Non-Standard Interactions in Radiative Neutrino Mass Models

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

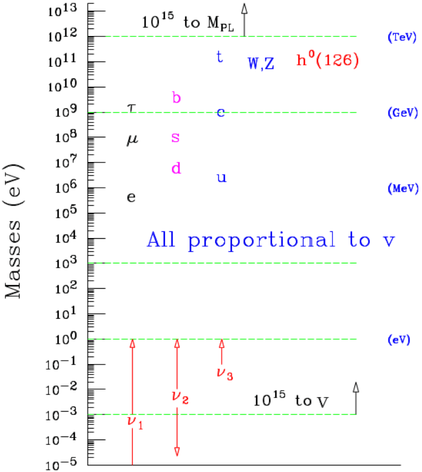
MAX-PLANCK-GESELLSCHAFT

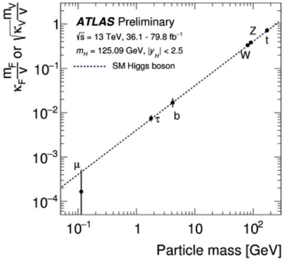
Talk based on:

- K.S. Babu, Bhupal Dev, SJ, Anil Thapa, arXiv:1907.09498
- K.S. Babu, Bhupal Dev, SJ, Yicong Sui, arXiv:1908.02779
- SJ, Ernest Ma, Vishnu P.K., Saikh Saad, arXiv:1910.xxxxx
- K.S. Babu, Dorival Gonçalves, SJ, Pedro Machado, arXiv:1910.xxxxx

Outline

❖ Neutrino Masses and Mixings > New physics beyond SM





$$m_\nu \sim y_\nu^{eff}\ v$$

$$y_\nu^{eff} < 10^{-12}$$

ν mass generation

- "Technically natural" in t'Hooft sense. Small values are protected by symmetry. At a cut-off scale Λ :
  "natural" - $\delta m_f \sim g^2/(16\pi^2)\, m_f \ln(\Lambda^2/m_f^2)$
  "unnatural" - $\delta m_H^2 \sim -\ y_t^2/(8\pi^2)\, \Lambda^2$

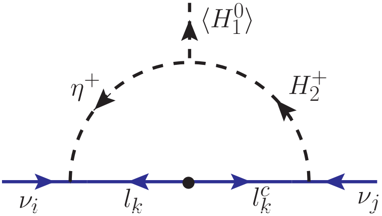
- **Two ways to generate small values naturally :**

- Suppression by integrating out heavy states :
  the higher dimension $1/\Lambda^n$, the lower Λ can be.

- Suppression by loop radiative generation:
  the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.

Radiative ν mass generation

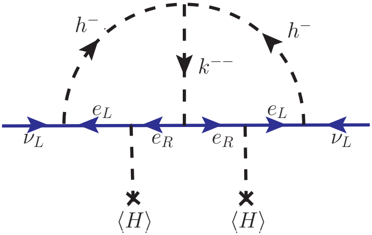
- Neutrino masses are zero at tree level as SM: ν_R may be absent.
- Small, finite Majorana masses are generated at the quantum level.
- Typically new heavy scalar fields introduced violates lepton number, gives rise to neutrino flavor transitions, and lepton flavor violation.
- Simple realization is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

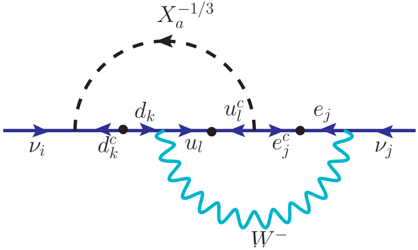
Type I radiative mechanism

- 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



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

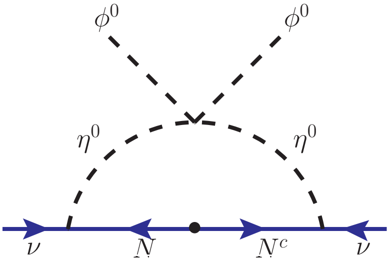
Babu, Julio (2010)

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

- 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

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

$\varepsilon^{f\,P}_{\alpha\beta}$ **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 $\alpha = \beta$

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

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

$$N_p = N_e$$

$$\varepsilon^p_{\alpha\beta} = 2\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta} \qquad \varepsilon^n_{\alpha\beta} = \varepsilon^u_{\alpha\beta} + 2\varepsilon^d_{\alpha\beta}$$

$$\Longrightarrow \quad \varepsilon_{\alpha\beta}(x) = \varepsilon^e_{\alpha\beta} + \varepsilon^p_{\alpha\beta} + Y_n \varepsilon^n_{\alpha\beta}$$

$$Y_n(x) = \frac{N_n(x)}{N_p(x)}$$

Nonstandard neutrino interactions

- These NSI are of great phenomenological interest, as their presence would modify the standard three neutrino oscillation picture.
- The NSI will modify scattering experiments, as the production and detection vertices are corrected; they would also modify neutrino oscillations, primarily through new contributions to matter effects.
- Presence of ε_{ij} affect mass ordering and CP violation
  Esteban, Gonzalez-Garcia, Maltoni (2019)
- There have been a variety of phenomenological studies of NSI in the context of oscillations, but relatively lesser effort has gone into the ultraviolet (UV) completion of models that yield such NSI.
- A major challenge in generating observable NSI in any UV-complete model is that there are severe constraints arising from charged-lepton flavor violation (cLFV).

