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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Outline

1. Radiative ν Mass Models
2. Non-Standard Neutrino Interaction
3. Consistency with Neutrino Oscillation Data
4. Collider and Flavor Constraints
5. Numerical Results for NSI
6. Conclusion

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

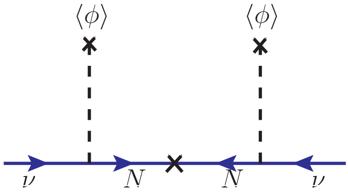
$$\mathcal{L}_Y : y_\nu \bar{\psi}_L \phi \nu_R + h.c.$$

  - $m_\nu \sim 0.1eV$, 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

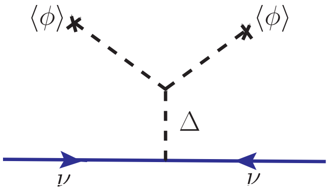
- Schemes for neutrino masses and mixings:
  - Tree-level Seesaw mechanism
  - Radiative schemes

Seesaw Paradigm

- Light neutrino mass is induced via Weingberg's dim-5 operator, $\frac{LL\phi\phi}{\Lambda}$.
- 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:
$N^1 \sim (1, 1, 0)$ $N^3 \sim (1, 3, 0)$

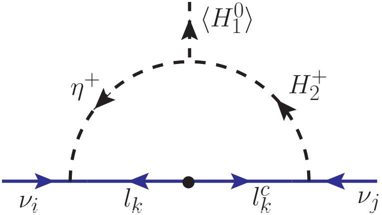


Type II:
ν-mass induced from scalar boson exchange $\Delta \sim (1, 3, 1)$

- The scale of new physics can be rather high

Radiative ν mass generation

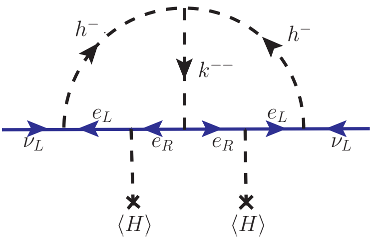
- Neutrino masses are zero at tree level as SM: ν_R may be absent.
- Small, finite Majorana masses are generated at the quantum level.
- Typically new heavy scalar fields introduced violates lepton number, gives rise to neutrino flavor transitions, and lepton flavor violation.
- Simple realization is 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.

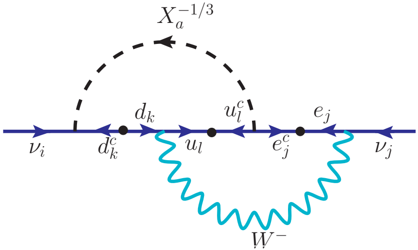
Type I radiative mechanism

- 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



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

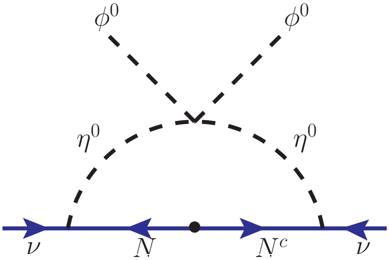
Babu, Julio (2010)

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

- Unknown couplings that involve neutrinos
- Many neutrino mass models naturally lead to NSI to some level
- New physics near TeV scale can generate nonstandard neutrino interactions (NSI)
- NSI effects happen in the neutrino production, ε^S, propagation through matter, ε^m, and the detection processes, ε^D.
- Most important effect of NSI is in neutrino propagation in matter

  Wolfenstein (1978)
- Phenomenological, NSI can be described with an effective four ferimion Lagrangian

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

$\varepsilon^{f\,P}_{\alpha\beta}$ **is the parameter that describes the strength of the NSI**

Nonstandard neutrino interactions

- Matter potential

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

- Note $\varepsilon_{\alpha\beta} \equiv$ real if $\alpha = \beta$

$$\varepsilon_{\alpha\beta}(x) \equiv \sum_{f=e,u,d} \varepsilon_{\alpha\beta}^f \frac{N_f(x)}{N_e(x)} \qquad \varepsilon_{\alpha\beta}^f = \varepsilon_{\alpha\beta}^{f,L} + \varepsilon_{\alpha\beta}^{f,R}$$

$$N_u = 2N_p + N_n \qquad N_d = N_p + 2N_n$$

$$N_p = N_e$$

$$\varepsilon_{\alpha\beta}^p = 2\varepsilon_{\alpha\beta}^u + \varepsilon_{\alpha\beta}^d \qquad \varepsilon_{\alpha\beta}^n = \varepsilon_{\alpha\beta}^u + 2\varepsilon_{\alpha\beta}^d$$

$$\Longrightarrow \quad \varepsilon_{\alpha\beta}(x) = \varepsilon_{\alpha\beta}^e + \varepsilon_{\alpha\beta}^p + y_n \varepsilon_{\alpha\beta}^n \qquad y_n(x) = \frac{N_n(x)}{N_p(x)}$$

