MAX-PLANCK-GESELLSCHAFT

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Non-Standard Interactions in Radiative Neutrino Mass Models

Sudip Jana
Max-Planck-Institut für Kernphysik

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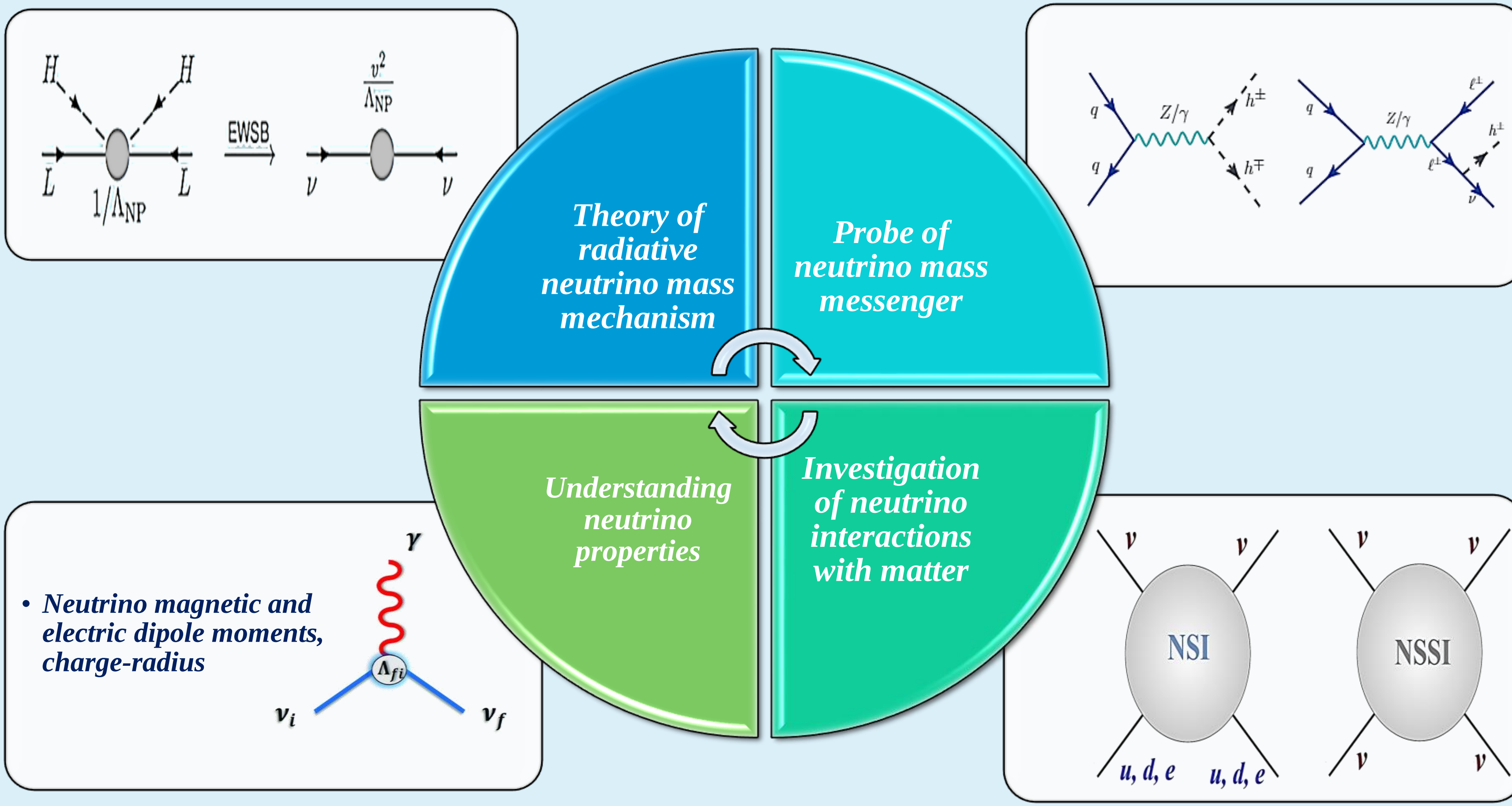
Based on:

1. arXiv: 1907.09498 [hep-ph], ***JHEP 03 (2020) 006*** , *in collaboration with* K.S. Babu, B. Dev, A. Thapa
2. arXiv: 1908.02779 [hep-ph], ***Phys.Rev.Lett. 124 (2020) 4, 041805***, *in collaboration with* K.S. Babu, B. Dev, Y. Sui
3. arXiv: 2007.04291 [hep-ph], ***JHEP 10 (2020) 040***, *in collaboration with* K.S. Babu, Manfred Lindner

Outline


Theory of radiative neutrino mass mechanism
Probe of neutrino mass messenger
Understanding neutrino properties
Investigation of neutrino interactions with matter
EWSB
$1/\Lambda_{NP}$
$\frac{v^2}{\Lambda_{NP}}$
H
L
ν
Z/γ
q
$h^\pm$
$h^\mp$
$\ell^\pm$
• Neutrino magnetic and electric dipole moments, charge-radius
γ
Λ_{fi}
ν_i
ν_f
NSI
NSSI
ν
u, d, e

Neutrino Oscillations: Harbinger of New Physics

Neutrino flavor oscillations have been firmly established from:

- Solar neutrinos (Homestake, SAGE, GALLEX, Kamiokande, Super-Kamiokande, SNO, Borexino,…)
- Atmospheric neutrinos (Super-Kamiokande, IceCube,…)
- Reactor neutrinos (KamLand, DayaBay, RENO, DoubleChooz …)
- Accelerator neutrinos (T2K, MINOS, NOVA…)

Oscillations can happen only if neutrinos have non-zero masses

- $\boldsymbol{\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\,\nu_i,}\qquad \alpha = (e, \mu, \tau)$
- **U is assumed to be unitary (Needs experimental check!)**

*“**Majorana phases**” (α, β) do not affect the oscillation probabilities, while the single “**Dirac phase**” δ does*

CP phase δ is unknown

- Recent **T2K** result (Nature, 2020): $\boldsymbol{\delta = -1.89^{+0.70}_{-0.58}}$

*All **three mixing angles** and **two mass splitting** have been measured with few percent precision*

There is a mass ordering ambiguity, normal ordering vs. inverted ordering (Sign of Δm^2_{32} is currently unknown)

Unitarity of U_{PMNS} remains to be tested

Flavor eigenstate

PMNS matrix

Mass eigenstate

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{Atmospheric term}} \underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}}_{\text{Reactor term}} \underbrace{\begin{pmatrix}\cos\theta_{12} & \cos\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar term}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Oscillation parameters:
  - Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
  - Mass squared differences: $\Delta m^2_{21}, \Delta m^2_{32}$ and the sign of Δm^2_{32}
  - Complex phase: $\delta \equiv \delta_{CP}$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13}\\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23}\\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23}\end{pmatrix}\cdot P$$

$$s_{ij} \equiv \sin(\theta_{ij}),\ c_{ij} \equiv \cos(\theta_{ij}),\ P = diag.\{e^{i\alpha}, e^{i\beta}, 1\}$$

Neutrino 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" - $\delta m_H^2 \sim -\, y_t^2/(8\pi^2)\, \Lambda^2$

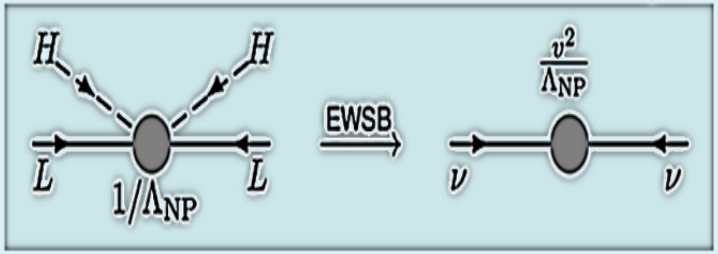
Two ways to generate small values naturally:

❖ 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.

- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

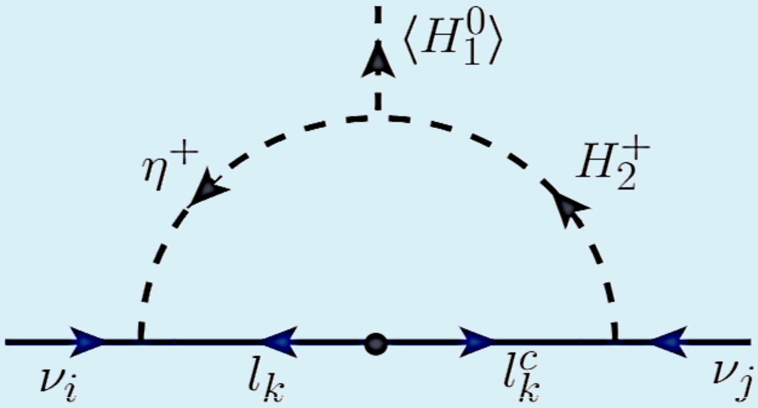
Weinberg, PRL43 (79) 1566



- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ⋆ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ⋆ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ⋆ Type-III Foot, Lew, He, Joshi (89), Ma (98)
    - ⋆ Linear, Inverse, etc ...
  - Loop-induced:
    - ⋆ 1-loop Zee (80), Ma (99)
    - ⋆ 2-loop Babu (88)

Radiative neutrino mass generation

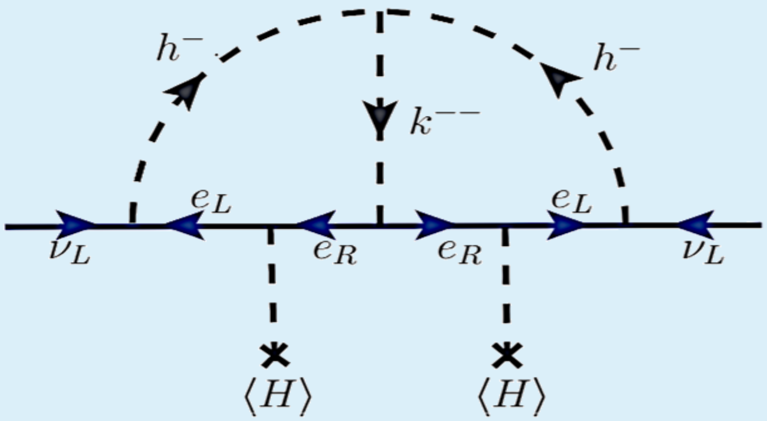
- Neutrino masses are zero at tree level as SM: ν_R may be absent.
- Small, finite Majorana masses are generated at the quantum level.
- Typically new heavy scalar fields introduced violates lepton number, gives rise to neutrino flavor transitions, and lepton flavor violation.
- Simple realization is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