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

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

- 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^+ :

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

where

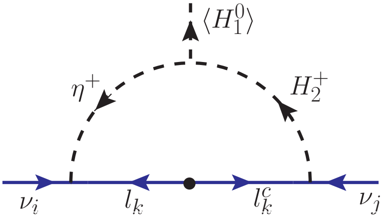
$$h^+ = \cos\varphi \eta^+ + \sin\varphi H_2^+$$
$$H^+ = -\sin\varphi \eta^+ + \cos\varphi H_2^+$$

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



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

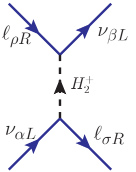
- If $Y \propto M_l$, which happens with a Z_2, then model is ruled out

  Wolfenstein (1980)

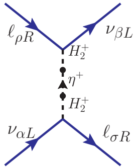
- In general, Y is not proportional to M_l, and the model gives reasonable fit to oscillation data
- NSI arises via the exchange of $h^\pm$ and $H^\pm$

NSI in Zee Model

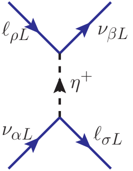
- The singly-charged scalars η^+ and H_2^+ induce NSI at tree level:



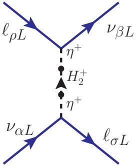
$$\sim \frac{\cos^2\varphi}{m_{H^+}^2} Y_{\alpha\beta} Y^*_{\sigma\rho}$$



$$\sim \frac{\sin^2\varphi}{m_{h^+}^2} Y_{\alpha\beta} Y^*_{\rho\sigma}$$



$$\sim \frac{\cos^2\varphi}{m_{H^+}^2} f_{\alpha\beta} f^*_{\sigma\rho}$$



$$\sim \frac{\sin^2\varphi}{m_{h^+}^2} f_{\alpha\beta} f^*_{\rho\sigma}$$

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 $f \sim 10^{-8} \implies$ NSI effect from f is heavily suppressed
- The effective NSI is:

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

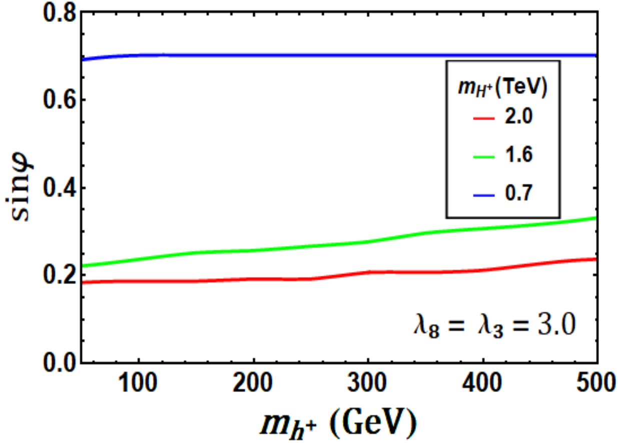
- The relevant Yukawas for NSI:

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

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

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

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



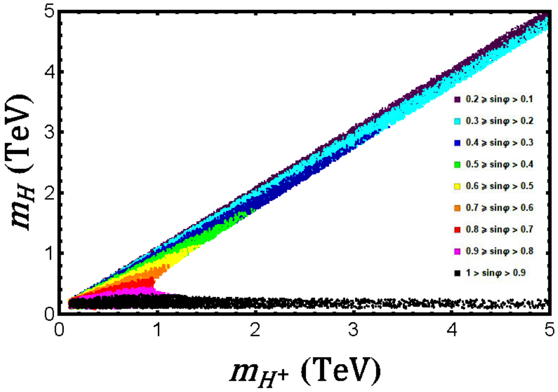
$\sin\varphi < 0.23$ for $m_{H^+} = 2$ TeV

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

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

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.

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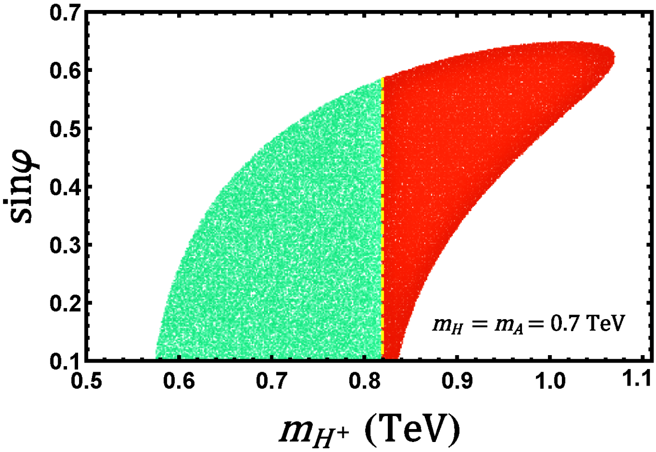
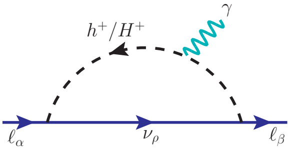
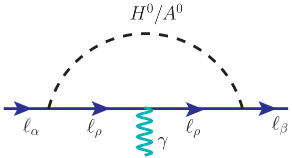


- For $m_H = 0.7\,\text{TeV}$ and $m_h^+ = 100\ \text{GeV}$, the maximum mixing is 0.63.

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

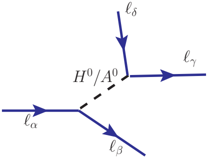




Process	Exp. bound	Constraint
$\mu \to e\gamma$	BR $< 4.2 \times 10^{-13}$	$\lvert Y^\star_{\mu e} Y_{ee}\rvert < 1.05 \times 10^{-3} \left(\frac{m_H}{700\text{ GeV}}\right)^2$
$\tau \to e\gamma$	BR $< 3.3 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{ee}\rvert < 0.69 \left(\frac{m_H}{700\text{ GeV}}\right)^2$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

Contd.

- 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}	$\lvert Y^\star_{\mu e} Y_{ee} \rvert < 3.28 \times 10^{-5} \left(\frac{m_H}{700\text{ GeV}}\right)^2$
$\tau^- \to e^+ e^- e^-$	BR < 1.4×10^{-8}	$\lvert Y^\star_{\tau e} Y_{ee} \rvert < 9.05 \times 10^{-3} \left(\frac{m_H}{700\text{ GeV}}\right)^2$
$\tau^- \to e^+ e^- \mu^-$	BR < 1.1×10^{-8}	$\lvert Y^\star_{\tau e} Y_{\mu e} \rvert < 5.68 \times 10^{-3} \left(\frac{m_H}{700\text{ GeV}}\right)^2$

- 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:

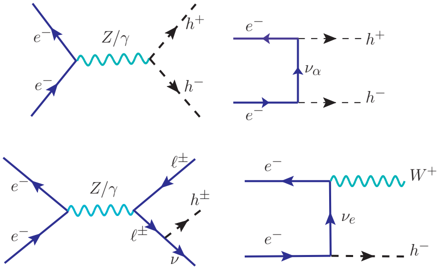
$$\mathcal{L}_{eff} = \frac{4\pi}{\Lambda^2(1+\delta_{ef})} \sum_{i,j=L,R} \eta^f_{ij} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j)$$