- In leptoquark models, one has $\varepsilon_{\alpha\beta}^{u,d}$ only
- Presence of ε_{ij} affect mass ordering and CP violation

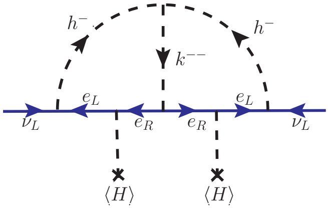
Esteban, Gonzalez-Garcia, Maltoni (2019)

NSI in Zee-Babu Model

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

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

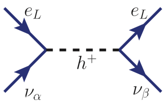
- Majorana neutrino masses are generated by 2-loop diagram:



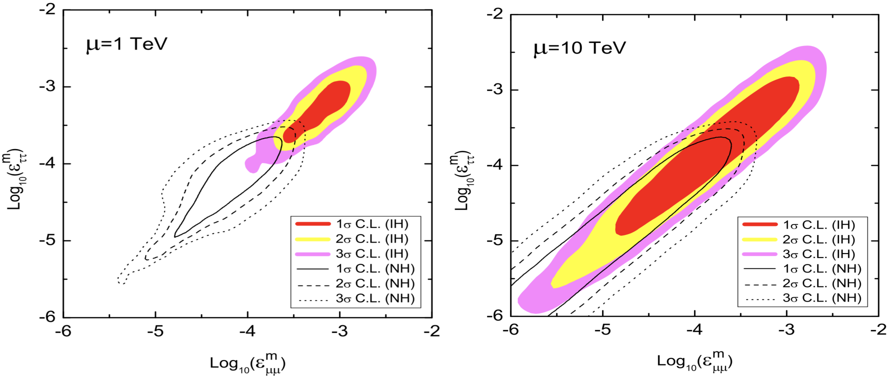
$$M_\nu \approx \frac{1}{(16\pi^2)^2}\frac{8\mu}{M^2}\,f_{ac}\,\tilde{h}_{cd}\,m_c\,m_d\,(f^\dagger)_{db}\,\tilde{I}(\frac{m_k^2}{m_h^2})$$

NSI in Zee-Babu Model

The heavy singly charged scalar induces nonstandard neutrino interactions:



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



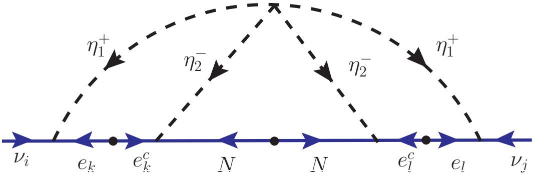
T. Ohlsson et al. (2009)

NSI in KNT Model

- Singlet fermion N and two singlet scalars η_1^+ and η_2^+ are introduced

$$\mathcal{L}_Y = f\, LL\eta_1^+ + g\, e^c N\eta_2^- + \frac{1}{2}M_N NN$$

- η_2^+ and N are odd under Z_2
- Majorana neutrino masses are generated via 3-loop diagram



- Only NSI is from η_1^+

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

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

- The Yukawa lagrangian reads:

$$\mathcal{L}_Y = f^{ab}(\psi^i_{aL}\, C\, \psi^j_{bL})\, \epsilon_{ij}\, \eta^+ + \overline{\psi}_L \tilde{y} H_1 e_R + \overline{\psi}_L y H_2 e_R + h.c.$$

$$V = \mu H_1^i H_2^j \eta^- + h.c. + ...$$

- Mixing between η^+ and H_2^+ :

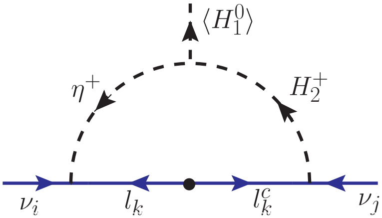
$$\begin{pmatrix} M_2^2 & -\mu \mathrm{v}/\sqrt{2} \\ -\mu \mathrm{v}/\sqrt{2} & M_3^2 \end{pmatrix}, \qquad \sin 2\varphi = \frac{\sqrt{2}\mathrm{v}\mu}{m^2_{h^+} - m^2_{H^+}}$$

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 masses:



$$M_\nu = \kappa \left(f M_l y^T + y M_l f^T \right)$$

$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$

Neutrino masses in the Zee Model

- 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

- Charged current NSI arises via the exchange of $h^{\pm}$

Consistency with Neutrino Oscillation Data

$$M_l = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \qquad y = \begin{pmatrix} 0 & 0 & y_{e\tau} \\ 0 & y_{\mu\mu} & y_{\mu\tau} \\ y_{\tau e} & 0 & y_{\tau\tau} \end{pmatrix}$$