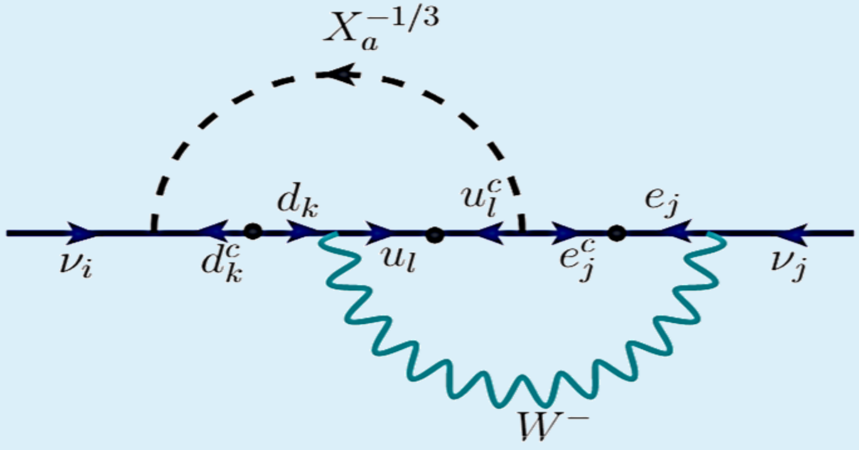
Type-I Radiative Mechanism

- 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



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

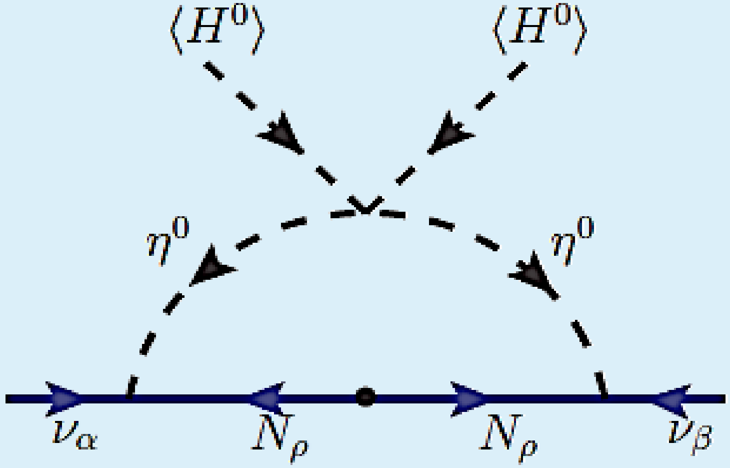
Babu, Julio (2010)

Classification: Babu, Leung (2001),
de Gouvea, Jenkins (2008)
Volkas et al. (2017)

Babu, Dev, SJ, Thapa (2019)

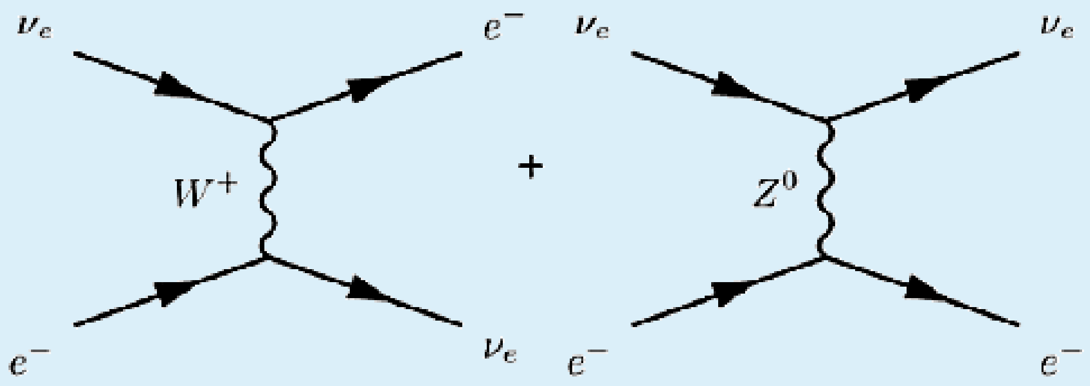
Type-II Radiative Mechanism

- No Standard Model particles inside loop
- Cannot be cut to generate $d = 7, 9, \ldots$ operators
- Scotogenic model is an example



- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) require TeV scale new physics Ma (2006)
- These models predict negligible NSI

Neutrino Standard Interaction



Charged current and Neutral current

- Coherent forward scattering of ν_e off electron in matter generates a matter potential:

  $V = \sqrt{2} G_F N_e \approx 8.2 \times 10^{-12}$ eV in solar core (Wolfenstein)

- Modifies refractive index of ν_e (Mikheyev-Smirnov)
- Neutral current interaction is universal

Neutrino NSI

Unknown couplings involving neutrinos.

Potentially observable effects in neutrino oscillation experiments. It can affect mass ordering and CP violation.

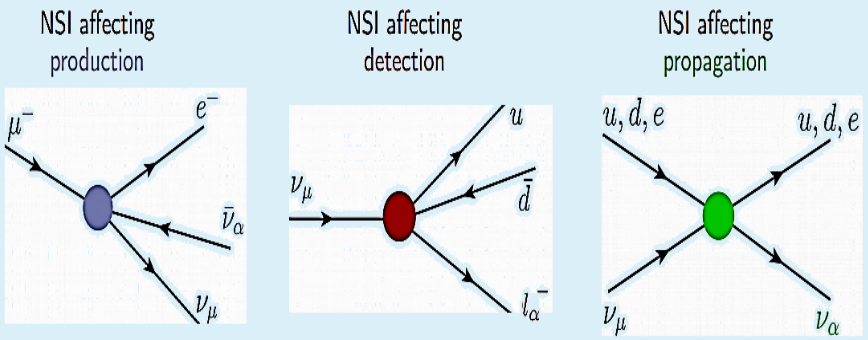
NSI effects happen in the neutrino production, propagation through matter, and the detection processes.

Most important effect of NSI is in neutrino propagation in matter *Wolfenstein (1978)*

*There have been **a variety of phenomenological studies** of NSI in the context of oscillations, but **relatively lesser effort** has gone into the **UV completion of models** that yield such NSI.*

*A **major challenge** in generating sizable NSI: **charged lepton flavor violation***

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6}} + \dots$$



$\varepsilon^{e\mu,P}_{\mu\alpha}\left(\bar{e}\gamma^\rho P\mu\right)\left(\bar{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$ $\quad \varepsilon^{ud,P}_{\mu\alpha}\left(\bar{d}\gamma^\rho Pu\right)\left(\bar{\nu}_\mu\gamma_\rho P_L l_\alpha\right)$ $\quad \varepsilon^{f,P}_{\mu\alpha}\left(\bar{f}\gamma^\rho Pf\right)\left(\bar{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$

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

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

NSI in radiative neutrino mass models

***An alternative to high scale seesaw** for neutrino mass generation is "radiative mechanism"*

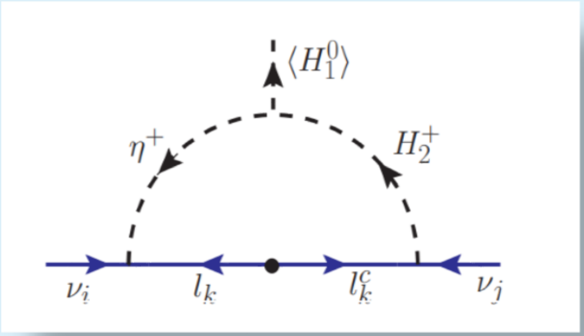
Small, finite Majorana masses are generated at the quantum level.

*The charged scalars **induce NSI at tree level***

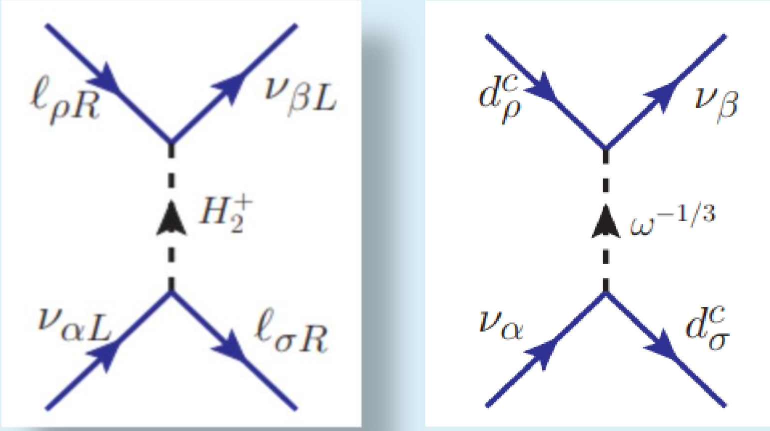
*Smallness of neutrino mass is explained via **loop and chiral suppression.***

Simple realization is the Zee Model, which has a second Higgs doublet and a charged singlet.

We have systematically analyzed these models for their predicted NSI.



Neutrino mass



NSI in radiative models

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:

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

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

- Mixing between η^+ and H_2^+ :

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

where

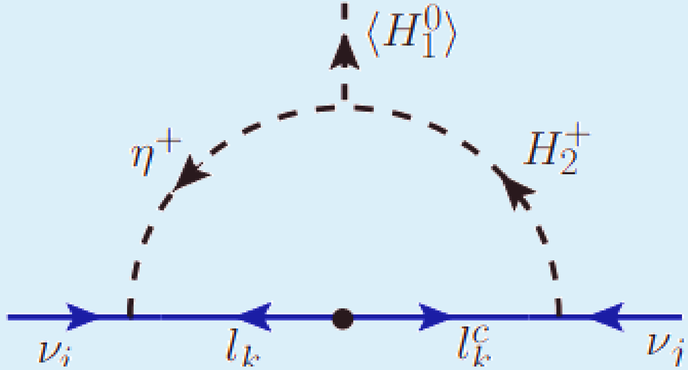
$$h^+ = \cos\varphi\eta^+ + \sin\varphi H_2^+$$
$$H^+ = -\sin\varphi\eta^+ + \cos\varphi H_2^+$$

NSI in 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



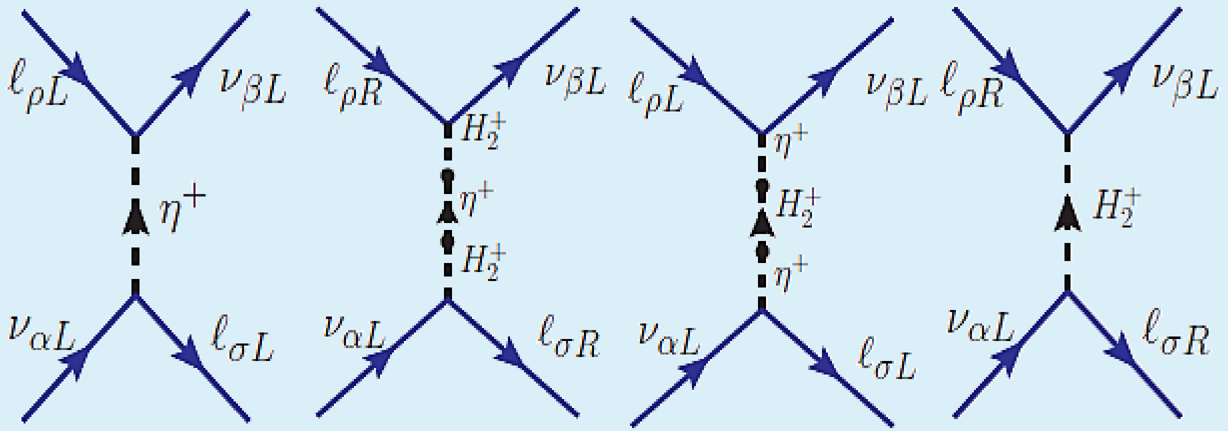
$$M_\nu = \kappa\,(f M_l Y^T + Y M_l f^T)$$
$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$