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

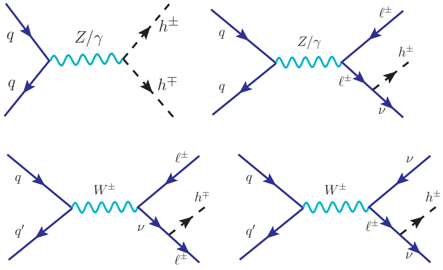
Process	LEP bound	Constraint
$e^+e^- \to e^+e^-$	$\Lambda^-_{LR/RL} > 10$ TeV	$\frac{m_H}{\lvert Y_{ee}\rvert} > 1.99$ TeV
$e^+e^- \to \mu^+\mu^-$	$\Lambda^-_{LR/RL} > 7.9$ TeV	$\frac{m_H}{\lvert Y_{\mu e}\rvert} > 1.58$ TeV
$e^+e^- \to \tau^+\tau^-$	$\Lambda^-_{LR/RL} > 2.2$ TeV	$\frac{m_H}{\lvert Y_{\tau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

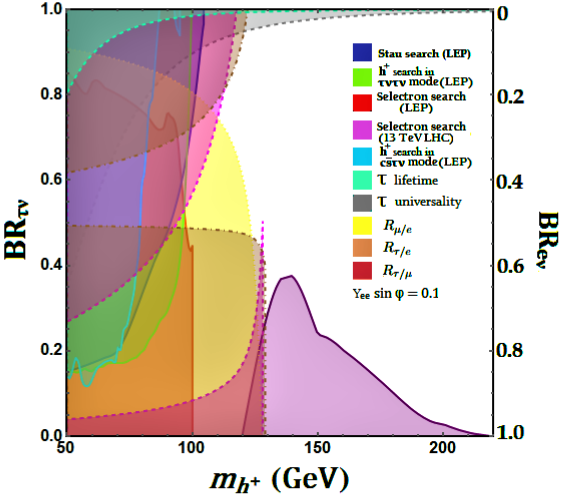


Dominant production in LEP



Dominant production in LHC

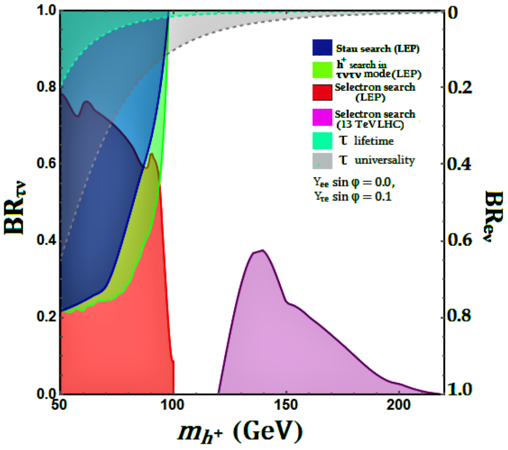
- $BR_{\tau\nu} + BR_{e\nu} = 1$ ($BR_{\mu\nu} \approx 0$) to avoid stringent limit from muon decay.



- The lowest charged higgs mass allowed is 110 GeV.

Contd.

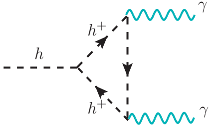
- $Y_{ee} \sin\varphi = 0 \Rightarrow$ no h^+ production with W boson $\Rightarrow$

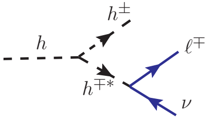


- The lowest charged higgs mass allowed is 96 GeV.

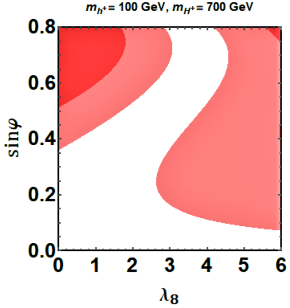
Constraints from Higgs Precision data

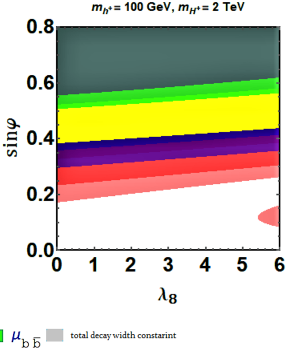
- Light charged scalar is leptophilic $\Rightarrow$ production rate not affected
- New contribution to loop-induced $h \to \gamma\gamma$



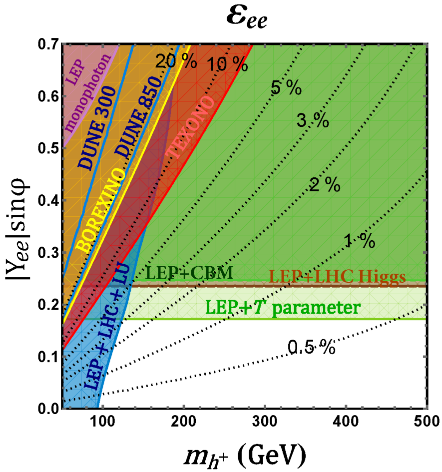


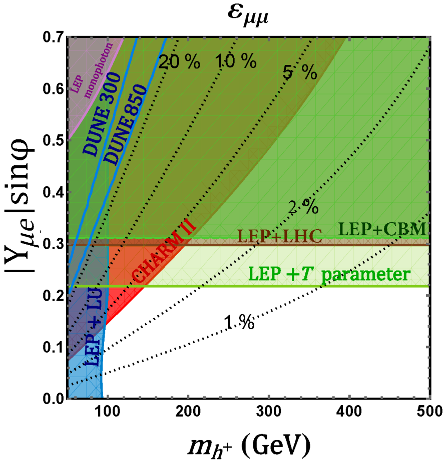
$$\lambda_{hh^+h^-} = -\sqrt{2}\mu \sin\varphi \cos\varphi + \lambda_3 v \sin^2\varphi + \lambda_8 v \cos^2\varphi$$





Numerical results for NSI





$\varepsilon_{ee}^{\max} \approx 3\%$ $\varepsilon_{\mu\mu}^{\max} \approx 3.8\%$