With the choice of parameters:

$$\frac{f_{e\mu}}{f_{\mu\tau}} = 0.42, \quad \frac{f_{e\tau}}{f_{\mu\tau}} = 4.34, \quad \frac{y_{e\tau}}{y_{\tau e}} = 0.003$$

$$\frac{y_{\mu\mu}}{y_{\tau e}} = 0.011, \quad \frac{y_{\mu\tau}}{y_{\tau e}} = -0.013, \quad \frac{y_{\tau\tau}}{y_{\tau e}} = 0.015$$

Parameters	**3σ range**	**Benchmark Points**
$\Delta m^2_{21}(10^{-5})$	6.79 - 8.01	7.32
$\Delta m^2_{23}(10^{-3})$	2.412 - 2.611	2.51
$\sin^2\theta_{12}$	0.275 - 0.350	0.349
$\sin^2\theta_{23}$	0.423 - 0.629	0.54
$\sin^2\theta_{13}$	0.02068 - 0.02463	0.0236

Consistency with Neutrino Oscillation Data

$$y = \begin{pmatrix} y_{ee} & 0 & y_{e\tau} \\ 0 & y_{\mu\mu} & y_{\mu\tau} \\ 0 & 0 & y_{\tau\tau} \end{pmatrix}$$

With the choice of parameters:

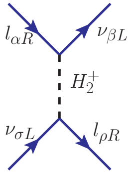
$$\frac{f_{e\mu}}{f_{\mu\tau}} = 4.55, \quad \frac{f_{e\tau}}{f_{\mu\tau}} = 1.79, \quad \frac{y_{e\tau}}{y_{ee}} = -0.049,$$

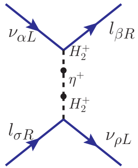
$$\frac{y_{\mu\mu}}{y_{ee}} = 0.99, \quad \frac{y_{\mu\tau}}{y_{ee}} = 0.046 \quad \frac{y_{\tau\tau}}{y_{ee}} = 0.21$$

Parameters	**3σ range**	**Benchmark Points**
$\Delta m^2_{21}(10^{-5})$	6.79 - 8.01	6.95
$\Delta m^2_{23}(10^{-3})$	2.412 - 2.611	2.44
$\sin^2\theta_{12}$	0.275 - 0.350	0.323
$\sin^2\theta_{23}$	0.423 - 0.629	0.581
$\sin^2\theta_{13}$	0.02068 - 0.02463	0.0208

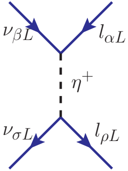
NSI in Zee Model

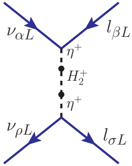
- The singly-charged scalars η^+ and H_2^+ induce NSI at tree level:





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





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

NSI in the Zee Model

- Considering, $y \sim \mathcal{O}(1)$, $m_\tau \sim 1.7\ \text{GeV}$ 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:

$$\varepsilon^m_{\alpha\beta} = -\frac{1}{4\sqrt{2}} \sin^2\varphi \frac{y^*_{\alpha e} y_{\beta e}}{G_F\, m^2_{h^+}}$$

- 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: $\varepsilon_{\alpha\alpha} < 0$

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

$$\Omega = \begin{pmatrix} \omega^{2/3} \\ \omega^{-1/3} \end{pmatrix} \qquad\qquad \chi^{-1/3}$$

- The Yukawa lagrangian reads:

$$\mathcal{L}_Y = y_{ij} L_i d_j^c \Omega + y'_{ij} L_i Q_j \chi^* + h.c.$$

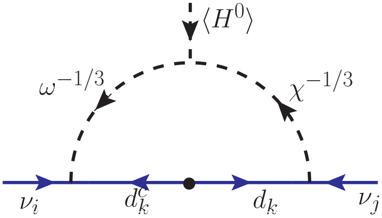
$$V = \mu \Omega \chi^* H^\dagger + h.c.$$

- Mixing between $\omega^{-1/3}$ and $\chi^{-1/3}$:

$$\begin{pmatrix} M_\omega^2 & \mu v \\ \mu v & M_\chi^{-1/3} \end{pmatrix}$$

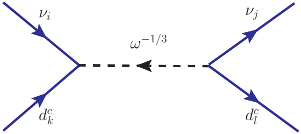
NSI in Leptoquark: Colored Zee Model

- Neutrino masses:



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

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



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

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

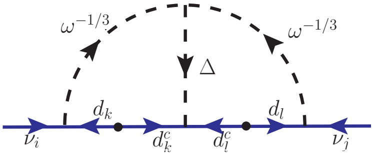
$$\text{For } \frac{N_n(x)}{N_p(x)} = 1 \Longrightarrow \varepsilon_{\alpha\beta}(x) = 3\varepsilon^d_{\alpha\beta}$$

2-loop Leptoquark Model

- Same as before as it assumes $\Omega \sim (3, 2, 1/6)$ and $\chi^{-1/3} \sim (3, 1, -1/3)$
- $\chi^{-1/3}$ coupling is modified

$$\mathcal{L}_y = Y_{ij} L_i d_j^c \Omega + F_{ij} e_i^c u_j^c \chi^{-1/3} + h.c.$$