- 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



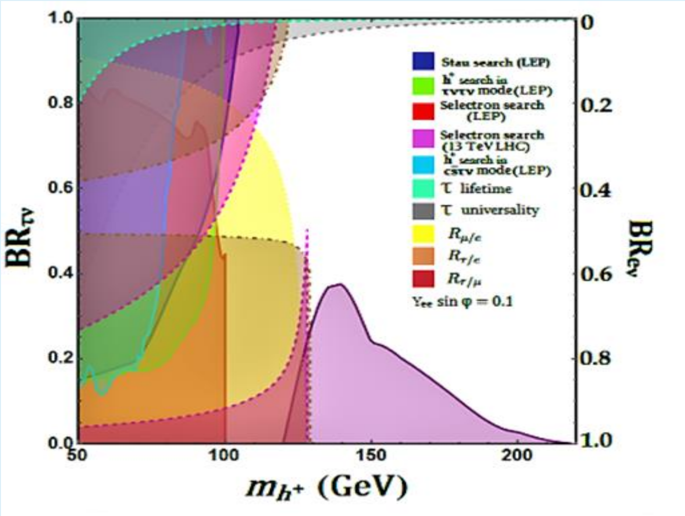
- The singly-charged scalars η^+ and H^+ induce NSI at tree level:

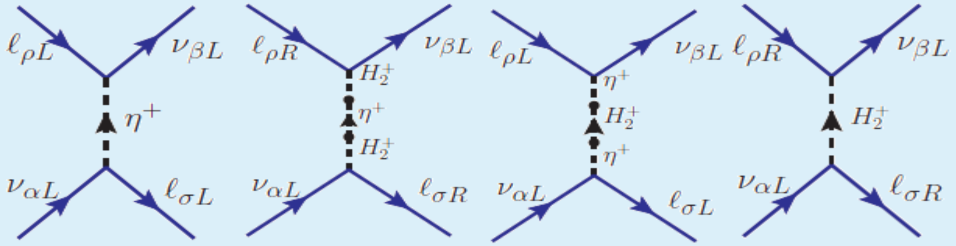
$$\boxed{\varepsilon_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^{(h^+)} + \varepsilon_{\alpha\beta}^{(H^+)} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y_{\beta e}^{\star} \left(\frac{\sin^2\varphi}{m_{h^+}^2} + \frac{\cos^2\varphi}{m_{H^+}^2} \right)}$$

Babu, Dev, SJ, Thapa (2019)

NSI in Zee model

- 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





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

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

- For a benchmark value of 100 GeV masses, we have:

$$\varepsilon_{ee}^{\max} \approx 3.5\%\,, \quad \varepsilon_{\mu\mu}^{\max} \approx 5.6\%\,, \quad \varepsilon_{\tau\tau}^{\max} \approx 71.6\%$$

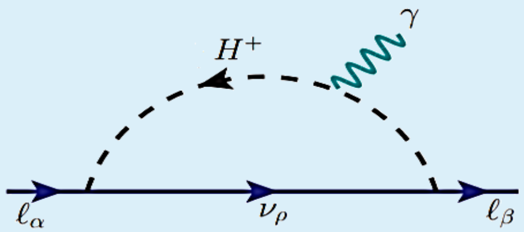
Babu, Dev, SJ, Thapa (2019)

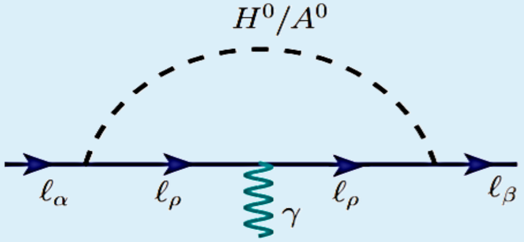
Charged lepton flavor violation

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

- Detection of LFV signals $\Longrightarrow$ clear evidence for BSM
- $\ell_i \to \ell_j \gamma$ arises at one loop level

$$\varepsilon^m_{ee} \sim |Y_{ee}|^2 \qquad \varepsilon^m_{e\mu} \sim Y^*_{ee} Y_{\mu e}$$
$$\varepsilon^m_{\mu\mu} \sim |Y_{\mu e}|^2 \qquad \varepsilon^m_{\mu\tau} \sim Y^*_{\mu e} Y_{\tau e}$$
$$\varepsilon^m_{\tau\tau} \sim |Y_{\tau e}|^2 \qquad \varepsilon^m_{e\tau} \sim Y^*_{ee} Y_{\tau e}$$

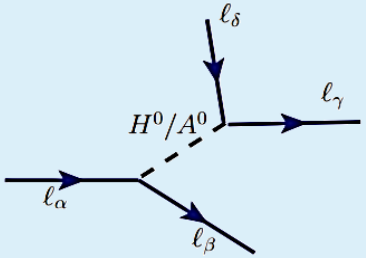




Process	Exp. bound	Constraint
$\mu \to e\gamma$	BR $< 4.2 \times 10^{-13}$	$\lvert Y^\star_{\mu e} Y_{ee}\rvert < 1.05 \times 10^{-3} \left(\frac{m_H}{700 \text{ GeV}}\right)^2$
$\tau \to e\gamma$	BR $< 3.3 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{ee}\rvert < 0.69 \left(\frac{m_H}{700 \text{ GeV}}\right)^2$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

Charged 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 $< 1.0 \times 10^{-12}$	$\lvert Y^\star_{\mu e} Y_{ee} \rvert < 3.28 \times 10^{-5} \left(\frac{m_H}{700\ \text{GeV}}\right)^2$
$\tau^- \to e^+ e^- e^-$	BR $< 1.4 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{ee} \rvert < 9.05 \times 10^{-3} \left(\frac{m_H}{700\ \text{GeV}}\right)^2$
$\tau^- \to e^+ e^- \mu^-$	BR $< 1.1 \times 10^{-8}$	$\lvert Y^\star_{\tau e} Y_{\mu e} \rvert < 5.68 \times 10^{-3} \left(\frac{m_H}{700\ \text{GeV}}\right)^2$

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

Collider constraints

- 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:

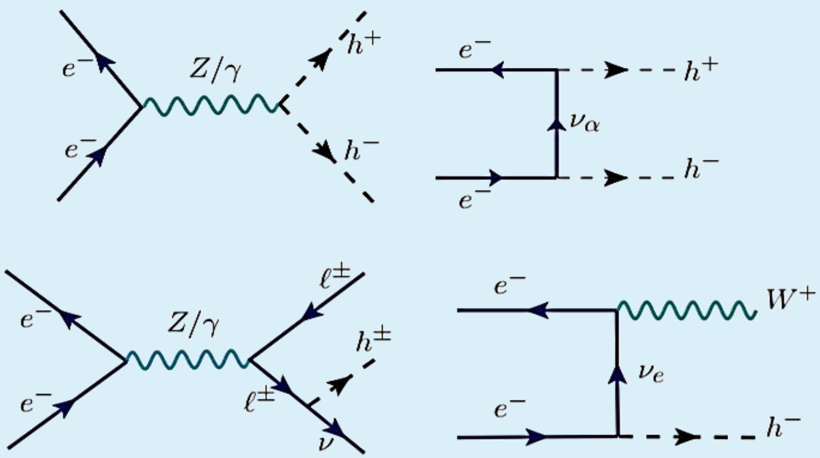
$$\mathcal{L}_{eff} = \frac{4\pi}{\Lambda^2(1+\delta_{ef})} \sum_{i,j=L,R} \eta^f_{ij} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j)$$

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

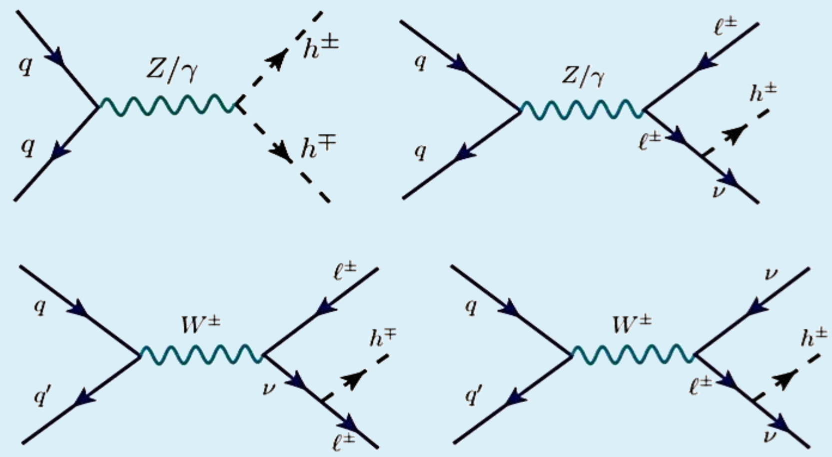
Process	LEP bound	Constraint
$e^+e^- \to e^+e^-$	$\Lambda^-_{LR/RL} > 10$ TeV	$\frac{m_H}{\lvert Y_{ee}\rvert} > 1.99$ TeV
$e^+e^- \to \mu^+\mu^-$	$\Lambda^-_{LR/RL} > 7.9$ TeV	$\frac{m_H}{\lvert Y_{\mu e}\rvert} > 1.58$ TeV
$e^+e^- \to \tau^+\tau^-$	$\Lambda^-_{LR/RL} > 2.2$ TeV	$\frac{m_H}{\lvert Y_{\tau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

Collider constraints

- 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.