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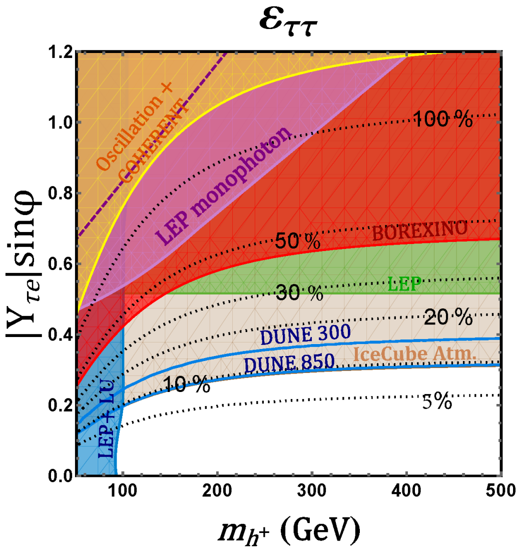

$\varepsilon_{\tau\tau}^{\max} \approx 9.3\%$

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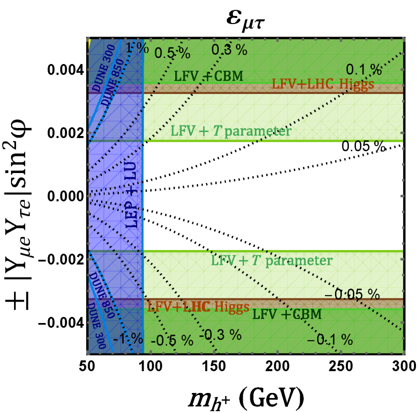
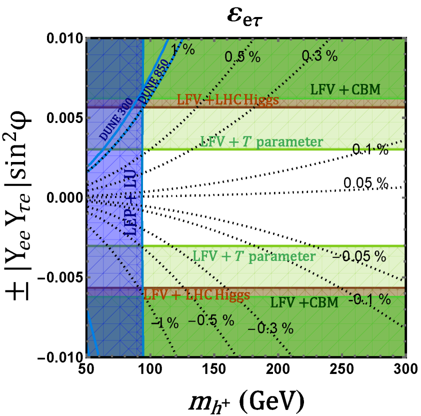


$\varepsilon_{\mu\tau}^{\max} \approx 2.5\%$



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

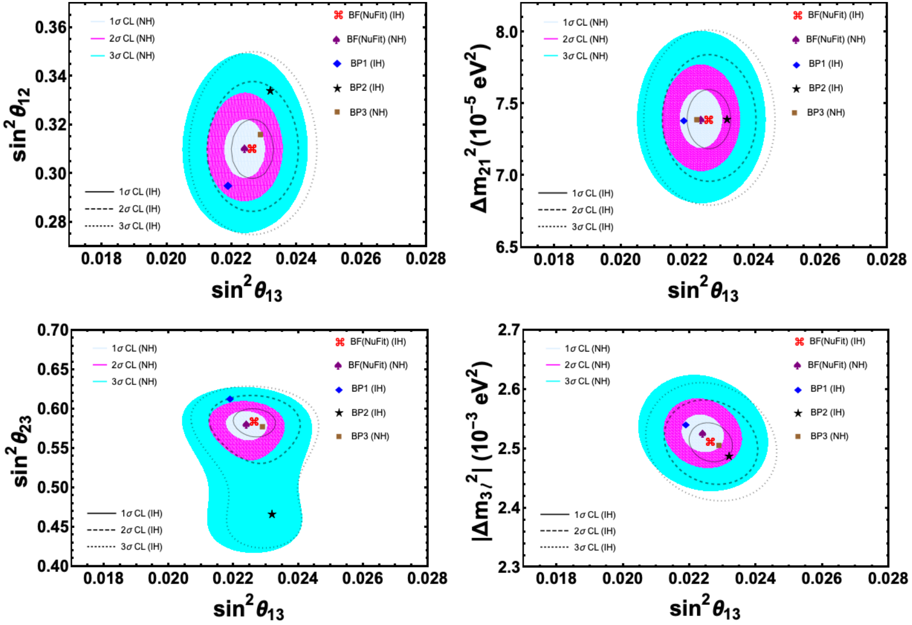
Consistency with Neutrino Oscillation Data

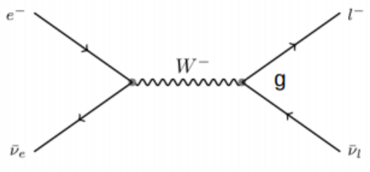
$$\begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}, \begin{pmatrix} 0 & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & 0 & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}, \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} &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

BPI BPII BPII

Oscillation parameters	3σ **allowed range from** `NuFit4`	**Model prediction**		
		BP I (IH)	BP II (IH)	BP III (NH)
$\Delta m^2_{21}(10^{-5}\ \mathrm{eV}^2)$	6.79 - 8.01	7.388	7.392	7.390
$\Delta m^2_{23}(10^{-3}\ \mathrm{eV}^2)$(IH)	2.412 - 2.611	2.541	2.488	-
$\Delta m^2_{31}(10^{-3}\ \mathrm{eV}^2)$(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)
$\sin^2\theta_{12}$
$\sin^2\theta_{13}$
Δm^2_{21} (10^{-5} eV^2)
$\sin^2\theta_{23}$
$|\Delta m^2_{3l}|$ (10^{-3} eV^2)
0.018
0.020
0.022
0.024
0.026
0.028
0.36
0.34
0.32
0.30
0.28
8.0
7.5
7.0
6.5
0.70
0.65
0.60
0.55
0.50
0.45
0.40
2.7
2.6
2.5
2.4
2.3

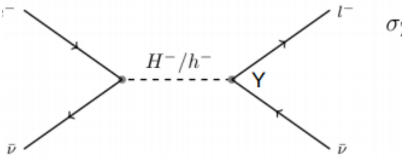


S. L. Glashow 1960

$$\sigma_{\text{Glashow}}(s) \sim \Gamma_W^2\, \mathrm{BR}(W^- \to \bar{\nu}_e e^-)\mathrm{BR}(W^- \to \mathrm{All}) \times \frac{s/m_W^2}{(s-m_W^2)^2 + (m_W\Gamma_W)^2}$$