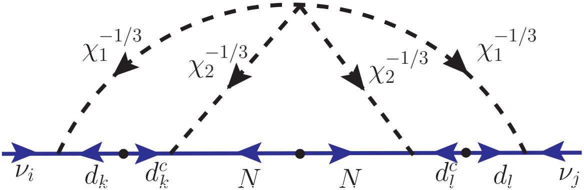
- Note F_{ij} do not lead to NSI.
- M_ν arises at 2-loops: Replace leptons by quarks in Zee-Babu Model



KNT Leptoquark Model

- Replace leptons by quarks

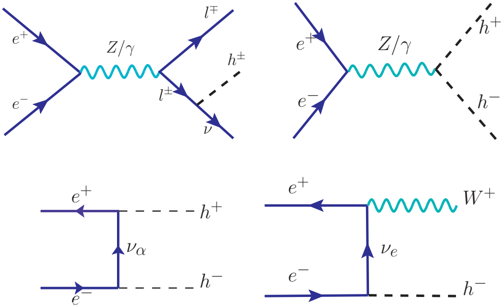
$$\mathcal{L}_y = fLQ\chi_1^{*1/3} + d^c N \chi_2^{-1/3} + \frac{1}{2} M_N NN$$



- $\chi_1^{-1/3}$ cause NSI.

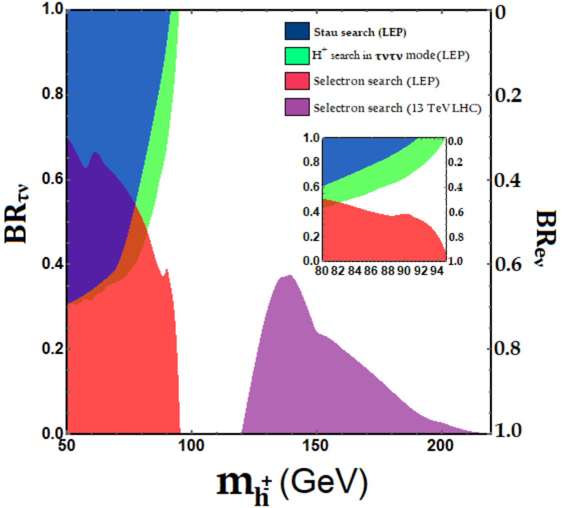
Collider constraints on $h^{\pm}$ mass

- New Physics at sub-TeV scale is highly constrained from direct prompt 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 mechanisms in LEP are:

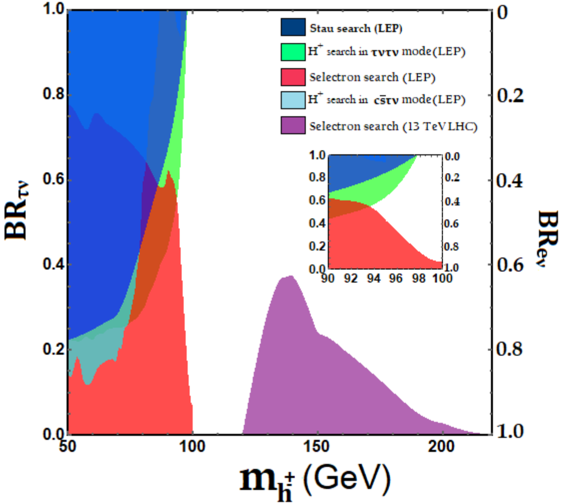


Constraints on Light Charged Scalar

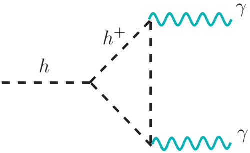
- The lowest charged higgs allowed is 82 GeV with $y_{ee} = 0$.

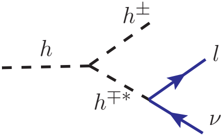


- The lowest charged higgs allowed is 94 GeV with $y_{\alpha e} = 1$.



Constraints from SM Higgs Observables





- The signal strength is expressed as:

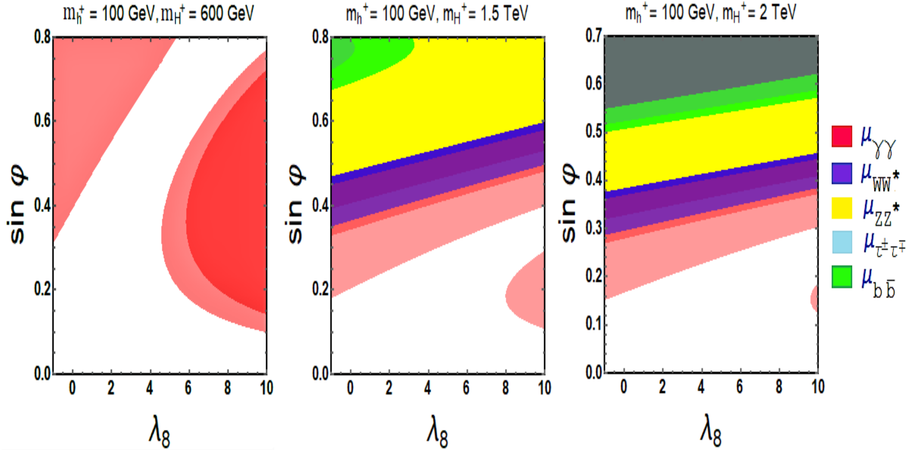
$$\mu_f^i = \frac{\sigma^i \cdot BR_f}{(\sigma^i)_{SM} \cdot (BR_f)_{SM}} = \mu^i \cdot \mu_f$$