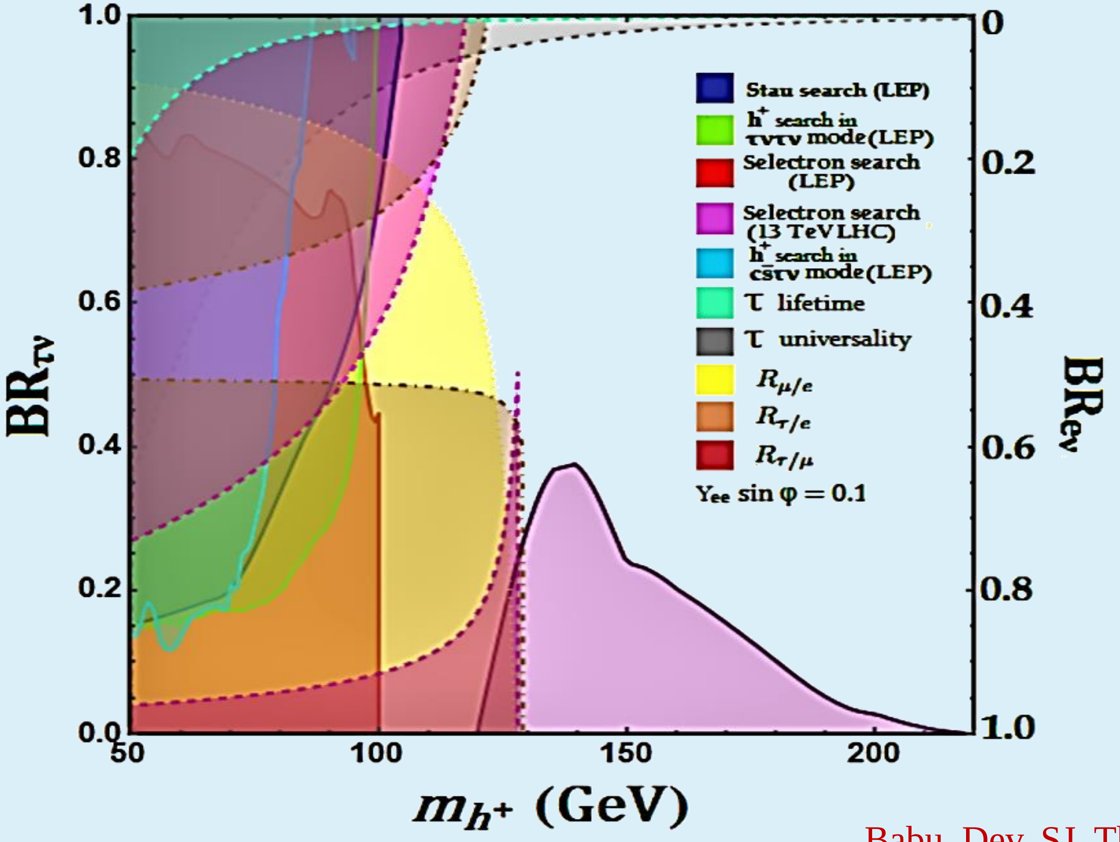
Dominant production in LEP



Dominant production in LHC

Collider constraints

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

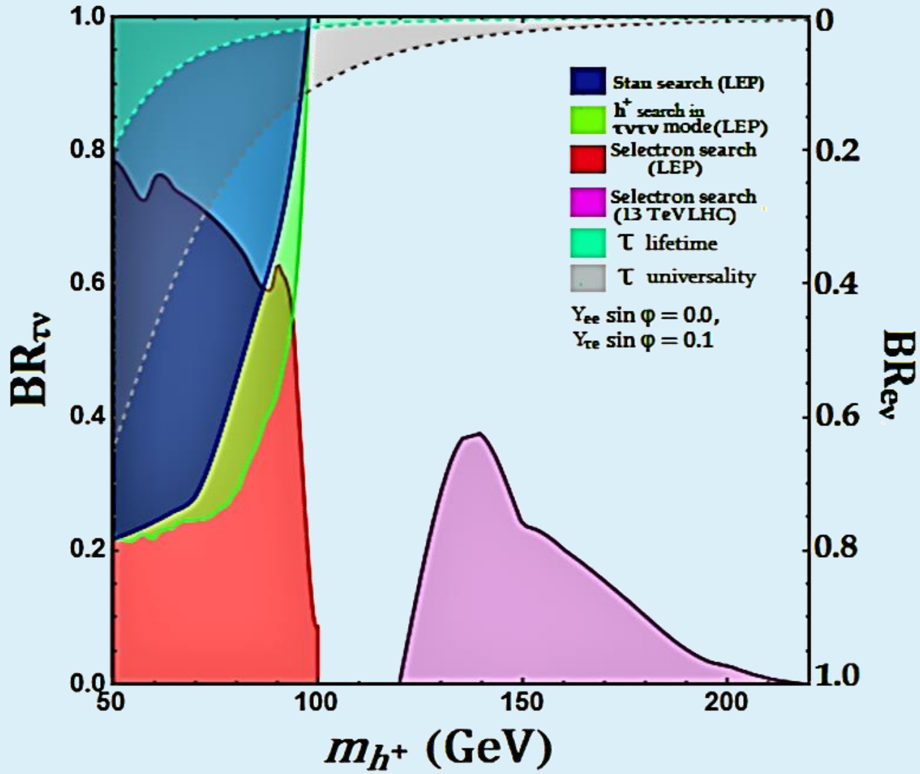


Babu, Dev, SJ, Thapa (2019)

- The lowest charged higgs mass allowed is 110 GeV.

Collider constraints

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

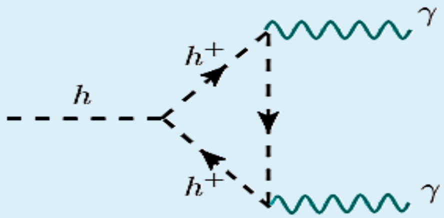


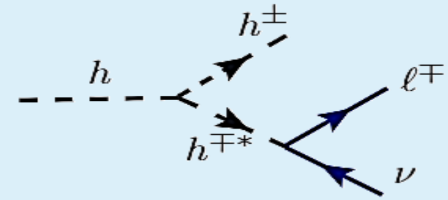
Babu, Dev, SJ, Thapa (2019)

- The lowest charged higgs mass allowed is 96 GeV.

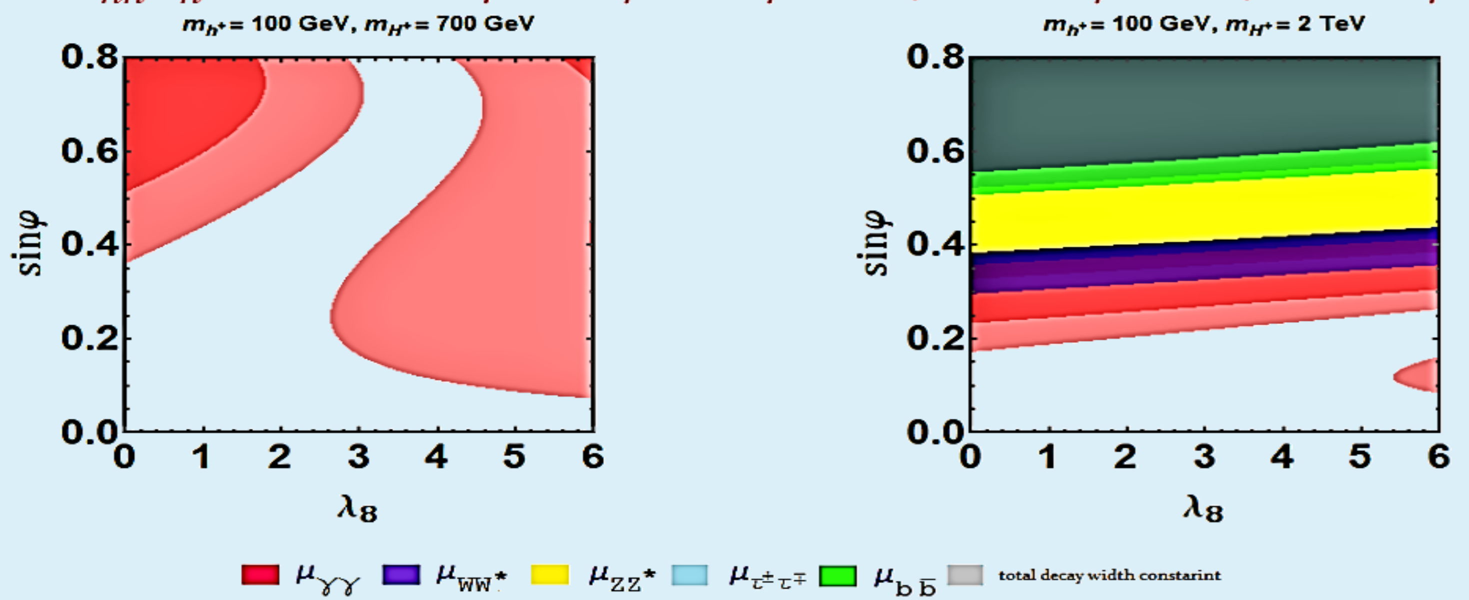
Constraints from Higgs observables

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





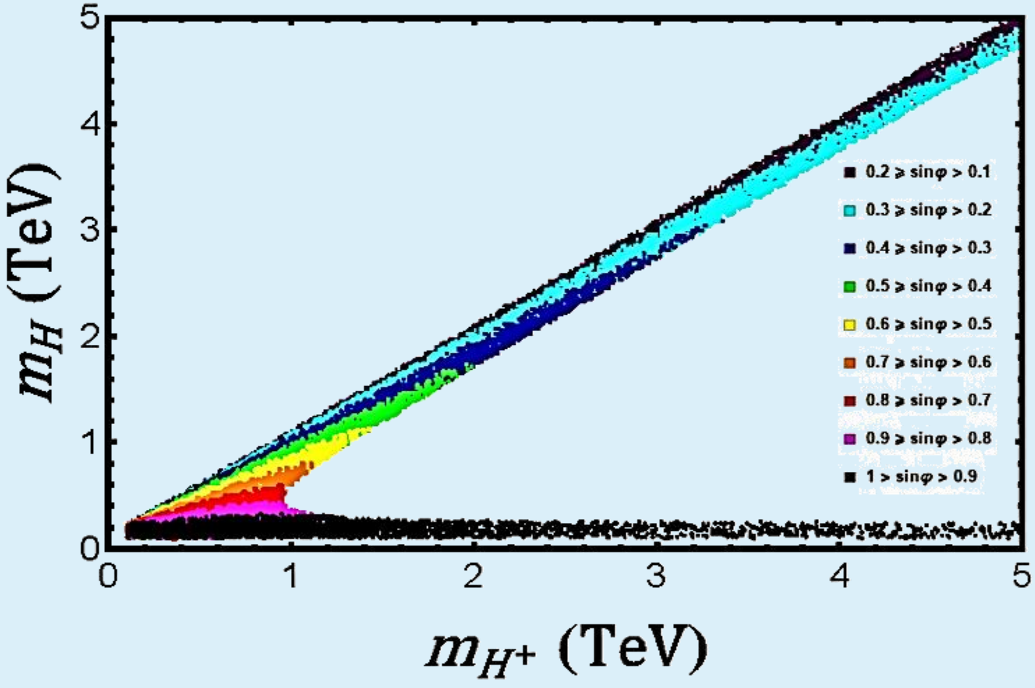
$$\lambda_{hh^+h^-} = -\sqrt{2}\mu \sin\varphi\cos\varphi + \lambda_3 v \sin^2\varphi + \lambda_8 v \cos^2\varphi$$



Babu, Dev, SJ, Thapa (2019)