@ resonance, becomes dominant

$$-\mathcal{L}_Y \supset f_{\alpha\beta} L_\alpha^i L_\beta^j \epsilon_{ij}\eta^+ + \widetilde{Y}_{\alpha\beta}\widetilde{H}_1^i L_\alpha^j \ell_\beta^c \epsilon_{ij} + Y_{\alpha\beta}\widetilde{H}_2^i L_\alpha^j \ell_\beta^c \epsilon_{ij} + \mathrm{H.c.}$$



Zee burst

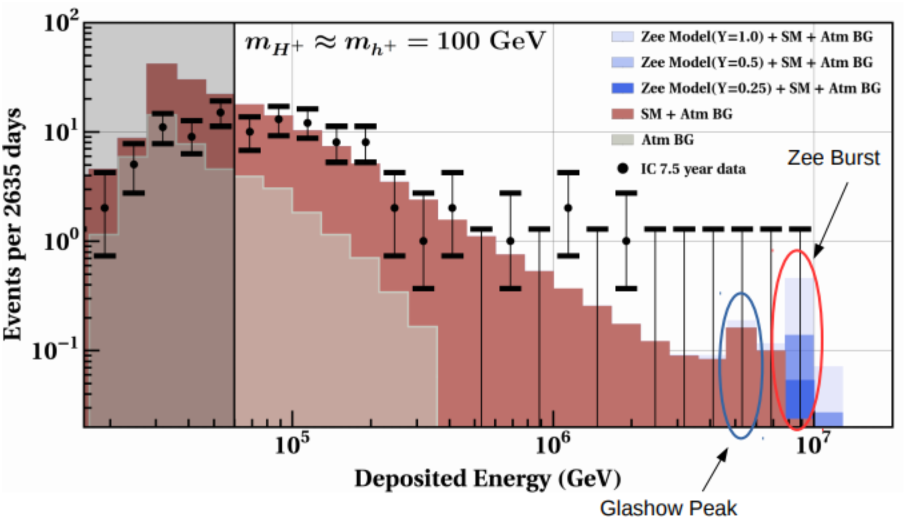
$$\sigma_{\text{Zee}}(s) \sim \Gamma_X^2\, \mathrm{BR}(X^- \to \bar{\nu}_\alpha e^-)\mathrm{BR}(X^- \to \mathrm{all}) \times \frac{s/m_X^2}{(s-m_X^2)^2 + (m_X\Gamma_X)^2}$$

$$\Gamma_X = \sum_{\alpha\beta} |Y_{\alpha\beta}|^2 \sin^2\varphi\, m_X/16\pi$$

$$E_\nu = m^2/2m_e \approx 6.3\ \mathrm{PeV},\ 9.8\ \mathrm{PeV}$$

m=80.4 GeV (→ 6.3 PeV) m=100 GeV (→ 9.8 PeV)

Zee-burst: Glashow like Spectrum

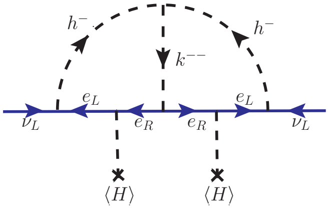


NSI in Zee-Babu Model

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

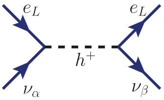
$$\mathcal{L} = \mathcal{L}_{SM} + f_{ab}\,\overline{\Psi^C_{aL}}\,\Psi_{bL} h^+ + h_{ab}\,\overline{l^C_{aR}}\,l_{bR}\,k^{++} - \mu h^- h^- k^{++} + h.c. + \mathrm{V}_H$$

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

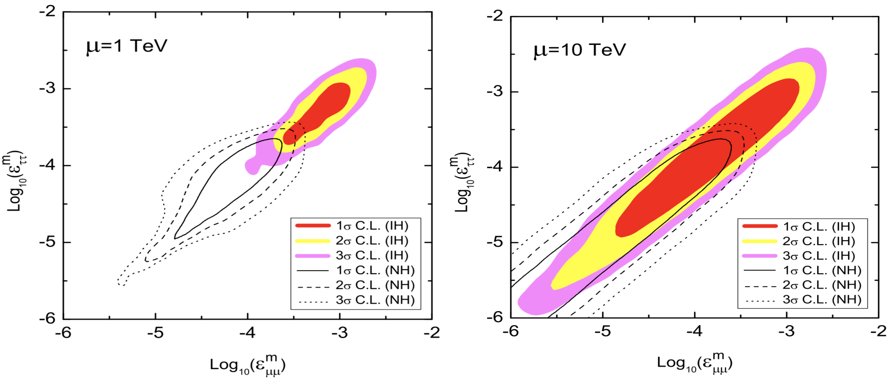


$$M_\nu \approx \frac{1}{(16\pi^2)^2}\frac{8\mu}{M^2}\,f_{ac}\,\tilde{h}_{cd}\,m_c\,m_d\,(f^\dagger)_{db}\,\tilde{I}(\frac{m_k^2}{m_h^2})$$

The heavy singly charged scalar induces nonstandard neutrino interactions:



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



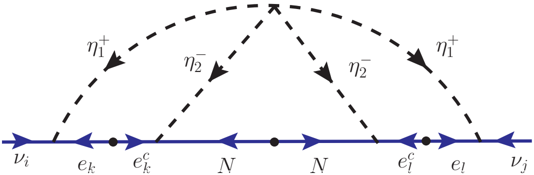
T. Ohlsson et al. (2009)

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^+

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

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

- The Yukawa lagrangian reads:

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

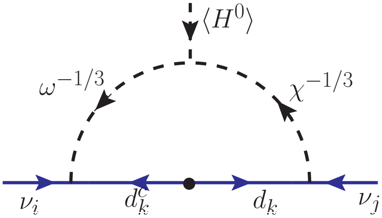
$$V = \mu \Omega \chi^* H^\dagger + h.c.$$

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

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

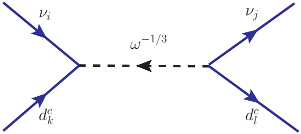
NSI in Leptoquark: Colored Zee Model

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



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

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

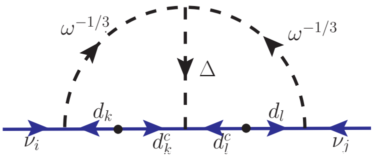
For $\frac{N_n(x)}{N_p(x)} = 1 \Longrightarrow \varepsilon_{\alpha\beta}(x) = 3\varepsilon^d_{\alpha\beta}$