- The effective coupling $\mu_{eff}(hh^{\pm}h^{\mp})$ parameterized as:

$$\mu_{eff} = -\sqrt{2}\mu \sin\varphi \cos\varphi + \lambda_3 \mathrm{v} \sin^2\varphi + \lambda_8 \mathrm{v} \cos^2\varphi$$

- λ_3 term is suppressed by $\sin^2\varphi$

Constraints from SM Higgs Observables



Contanct Interaction Constraints on Neutral Higgs

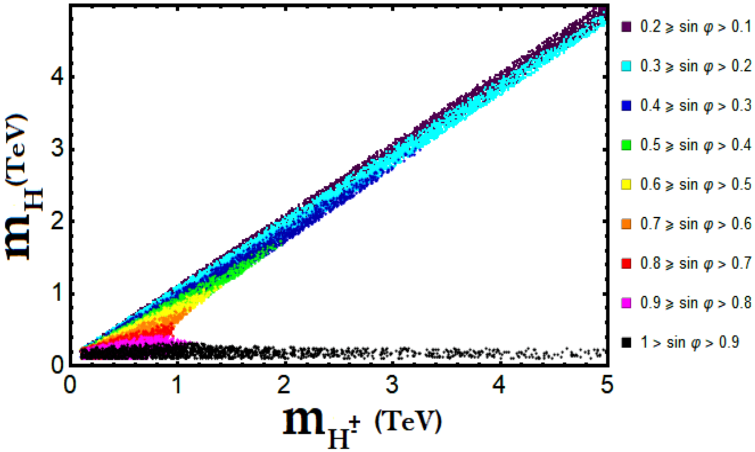
- At LEP experiment, e^+e^- collision above the Z boson mass imposes significant constraints on contact interactions involving e^+e^- and fermion pair.
- An effective Lagrangian has the form:

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

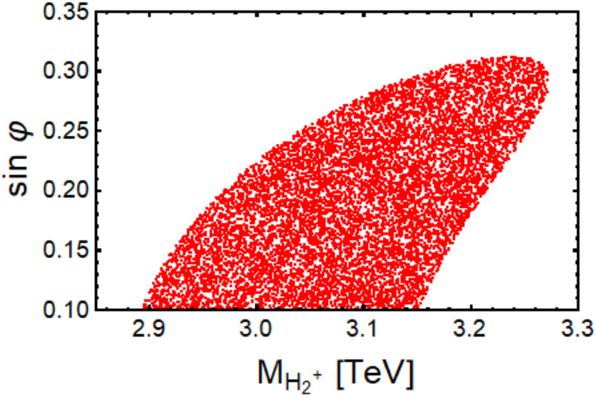
$$\frac{m_H}{|y_{e\mu}|\cos\varphi} > 1.577 \text{ TeV}, \qquad \frac{m_H}{|y_{e\tau}|\cos\varphi} > 438.9 \text{ GeV},$$

$$\frac{m_H}{|y_{ee}|\cos\varphi} > 1.994 \text{ TeV}$$

Bound from EW Precision Constraints



Bound from EW Precision Constraints



Lepton Flavor Violation

- Lepton number(L) is an accidental discrete or Abelian symmetry of the standard model (SM)
- Lepton flavor violation (LFV) is transition between e, μ, τ sectors that violates lepton family number.
- Detection of LFV signals $\Longrightarrow$ clear evidence for BSM

LFV Constraints in Zee Model

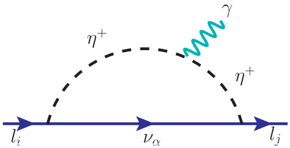
- The presence of the second Higgs doublet gives rise to tree-level trilepton decays $l_i \to l_j l_k l_l$