EW precision constraints

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

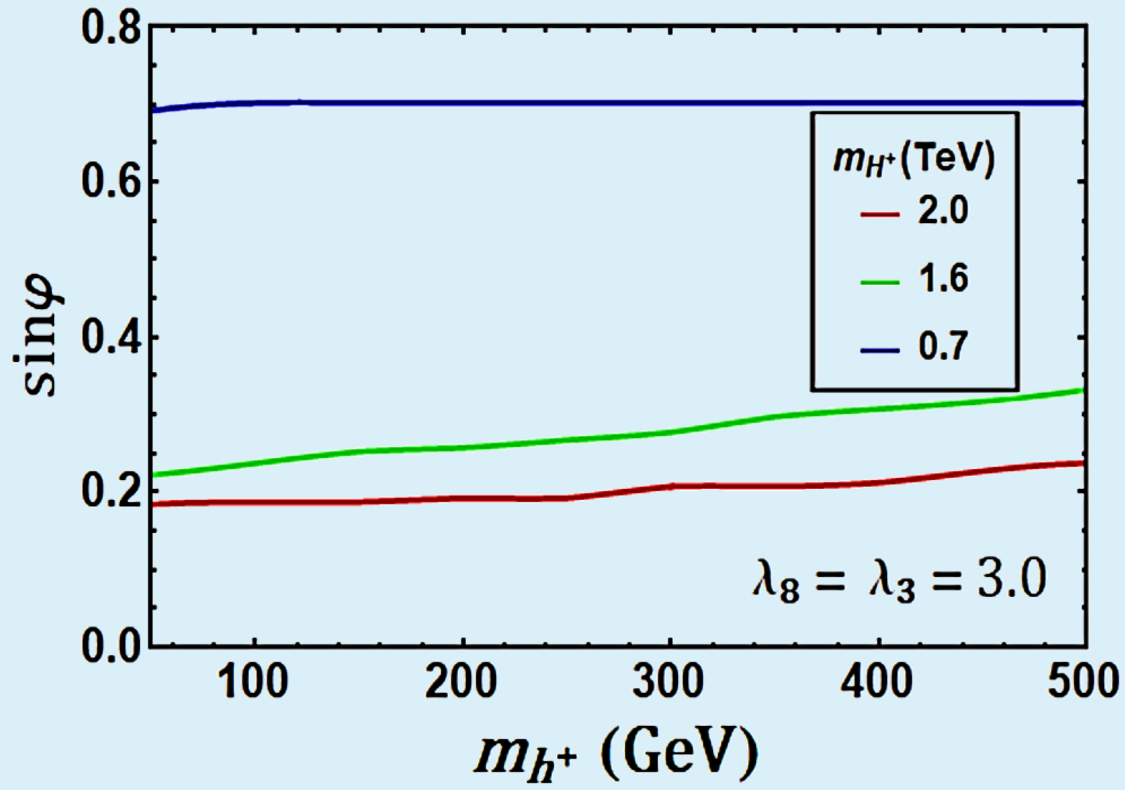


- For $m_H = 0.7\,\text{TeV}$ and $m_h^+ = 100\ \text{GeV}$, the maximum mixing is 0.63.

Babu, Dev, SJ, Thapa (2019)

Charge breaking minima

- 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



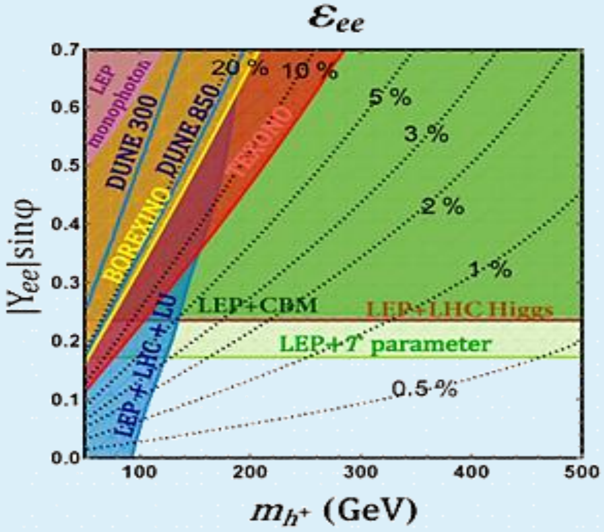
$\sin\varphi < 0.23$ for $m_{H^+} = 2$ TeV

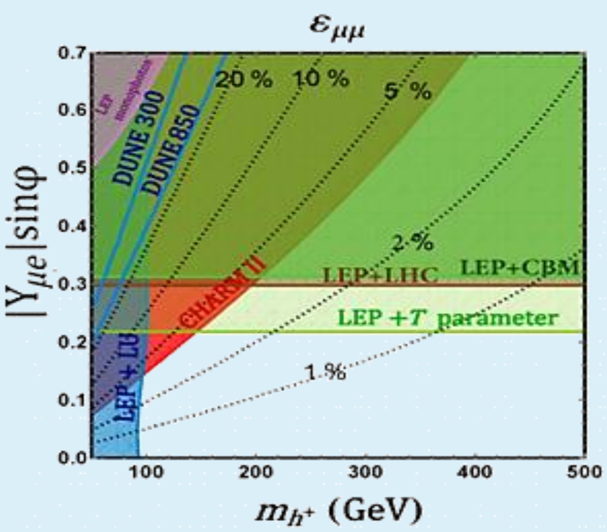
$\sin\varphi \sim 0.707$ for $m_{H^+} = 0.7$ TeV

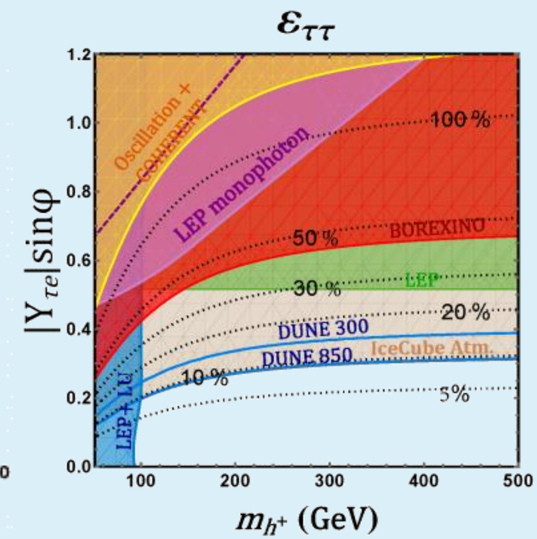
- Max. value of μ is found to be 4.1 times the heavier mass m_{H^+}

Babu, Dev, SJ, Thapa (2019)

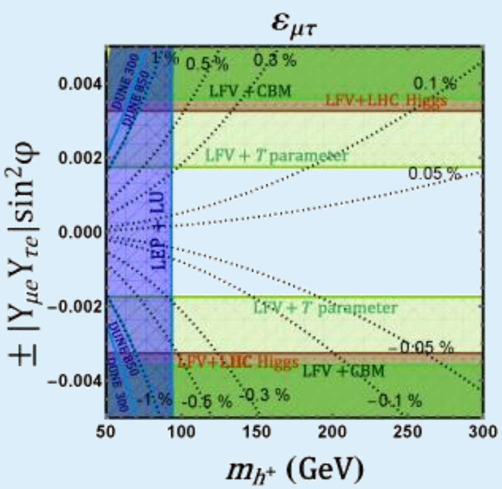
NSI in Zee model

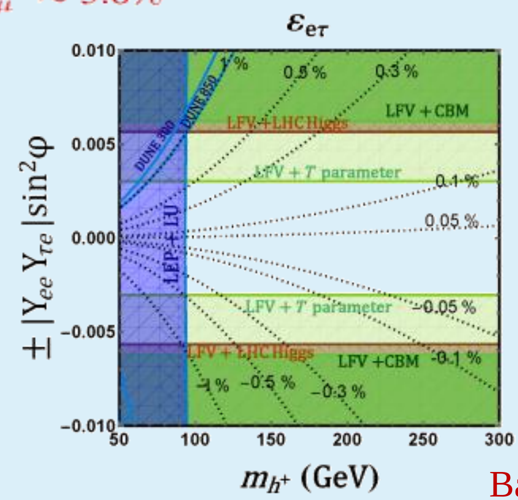






$\varepsilon_{ee}^{\max} \approx 3\%$ $\varepsilon_{\mu\mu}^{\max} \approx 3.8\%$ $\varepsilon_{\tau\tau}^{\max} \approx 9.3\%$





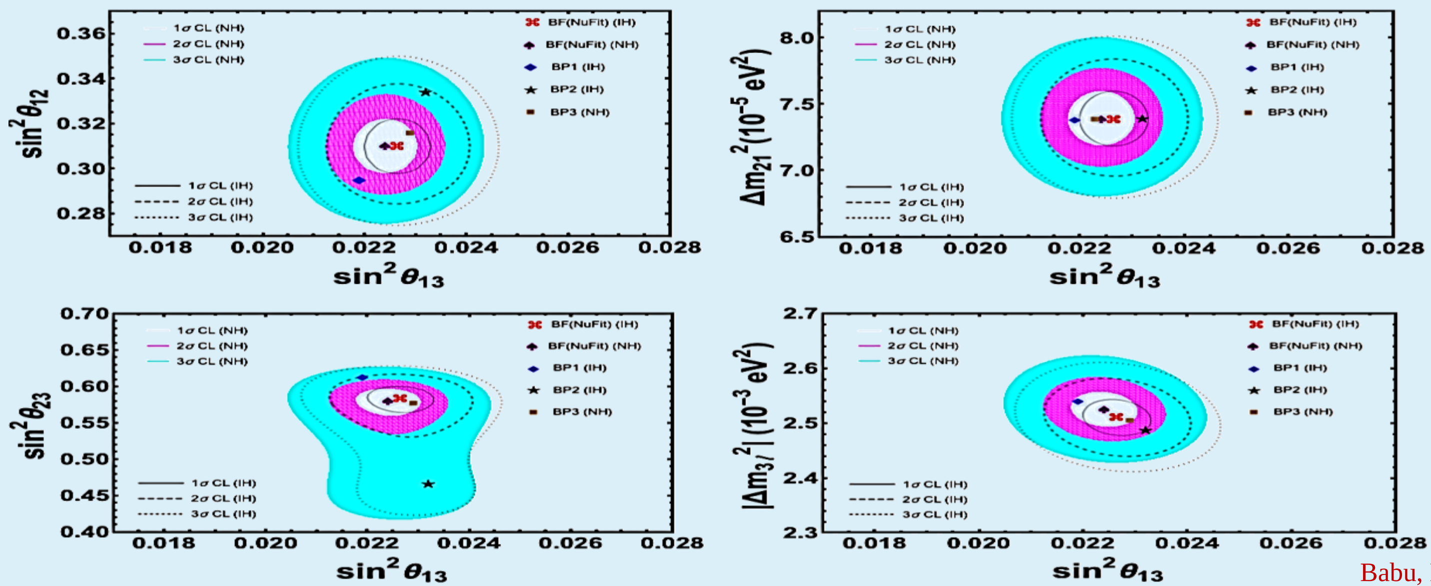
Babu, Dev, SJ, Thapa (2019)