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

$$\mathcal{L}_y = Y_{ij} L_i d^c_j \Omega + F_{ij} e^c_i u^c_j \chi^{-1/3} + h.c.$$

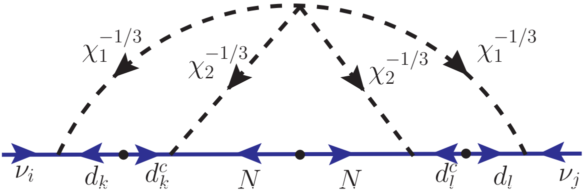
- Note F_{ij} do not lead to NSI.
- M_ν arises at 2-loops: Replace leptons by quarks in Zee-Babu Model



KNT Leptoquark Model

- Replace leptons by quarks

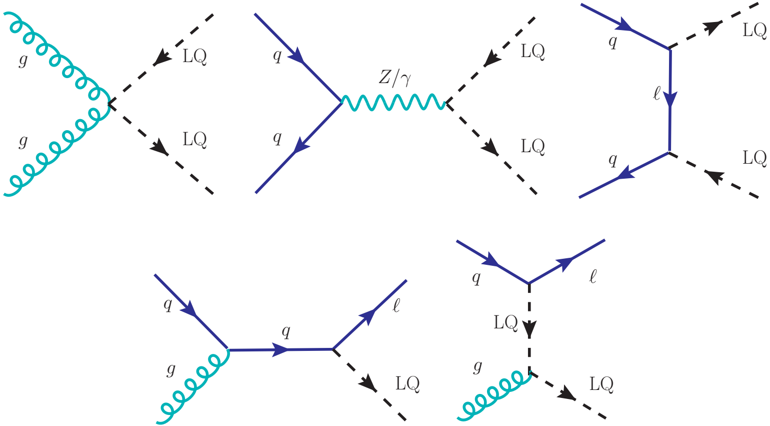
$$\mathcal{L}_y = fLQ\chi_1^{*1/3} + d^c N\chi_2^{-1/3} + \frac{1}{2}M_N NN$$



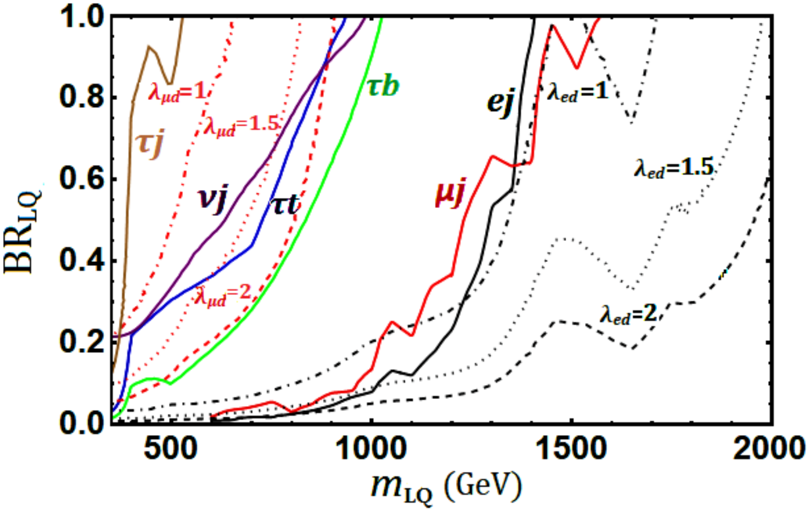
- $\chi_1^{-1/3}$ cause NSI.

Collider constraints on Leptoquarks

Feynman diagrams for pair- and single-production of LQ at the LHC:



Constraints on Leptoquarks



Numerical results for Leptoquark Colored Zee Model

- 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.

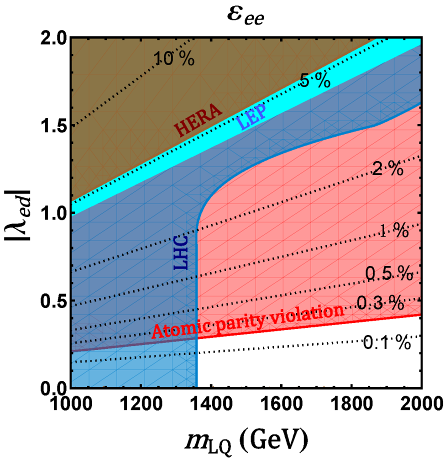
- Atomic Parity Violation constraints:

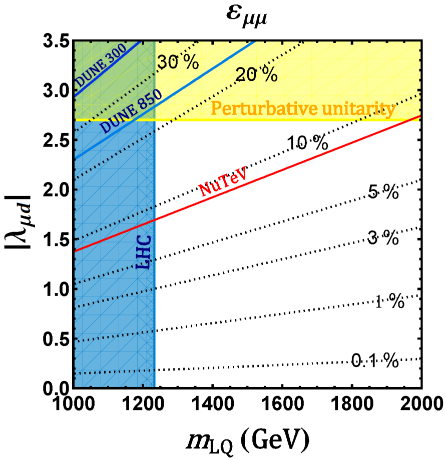
$$y_{11} < 0.03 \frac{M_\omega^{2/3}}{100GeV} \qquad y'_{11} < 0.03 \frac{M_\chi}{100GeV}$$

- 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

$$\varepsilon_{ee} \approx 0.33\% \quad \varepsilon_{e\mu} = 10^{-7}\% \quad \varepsilon_{e\tau} = 0.36\%$$
$$\varepsilon_{\mu\mu} = 21.6\% \quad \varepsilon_{\mu\tau} \approx 0.43\% \quad \varepsilon_{\tau\tau} \approx 34.3\%$$

Numerical results for NSI (Doublet)