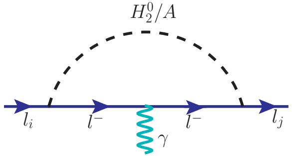
Process	Exp. bound	Constraint
$\mu^- \to e^+ e^- e^-$	Br. $< 1.0 \times 10^{-12}$	$\frac{\lvert y^*_{\mu e} y_{ee} \rvert}{m_H^2} < 6.6 \times 10^{-11}$ GeV^{-2}
$\tau^- \to e^+ e^- e^-$	Br. $< 2.7 \times 10^{-8}$	$\frac{\lvert y^*_{\tau e} y_{ee} \rvert}{m_H^2} < 2.4 \times 10^{-9}$ GeV^{-2}
$\tau^- \to e^+ \mu^- \mu^-$	Br. $< 1.7 \times 10^{-8}$	$\frac{\lvert y^*_{\tau \mu} y_{\mu e} \rvert}{m_H^2} < 2.04 \times 10^{-9}$ GeV^{-2}
$\tau^- \to e^+ e^- \mu^-$	Br. $< 1.8 \times 10^{-8}$	$\frac{\lvert y^*_{\tau \mu} y_{ee} \rvert}{m_H^2} < 2.12 \times 10^{-9}$ GeV^{-2}
$\tau^- \to \mu^+ e^- e^-$	Br. $< 1.5 \times 10^{-8}$	$\frac{\lvert y^*_{\tau e} y_{e\mu} \rvert}{m_H^2} < 1.8 \times 10^{-9}$ GeV^{-2}
$\tau^- \to \mu^+ \mu^- \mu^-$	Br. $< 2.1 \times 10^{-8}$	$\frac{\lvert y^*_{\tau \mu} y_{\mu\mu} \rvert}{m_H^2} < 2.21 \times 10^{-9}$GeV^{-2}
$\tau^- \to \mu^+ e^- \mu^-$	Br. $< 2.7 \times 10^{-8}$	$\frac{\lvert y^*_{\tau \mu} y_{e\mu} \rvert}{m_H^2} < 3 \times 10^{-9}$GeV^{-2}

- These tree-level processes do not restrict the parameter space as much as $l_i \to l_j \gamma$

LFV Constraints in Zee Model

- One of the most constrained cLFV process is the radiative process $l_i \to l_j \gamma$
- This process always arises at loop level



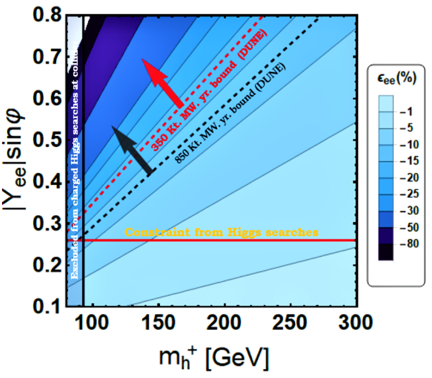


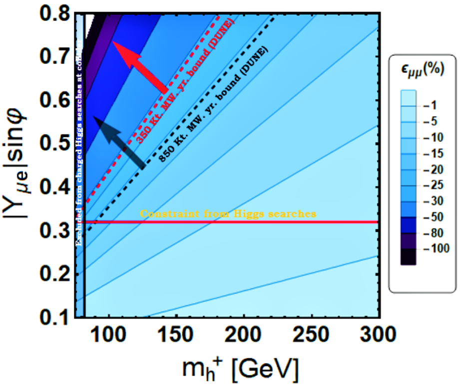
Process	Exp. bound	Constraint
$e \to e\gamma$	$\delta(g-2)_e < 1.34 \times 10^{-12}$	$\frac{\sin^2\varphi}{m^2_{h^+}}(\lvert y_{ee}\rvert^2 + \lvert y_{\mu e}\rvert^2 + \lvert y_{\tau e}\rvert^2) < \frac{5.092 \times 10^{-3}}{\text{GeV}^2}$
$\mu \to \mu\gamma$	$\delta(g-2)_\mu < 3.64 \times 10^{-9}$	$\frac{\sin^2\varphi}{m^2_{h^+}}(\lvert y_{e\mu}\rvert^2 + \lvert y_{\mu\mu}\rvert^2 + \lvert y_{\tau\mu}\rvert^2) < \frac{3.155 \times 10^{-5}}{\text{GeV}^2}$
$\mu \to e\gamma$	Br. $< 4.2 \times 10^{-13}$	$\frac{\sin^4\varphi}{m^4_{h^+}}(\lvert y^*_{ee}y_{e\mu}\rvert^2 + \lvert y^*_{\mu e}y_{\mu\mu}\rvert^2 + \lvert y^*_{\tau e}y_{\tau\mu}\rvert^2) < \frac{9.52 \times 10^{-18}}{\text{GeV}^4}$
$\tau \to e\gamma$	Br. $< 3.3 \times 10^{-8}$	$\frac{\sin^4\varphi}{m^4_{h^+}}(\lvert y^*_{ee}y_{e\tau}\rvert^2 + \lvert y^*_{\mu e}y_{\mu\tau}\rvert^2 + \lvert y^*_{\tau e}y_{\tau\tau}\rvert^2) < \frac{3.91 \times 10^{-12}}{\text{GeV}^4}$
$\tau \to \mu\gamma$	Br. $< 4.4 \times 10^{-8}$	$\frac{\sin^4\varphi}{m^4_{h^+}}(\lvert y^*_{e\mu}y_{e\tau}\rvert^2 + \lvert y^*_{\mu\mu}y_{\mu\tau}\rvert^2 + \lvert y^*_{\tau\mu}y_{\tau\tau}\rvert^2) < \frac{5.25 \times 10^{-12}}{\text{GeV}^4}$