Consistency with neutrino oscillation data

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

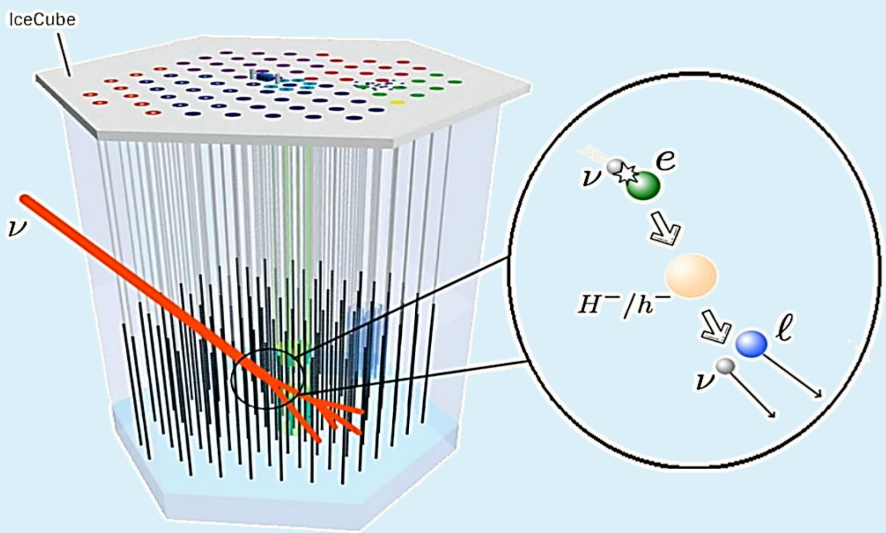
BPI BPII BPII

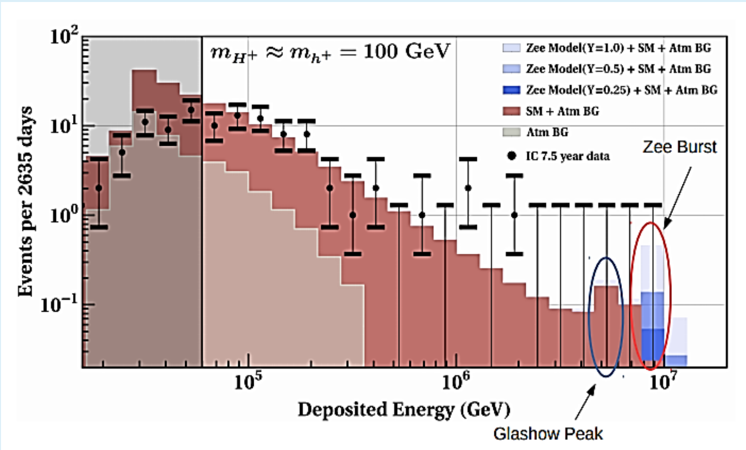
Oscillation parameters	3σ allowed range from NuFit4	Model prediction		
		BP I (IH)	BP II (IH)	BP III (NH)
$\Delta m^2_{21}(10^{-5}\ \mathrm{eV}^2)$	6.79 - 8.01	7.388	7.392	7.390
$\Delta m^2_{23}(10^{-3}\ \mathrm{eV}^2)$(IH)	2.412 - 2.611	2.541	2.488	-
$\Delta m^2_{31}(10^{-3}\ \mathrm{eV}^2)$(NH)	2.427 - 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



Babu, Dev, SJ, Thapa (2019)

Zee-Burst: A new test of NSI at IceCube





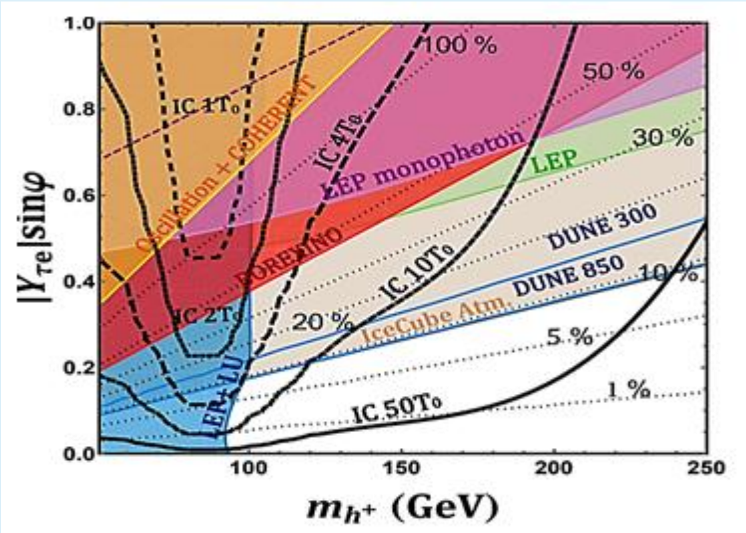
- Ultra High Energy neutrinos at IceCube can probe NSI in the Zee model
- $\overline{\nu_e} + e^- \to W^- \to$ anything has a resonant enhancement at

  $E_\nu = \frac{m_W^2}{2m_e} = 6.3\,\mathrm{PeV}$ Glashow resonance

- Since $h^\pm$ and $H^\pm$ in Zee model are allowed to be as light as 100 GeV, $\overline{\nu}_\alpha + e^- \to h^- \to$ anything is resonantly enhanced

  $E_\nu = \frac{m_h^2}{2m_e} \simeq 9.3\,\mathrm{PeV}$ "Zee burst"

- We have analyzed this possibility of "Zee burst"



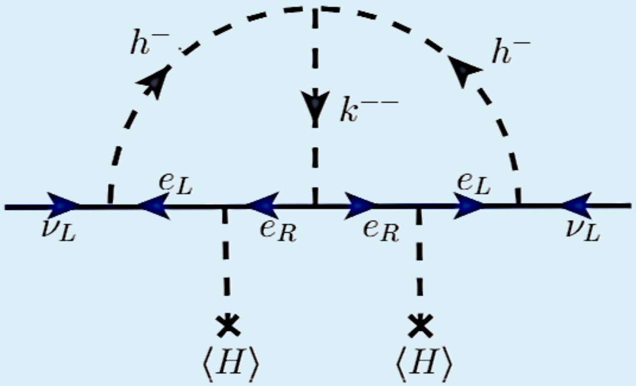
Babu, Dev, SJ , Sui (PRL' 2019)

NSI in Zee-Babu model

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

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

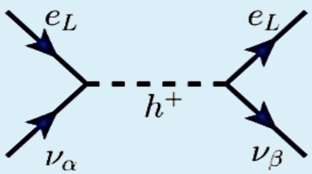
- Majorana neutrino masses are generated by 2-loop diagram:



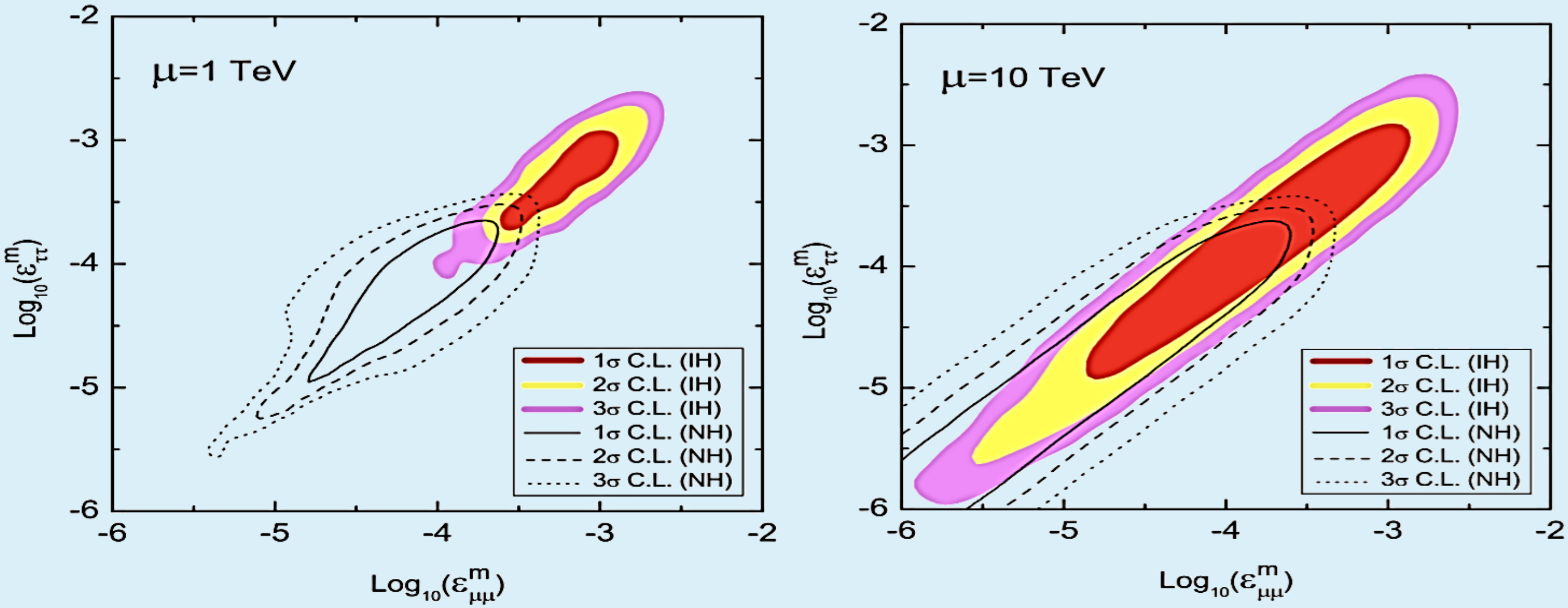
$$M_\nu \approx \frac{1}{(16\pi^2)^2} \frac{8\mu}{M^2}\, f_{ac}\, \tilde{h}_{cd}\, m_c\, m_d\, (f^\dagger)_{db}\, \tilde{I}(\frac{m_k^2}{m_h^2})$$

NSI in Zee-Babu model

The heavy singly charged scalar induces nonstandard neutrino interactions:



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



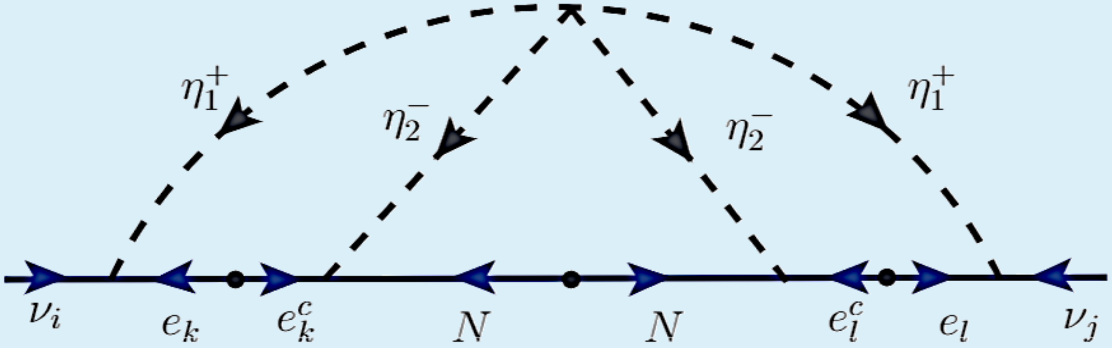
T. Ohlsson et al. (2009)

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 1-loop LQ (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:

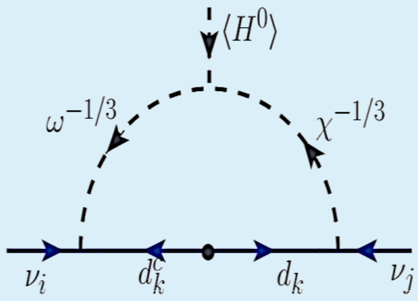
$$\mathcal{L}_Y = y_{ij} L_i d_j^c \Omega + y'_{ij} L_i Q_j \chi^* + h.c.$$

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

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

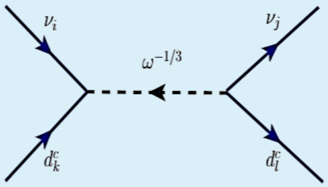
$$\begin{pmatrix} M_\omega^2 & \mu v \\ \mu v & M_\chi^{-1/3} \end{pmatrix}$$