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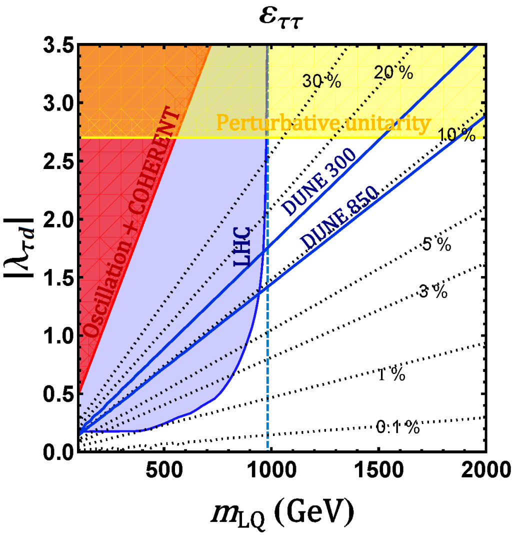
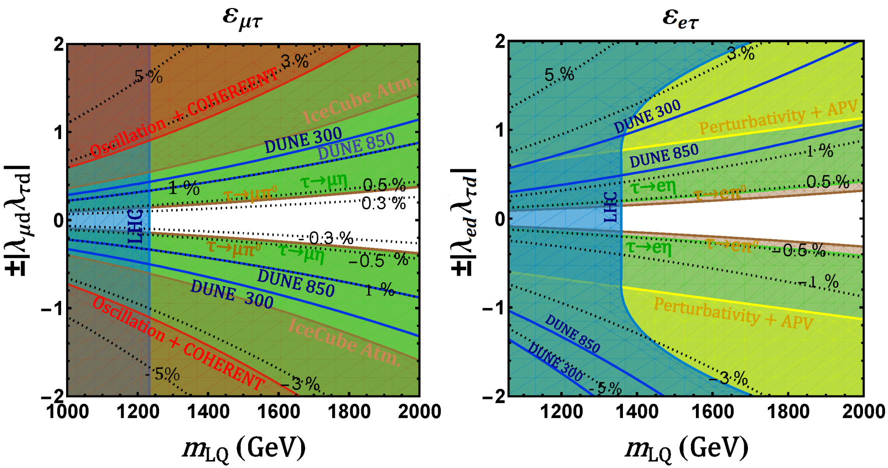
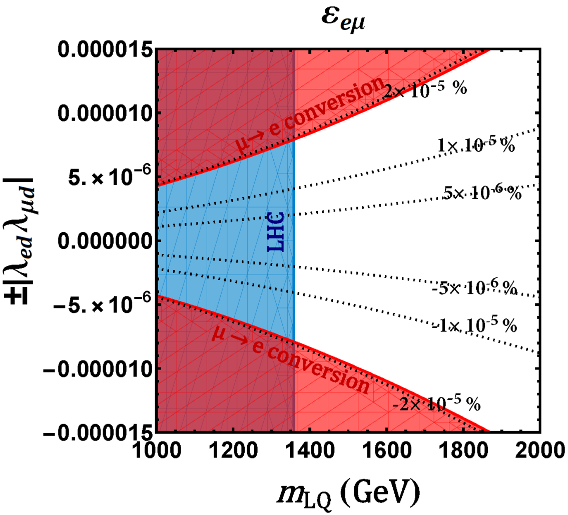


$\varepsilon_{\tau\tau}^{\rm max} \approx 34.3\%$

Numerical results for NSI (Doublet)

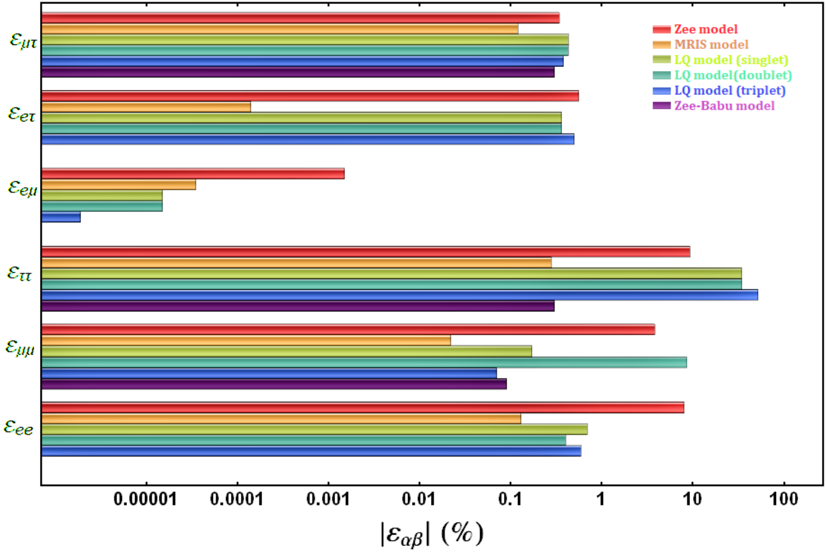


Contd.



εeμ
0.000015
0.000010
5.×10⁻⁶
0.000000
−5.×10⁻⁶
−0.000010
−0.000015
1000
1200
1400
1600
1800
2000
±|λedλμd|
mLQ (GeV)
μ→ e conversion
μ→ e conversion
LHC
2×10⁻⁵ %
1×10⁻⁵ %
5×10⁻⁶ %
-5×10⁻⁶ %
-1×10⁻⁵ %
-2×10⁻⁵ %