Numerical results for NSI

$$\varepsilon^m_{ee} = -\frac{1}{4\sqrt{2}}\sin^2\varphi\frac{|y_{ee}|^2}{G_F\, m^2_{h^+}}$$

$$\varepsilon^m_{\mu\mu} = -\frac{1}{4\sqrt{2}}\sin^2\varphi\frac{|y_{\mu e}|^2}{G_F\, m^2_{h^+}}$$



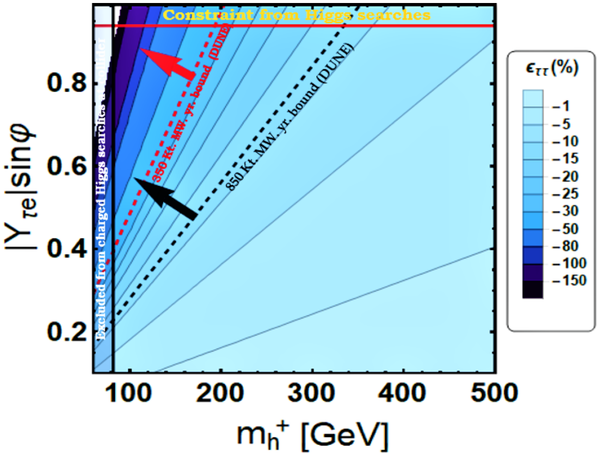


$\varepsilon^{\max}_{ee} \approx 11\%$

$\varepsilon^{\max}_{\mu\mu} \approx 20\%$

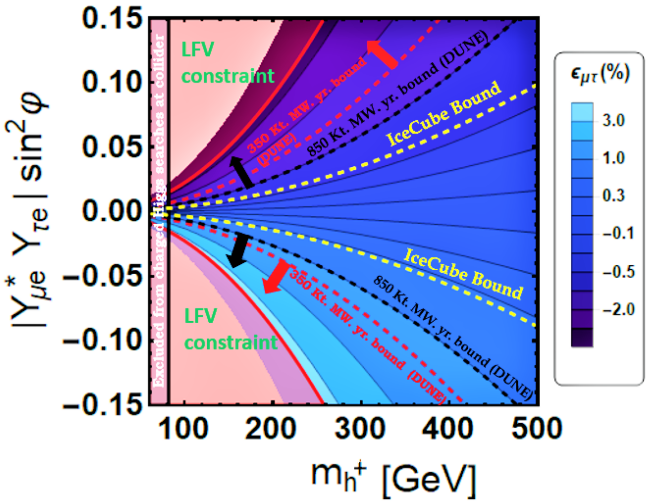
Contd.

$$\varepsilon_{\tau\tau}^{m} = -\frac{1}{4\sqrt{2}}\sin^2\varphi\frac{|y_{\tau e}|^2}{G_F\, m_{h^+}^2}$$



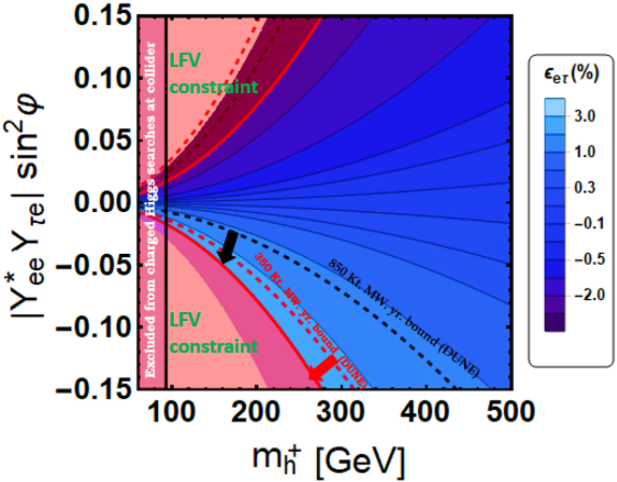
$$\varepsilon_{\tau\tau}^{\max} \approx 150\%$$

Contd.