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



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

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

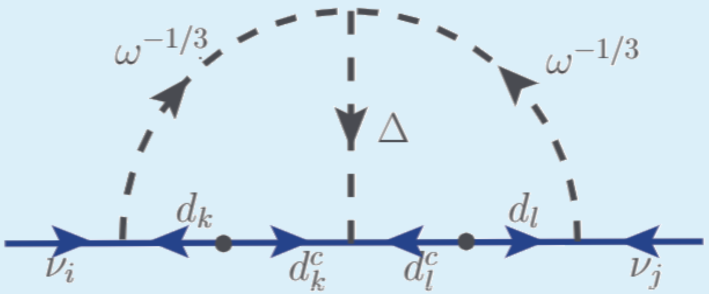
For $\dfrac{N_n(x)}{N_p(x)} = 1 \Longrightarrow \varepsilon_{\alpha\beta}(x) = 3\varepsilon^d_{\alpha\beta}$

NSI in 2-loop LQ 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

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

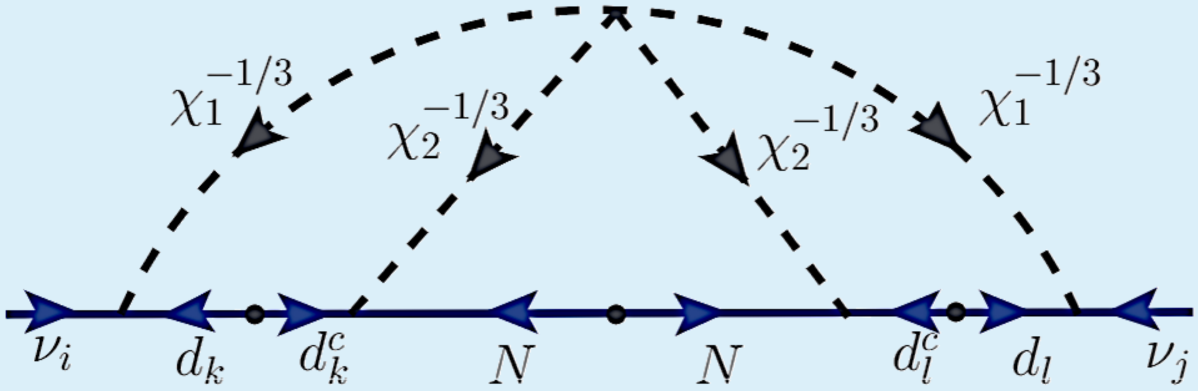
- Note F_{ij} do not lead to NSI.
- M_ν arises at 2-loops: Replace leptons by quarks in Zee-Babu Model



NSI in 3-loop LQ model

- Replace leptons by quarks

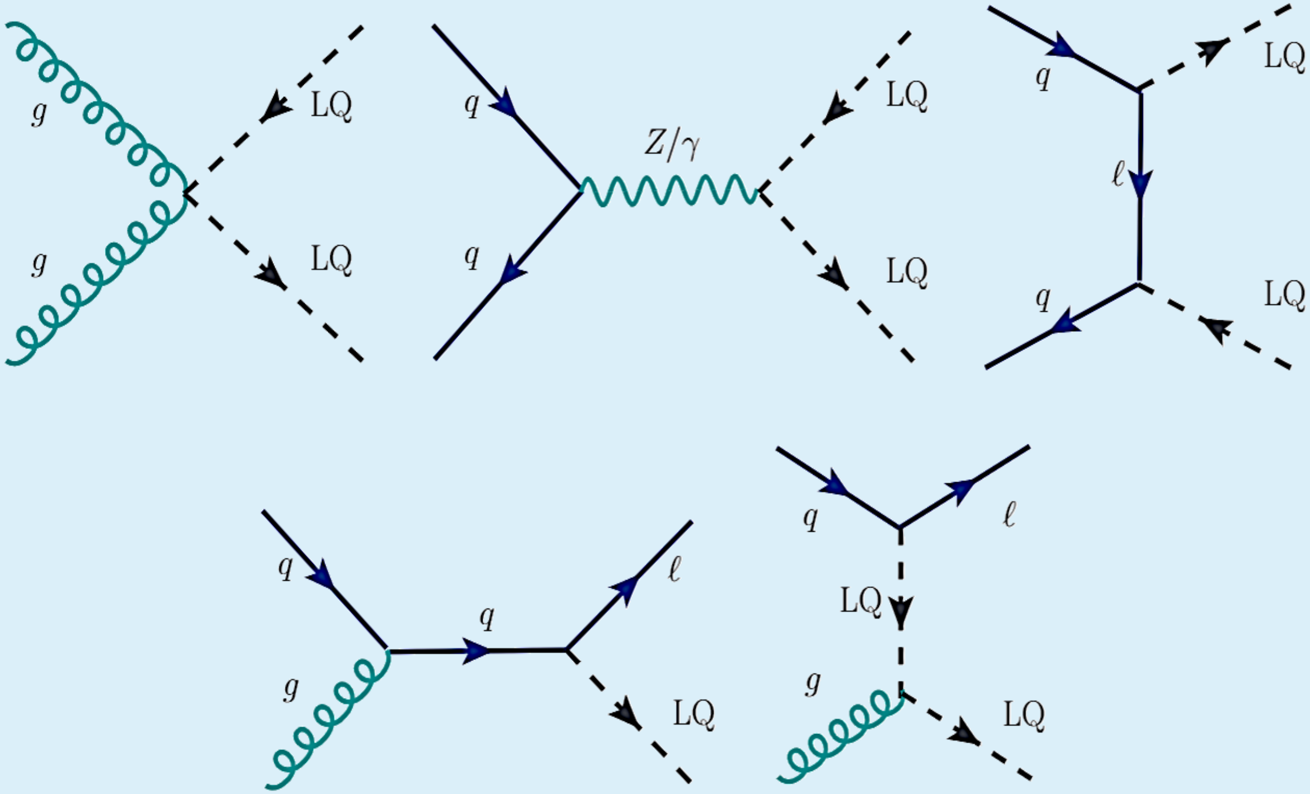
$$\mathcal{L}_y = fLQ\chi_1^{*1/3} + d^c N \chi_2^{-1/3} + \frac{1}{2} M_N NN$$



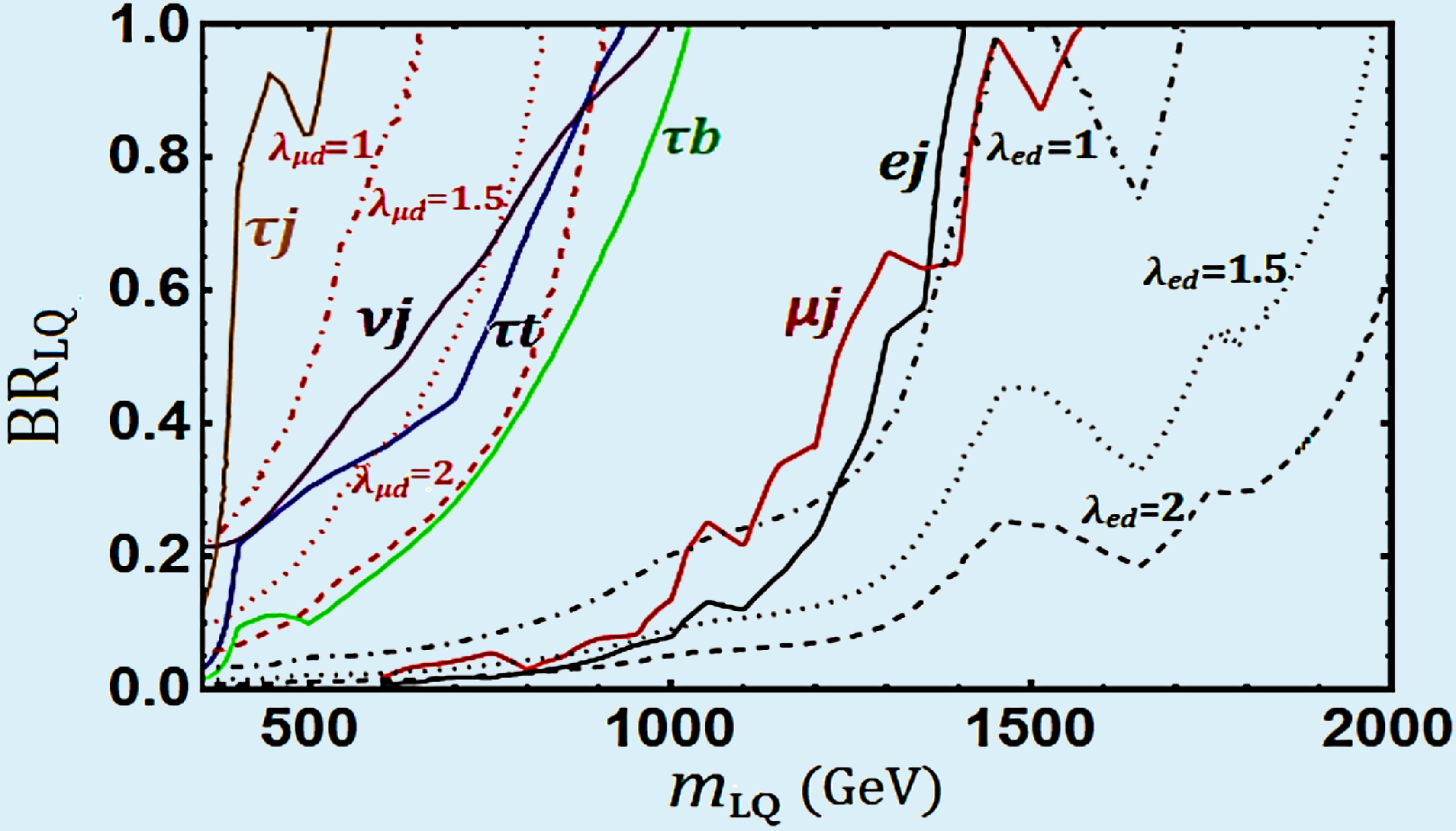
- $\chi_1^{-1/3}$ cause NSI.