Summary of Maximum NSI



Term	$\mathcal{O}$	Model	Loop level	$\mathcal{S}/\mathcal{F}$	New particles	Max NSI @ tree-level $\lvert\varepsilon_{ee}\rvert$	$\lvert\varepsilon_{\mu\mu}\rvert$	$\lvert\varepsilon_{\tau\tau}\rvert$	$\lvert\varepsilon_{e\mu}\rvert$	$\lvert\varepsilon_{e\tau}\rvert$	$\lvert\varepsilon_{\mu\tau}\rvert$
$L\ell^c\Phi^*$	$\mathcal{O}_2^2$	Zee [14]	1	$\mathcal{S}$	$\eta^+(\mathbf{1},\mathbf{1},1)$, $\Phi_2(\mathbf{1},\mathbf{2},1/2)$	0.08	0.038	0.093	$\mathcal{O}(10^{-5})$	0.0056	0.0034
$LL\eta$	$\mathcal{O}_9$	Zee-Babu [15, 16]	2	$\mathcal{S}$	$h^+(\mathbf{1},\mathbf{1},1)$, $k^{++}(\mathbf{1},\mathbf{1},2)$	0	0.0009	0.003	0	0	0.003
	$\mathcal{O}_9$	KNT [36]	3	$\mathcal{S}$ $\mathcal{F}$	$\eta_1^+(\mathbf{1},\mathbf{1},1)$, $\eta_2^+(\mathbf{1},\mathbf{1},1)$ $N(\mathbf{1},\mathbf{1},0)$						
	$\mathcal{O}_9$	1S-1S-1F [55]	3	$\mathcal{S}$ $\mathcal{F}$	$\eta_1(\mathbf{1},\mathbf{1},1)$, $\eta_2(\mathbf{1},\mathbf{1},3)$ $F(\mathbf{1},\mathbf{1},2)$						
	$\mathcal{O}_2^1$	1S-2VLL [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\eta(\mathbf{1},\mathbf{1},1)$ $\Psi(\mathbf{1},\mathbf{2},-3/2)$						
$L\ell^c\phi^*$	$\mathcal{O}_3'$	AKS [38]	3	$\mathcal{S}$ $\mathcal{F}$	$\Phi_2(\mathbf{1},\mathbf{2},1/2)$, $\eta^+(\mathbf{1},\mathbf{1},1)$, $\eta^0(\mathbf{1},\mathbf{1},0)$ $N(\mathbf{1},\mathbf{1},0)$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$
—	$\mathcal{O}_{d=15}$	Cocktail [39]	3	$\mathcal{S}$	$\eta^+(\mathbf{1},\mathbf{1},1)$, $k^{++}(\mathbf{1},\mathbf{1},2)$, $\Phi_2(\mathbf{1},\mathbf{2},1/2)$	0	0	0	0	0	0
W/Z	$\mathcal{O}_2'$	MRIS [43]	1	$\mathcal{F}$	$N(\mathbf{1},\mathbf{1},0)$, $S(\mathbf{1},\mathbf{1},0)$	0.0013	$\mathcal{O}(10^{-4})$	0.0028	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$	0.0012
$L\Omega d^c$	$\mathcal{O}_3^8$	LQ variant of Zee [30]	1	$\mathcal{S}$	$\Omega(\mathbf{3},\mathbf{2},1/6)$, $\chi(\mathbf{3},\mathbf{1},-1/3)$	0.004	0.216	0.343	$\mathcal{O}(10^{-7})$	0.0036	0.0043
$(LQ\chi^*)$	$\mathcal{O}_8^4$	2LQ-1LQ [33]	2	$\mathcal{S}$	$\Omega(\mathbf{3},\mathbf{2},1/6)$, $\chi(\mathbf{3},\mathbf{1},-1/3)$	(0.0069)	(0.0086)				
$L\Omega d^c$	$\mathcal{O}_3^3$	2LQ-1VLQ [34]	2	$\mathcal{S}$ $\mathcal{F}$	$\Omega(\mathbf{3},\mathbf{2},1/6)$ $U(\mathbf{3},\mathbf{1},2/3)$	0.004	0.093	0.093	$\mathcal{O}(10^{-7})$	0.0036	0.0043
	$\mathcal{O}_3^6$	2LQ-3VLQ [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\Omega(\mathbf{3},\mathbf{2},1/6)$ $\Sigma(\mathbf{3},\mathbf{3},2/3)$						
	$\mathcal{O}_8^2$	2LQ-2VLL [31]	2	$\mathcal{S}$ $\mathcal{F}$	$\Omega(\mathbf{3},\mathbf{2},1/6)$ $\psi(\mathbf{1},\mathbf{2},-1/2)$						
	$\mathcal{O}_8^3$	2LQ-2VLQ [31]	2	$\mathcal{S}$ $\mathcal{F}$	$\Omega(\mathbf{3},\mathbf{2},1/6)$ $\xi(\mathbf{3},\mathbf{2},7/6)$						
$L\Omega d^c$ $(LQ\bar{\rho})$	$\mathcal{O}_3^9$	Triplet-Doublet LQ [31]	1	$\mathcal{S}$	$\rho(\mathbf{3},\mathbf{3},-1/3)$, $\Omega(\mathbf{3},\mathbf{2},1/6)$	0.0059	0.0249	0.517	$\mathcal{O}(10^{-8})$	0.0050	0.0038
$LQ\chi^*$	$\mathcal{O}_{11}$	LQ/DQ variant Zee-Babu [32]	2	$\mathcal{S}$	$\chi(\mathbf{3},\mathbf{1},-1/3)$, $\Delta(\mathbf{6},\mathbf{1},-2/3)$	0.0069	0.0086	0.093	$\mathcal{O}(10^{-7})$	0.0036	0.0043
	$\mathcal{O}_{11}$	Angelic [35]	2	$\mathcal{S}$ $\mathcal{F}$	$\chi(\mathbf{3},\mathbf{1},1/3)$ $F(\mathbf{8},\mathbf{1},0)$						
	$\mathcal{O}_{11}$	LQ variant of KNT [37]	3	$\mathcal{S}$ $\mathcal{F}$	$\chi(\mathbf{3},\mathbf{1},-1/3)$, $\chi_2(\mathbf{3},\mathbf{1},-1/3)$ $N(\mathbf{1},\mathbf{1},0)$						
	$\mathcal{O}_3^4$	1LQ-2VLQ [31]	1	$\mathcal{S}$ $\mathcal{F}$	$\chi(\mathbf{3},\mathbf{1},-1/3)$ $\mathcal{Q}(\mathbf{3},\mathbf{2},-5/6)$						
$Lu^c\delta$ $(LQ\bar{\rho})$	$\tilde{\mathcal{O}}_1$	**3LQ-2LQ-1LQ (New)**	1	$\mathcal{S}$	$\bar{\rho}(\bar{\mathbf{3}},\mathbf{3},1/3)$, $\delta(\mathbf{3},\mathbf{2},7/6)$, $\xi(\mathbf{3},\mathbf{1},2/3)$	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	$\mathcal{S}$	$\delta(\mathbf{3},\mathbf{2},7/6)$, $\Omega(\mathbf{3},\mathbf{2},1/6)$, $\bar{\Delta}(\mathbf{6}^*,\mathbf{3},-1/3)$	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	$\mathcal{S}$ $\mathcal{F}$	$\bar{\rho}(\bar{\mathbf{3}},\mathbf{3},-1/3)$ $\mathcal{Q}(\mathbf{3},\mathbf{2},-5/6)$	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

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 34.3$\%$
- 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