.02463	0.0219	0.0232	-
$\sin^2\theta_{13}$(NH)	0.02045 - 0.02439	-	-	0.0229

Contd.


1σ CL (NH)
2σ CL (NH)
3σ CL (NH)
1σ CL (IH)
2σ CL (IH)
3σ CL (IH)
BF(NuFit) (IH)
BF(NuFit) (NH)
BP1 (IH)
BP2 (IH)
BP3 (NH)
sin²θ12
sin²θ13
Δm21² (10⁻⁵ eV²)
sin²θ23
|Δm3l²| (10⁻³ eV²)
0.018 0.020 0.022 0.024 0.026 0.028
0.28 0.30 0.32 0.34 0.36
6.5 7.0 7.5 8.0
0.40 0.45 0.50 0.55 0.60 0.65 0.70
2.3 2.4 2.5 2.6 2.7

Bound on Leptoquark

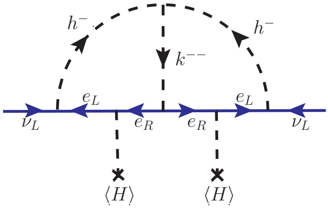


NSI in Zee-Babu Model

- Two $SU(2)_L$ singlet Higgs fields, h^+ and k^{++} are introduced
- The corresponding Lagrangina reads:

$$\mathcal{L} = \mathcal{L}_{SM} + f_{ab}\,\overline{\Psi^C_{aL}}\,\Psi_{bL} h^+ + h_{ab}\,\overline{l^C_{aR}}\,l_{bR}\,k^{++} - \mu h^- h^- k^{++} + h.c. + \mathrm{V}_H$$

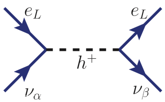
- Majorana neutrino masses are generated by 2-loop diagram:



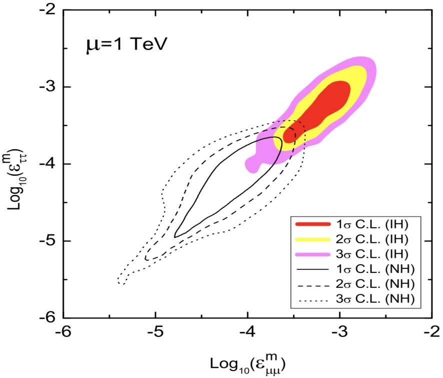
$$M_\nu \approx \frac{1}{(16\pi^2)^2}\frac{8\mu}{M^2}\, f_{ac}\,\tilde{h}_{cd}\,m_c\,m_d\,(f^\dagger)_{db}\,\tilde{I}(\frac{m_k^2}{m_h^2})$$

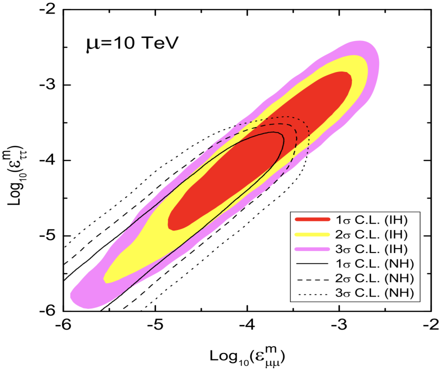
NSI in Zee-Babu Model

The heavy singly charged scalar induces nonstandard neutrino interactions:



$$\varepsilon^{m}_{\alpha\beta} = \varepsilon^{ee}_{\alpha\beta} = \frac{f_{e\beta} f^{*}_{e\alpha}}{\sqrt{2} G_F\, m_h^2}$$





T. Ohlsson et al. (2009)