Collider constraints on leptoquarks

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



Collider constraints on leptoquarks



Babu, Dev, SJ , Thapa (2019)

Other constraints on leptoquarks

- 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

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

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

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

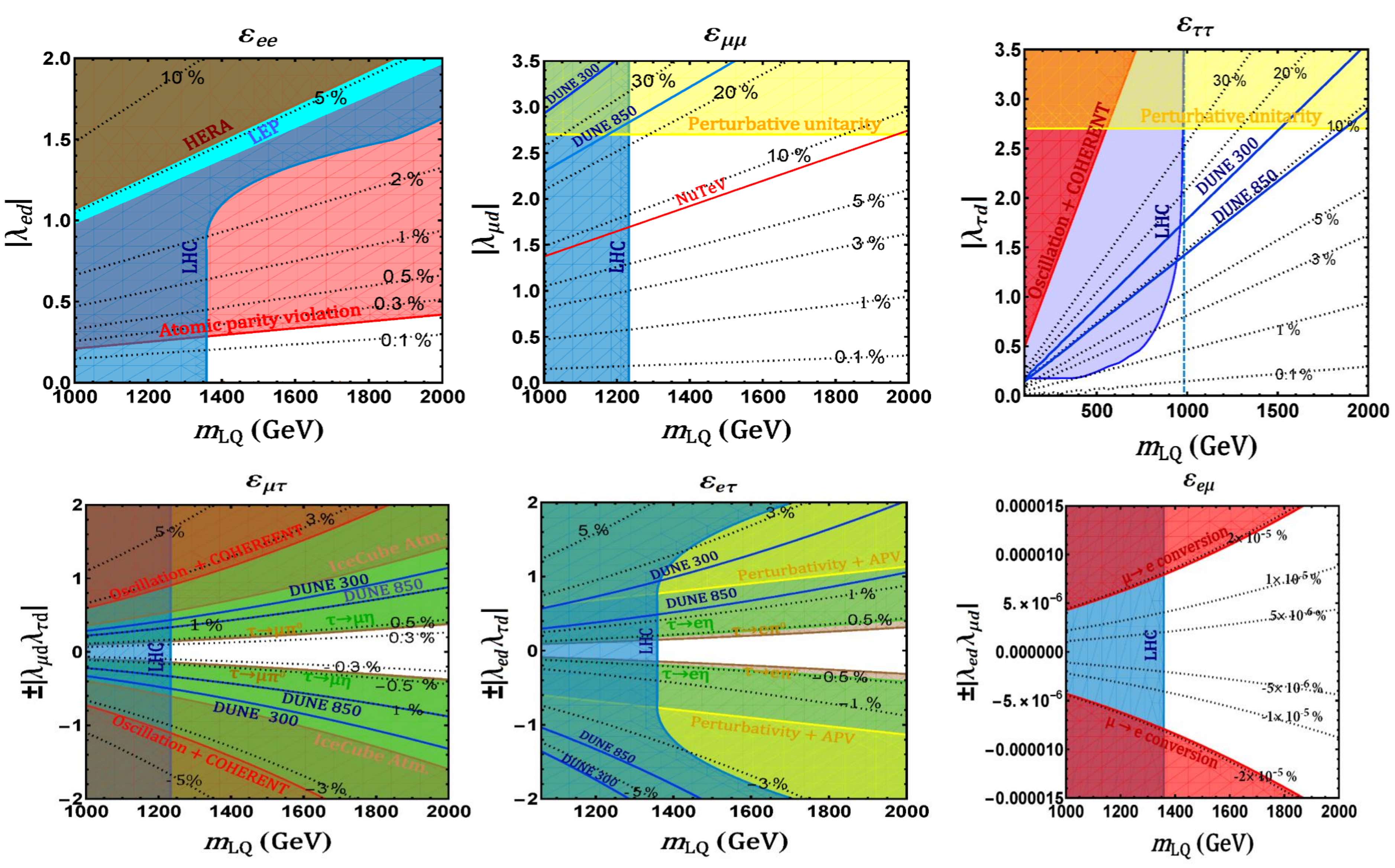
- Atomic Parity Violation constraints:

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

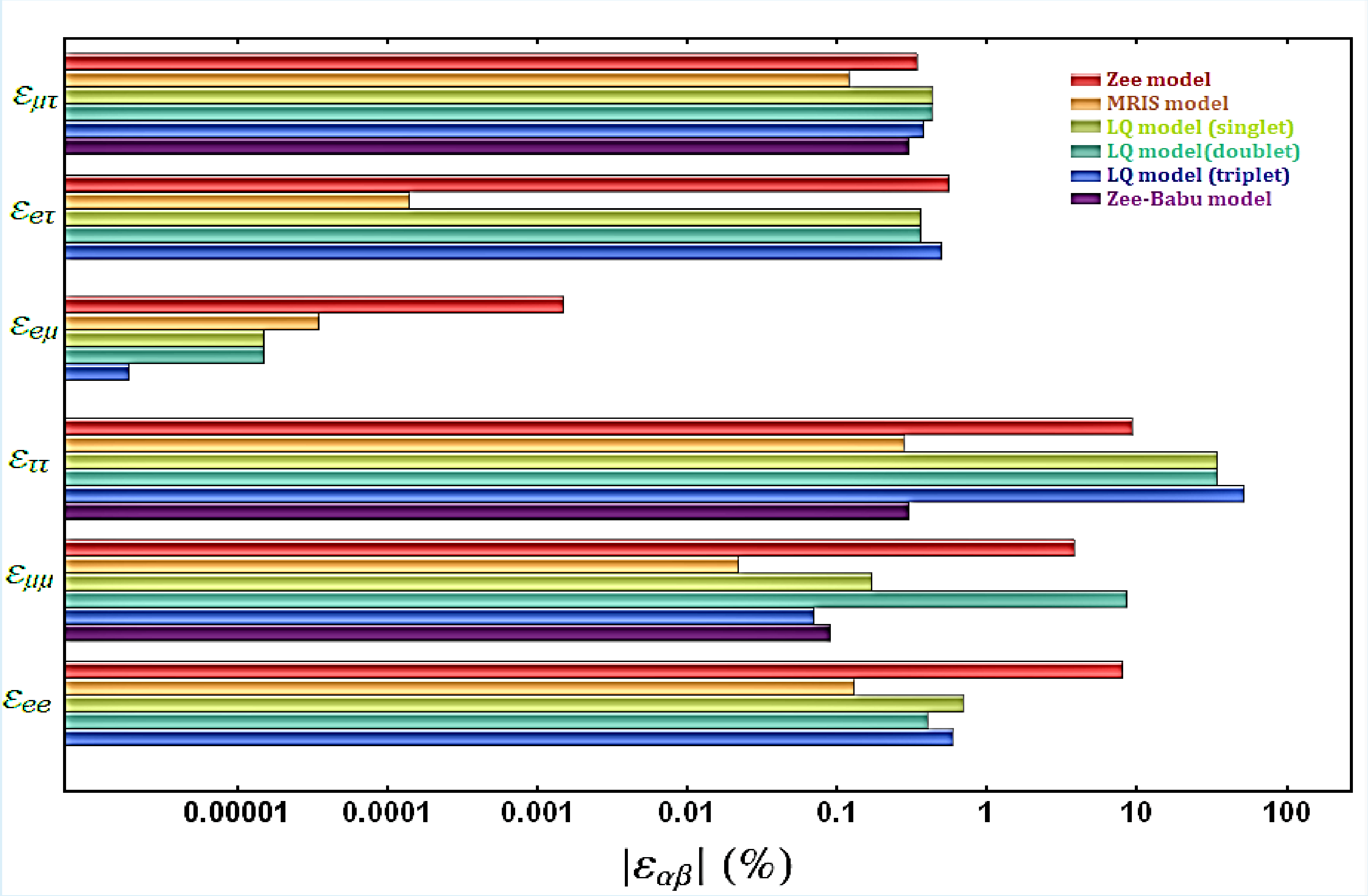
- ϵ_{ee}, $\epsilon_{e\mu}$, and $\epsilon_{e\tau}$ cannot be too large as one y_{e1} factor is order 0.3 for 1 TeV Leptoquark mass

$$\boxed{\begin{array}{lll} \varepsilon_{ee} \approx 0.33\% & \varepsilon_{e\mu} = 10^{-7}\% & \varepsilon_{e\tau} = 0.36\% \\ \varepsilon_{\mu\mu} = 21.6\% & \varepsilon_{\mu\tau} \approx 0.43\% & \varepsilon_{\tau\tau} \approx 34.3\% \end{array}}$$

NSI via leptoquarks in radiative models



Summary of NSI in radiative models



Babu, Dev, SJ , Thapa (2019)

Summary of NSI in radiative 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	0.093	$\mathcal{O}(10^{-5})$	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	$\mathcal{S}$	$\eta_1^+(1,1,1)$, $\eta_2^+(1,1,1)$						
				$\mathcal{F}$	$N(1,1,0)$	0	0.0009	0.003	0	0	0.003
$LL\eta$	$\mathcal{O}_9$	1S-1S-1F [55]	3	$\mathcal{S}$	$\eta_1(1,1,1)$, $\eta_2(1,1,3)$						
				$\mathcal{F}$	$F(1,1,2)$						
	$\mathcal{O}_2^1$	1S-2VLL [31]	1	$\mathcal{S}$	$\eta(1,1,1)$						
				$\mathcal{F}$	$\Psi(1,2,-3/2)$						
	$\mathcal{O}_3'$	AKS [38]	3	$\mathcal{S}$	$\Phi_2(1,2,1/2)$, $\eta^+(1,1,1)$, $\eta^0(1,1,0)$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-10})$
$L\ell^c\phi^\star$				$\mathcal{F}$	$N(1,1,0)$						
—	$\mathcal{O}_{d=15}$	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	$\mathcal{F}$	$N(1,1,0)$, $S(1,1,0)$	0.0013	$\mathcal{O}(10^{-4})$	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	$\mathcal{S}$	$\Omega(3,2,1/6)$, $\chi(3,1,-1/3)$	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	$\mathcal{S}$	$\Omega(3,2,1/6)$						
				$\mathcal{F}$	$U(3,1,2/3)$						
$L\Omega d^c$	$\mathcal{O}_3^6$	2LQ-3VLQ [31]	1	$\mathcal{S}$	$\Omega(3,2,1/6)$						
				$\mathcal{F}$	$\Sigma(3,3,2/3)$	0.004	0.093	0.093	$\mathcal{O}(10^{-7})$	0.0036	0.0043
	$\mathcal{O}_8^2$	2LQ-2VLL [31]	2	$\mathcal{S}$	$\Omega(3,2,1/6)$						
				$\mathcal{F}$	$\psi(1,2,-1/2)$						
	$\mathcal{O}_8^3$	2LQ-2VLQ [31]	2	$\mathcal{S}$	$\Omega(3,2,1/6)$						
				$\mathcal{F}$	$\xi(3,2,7/6)$						
$L\Omega d^c$	$\mathcal{O}_3^9$	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
$(LQ\bar{\rho})$											
	$\mathcal{O}_{11}$	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	$\mathcal{S}$	$\chi(3,1,1/3)$						
				$\mathcal{F}$	$F(8,1,0)$						
$LQ\chi^\star$	$\mathcal{O}_{11}$	LQ variant of KNT [37]	3	$\mathcal{S}$	$\chi(3,1,-1/3)$, $\chi_2(3,1,-1/3)$	0.0069	0.0086	0.093	$\mathcal{O}(10^{-7})$	0.0036	0.0043
				$\mathcal{F}$	$N(1,1,0)$						
	$\mathcal{O}_3^4$	1LQ-2VLQ [31]	1	$\mathcal{S}$	$\chi(3,1,-1/3)$						
				$\mathcal{F}$	$\mathcal{Q}(3,2,-5/6)$						
$Lu^c\delta$	$\tilde{\mathcal{O}}_1$	**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	0.216	0.343	$\mathcal{O}(10^{-7})$	0.0036	0.0043
$(LQ\bar{\rho})$						(0.0059)	(0.007)	(0.517)		(0.005)	(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	$\mathcal{S}$	$\bar{\rho}(\bar{3},3,-1/3)$						
				$\mathcal{F}$	$\mathcal{Q}(3,2,-5/6)$	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

Babu, Dev, SJ , Thapa (2019)

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!