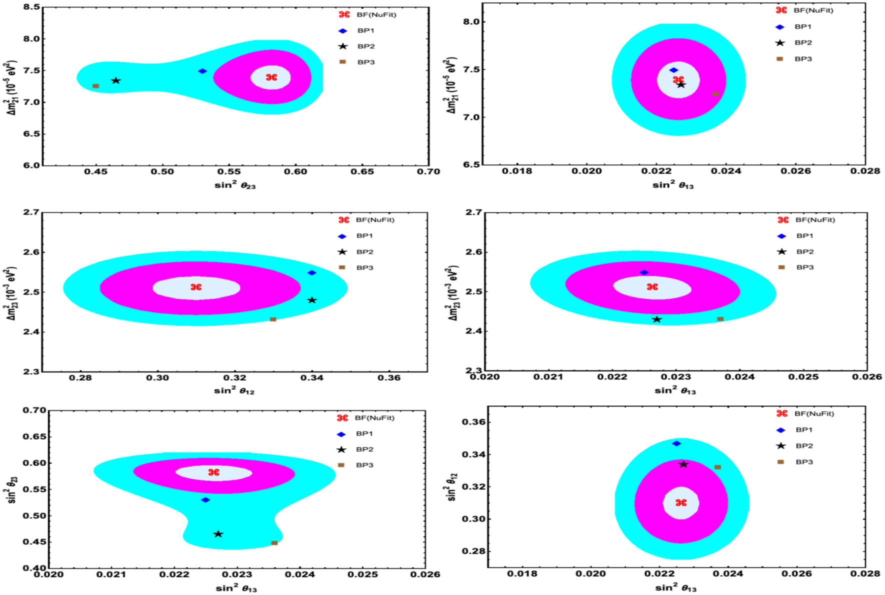
$$\varepsilon_{\mu\tau}^{\max} \approx 2.5\%$$

Contd.



$$\varepsilon_{e\tau}^{\max} \approx 2.5\%$$

Consistency with Neutrino Oscillation Data



Numerical results for Leptoquark Colored Zee Model

- Considering the pair-production channel, the current CMS limits on leptoquark masses are 1.43 TeV for first generation, 1.25 TeV for second generation, and 1.02 TeV for third generation.
- Constraints on Yukawa $y_{\alpha i}$
  - $\mu \to e\gamma$: No significant constraints due to cancellations. This suppresses amplitude by $\frac{m_b^2}{m_\omega^2} << 1$
  - $\mu \to 3e$

$$|y_{13}y_{23}| < 7.6 \times 10^{-3} \qquad M_\omega = 1TeV$$

  - $\mu - e$ conversion

$$|y_{11}y_{21}| < 3.3 \times 10^{-7} \qquad M_\omega = 1TeV$$

- $\tau^- \to e^-\eta$ and $\tau^- \to \mu^-\eta$

$$|y_{12}y_{32}| < 1.2 \times 10^{-2}(\frac{M_\omega}{300GeV})^2 \qquad |y_{22}y_{32}| < 1.0 \times 10^{-2}(\frac{M_\omega}{300GeV})^2$$

Contd.

- Atomic Parity Violation constraints:

$$y_{11} < 0.03 \frac{M_\omega^{2/3}}{100GeV} \qquad y'_{11} < 0.03 \frac{M_\chi}{100GeV}$$

- ϵ_{ee}, $\epsilon_{e\mu}$, and $\epsilon_{e\tau}$ cannot be too large as one y_{e1} factor is order 0.3 for 1 TeV Leptoquark mass

$$\varepsilon_{ee} \approx 0.33\% \quad \varepsilon_{e\mu} = 2.2\% \quad \varepsilon_{e\tau} = 2.2\%$$

$$\varepsilon_{\mu\mu} = 14.7\% \quad \varepsilon_{\mu\tau} \approx 14.7\% \quad \varepsilon_{\tau\tau} \approx 14.7\%$$

Conclusion

- Matter NSI in the radiative mass models has been studied.
- Mass as low as 82 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 (11 % , 20 %, 150 %) for $(\varepsilon_{ee}, \varepsilon_{\mu\mu}, \varepsilon_{\tau\tau})$, while off-diagonal NSIs are allowed to be (-, 2.5 % , 2.5 %) for $(\varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{\mu\tau})$.
- NSI in leptoquark models are studied.
- Radiative neutrino mass model allows parameters which are in good agreement with the neutrino oscillation experiments

Thank You

Dune Projected Limits

NSI Parameter	300 Kt.MW.yr bound ($\leq 90\%$)	850 Kt.MW.yr bound ($\leq 90\%$)
$\varepsilon_{e\mu}$	-0.025 $\rightarrow$ +0.052	-0.017 $\rightarrow$ +0.04
$\varepsilon_{e\tau}$	-0.055 $\rightarrow$ +0.023	-0.042 $\rightarrow$ +0.012
$\varepsilon_{\mu\tau}$	-0.015 $\rightarrow$ +0.013	-0.01 $\rightarrow$ +0.01
ε_{ee}	-0.185 $\rightarrow$ +0.38	-0.13 $\rightarrow$ +0.185
$\varepsilon_{\mu\mu}$	-0.29 $\rightarrow$ +0.39	-0.192 $\rightarrow$ +0.24
$\varepsilon_{\tau\tau}$	-0.36 $\rightarrow$ +0.145	-0.12 $\rightarrow$ +0.095