

Neutrinos: A gateway to beyond the Standard Model

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Thesis Defense

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Completed Projects

1. N. Okada, D. Raut, Q. Shafi and **A. Thapa**, “Pseudo-Goldstone Dark Matter in $SO(10)$,” [arXiv:2105.03419 [hep-ph]].
2. K. S. Babu and **A. Thapa**, “Left-Right Symmetric Model without Higgs Triplets,” [arXiv: 2012.13420 [hep-ph]].
3. K. S. Babu, P. S. B. Dev, S. Jana and **A. Thapa**, “Unified framework for B-anomalies, muon g-2 and neutrino masses,” JHEP 03 (2021), 179 [arXiv: 2009.01771 [hep-ph]].
4. Z. Chacko, P. S. B. Dev, R. N. Mohapatra and **A. Thapa**, “Predictive Dirac and Majorana Neutrino Mass Texture from $SU(6)$ Grand Unified Theories,” Phys. Rev. D 102 (2020) no.3, 035020 [arXiv: 2005.05413 [hep-ph]].
5. S. Saad and **A. Thapa**, “Common Origin of Neutrino masses and $R_{D^{(*)}}, R_{K^{(*)}}$ anomalies,” Phys. Rev. D 102 (2020) no.1, 015014 [arXiv:2004.07880 [hep-ph]].
6. K. S. Babu, P. S. B. Dev, S. Jana and **A. Thapa**, “Non-standard Interactions in Radiative Neutrino Mass Models,” JHEP 03 (2020), 006 [arXiv: 1907.09498 [hep-ph]].
7. P. S. Bhupal Dev et al. “Neutrino Non-Standard Interactions: A Status Report,” SciPost Phys.Proc. 2 (2019) 001 [arXiv:1907.00991 [hep-ph]].

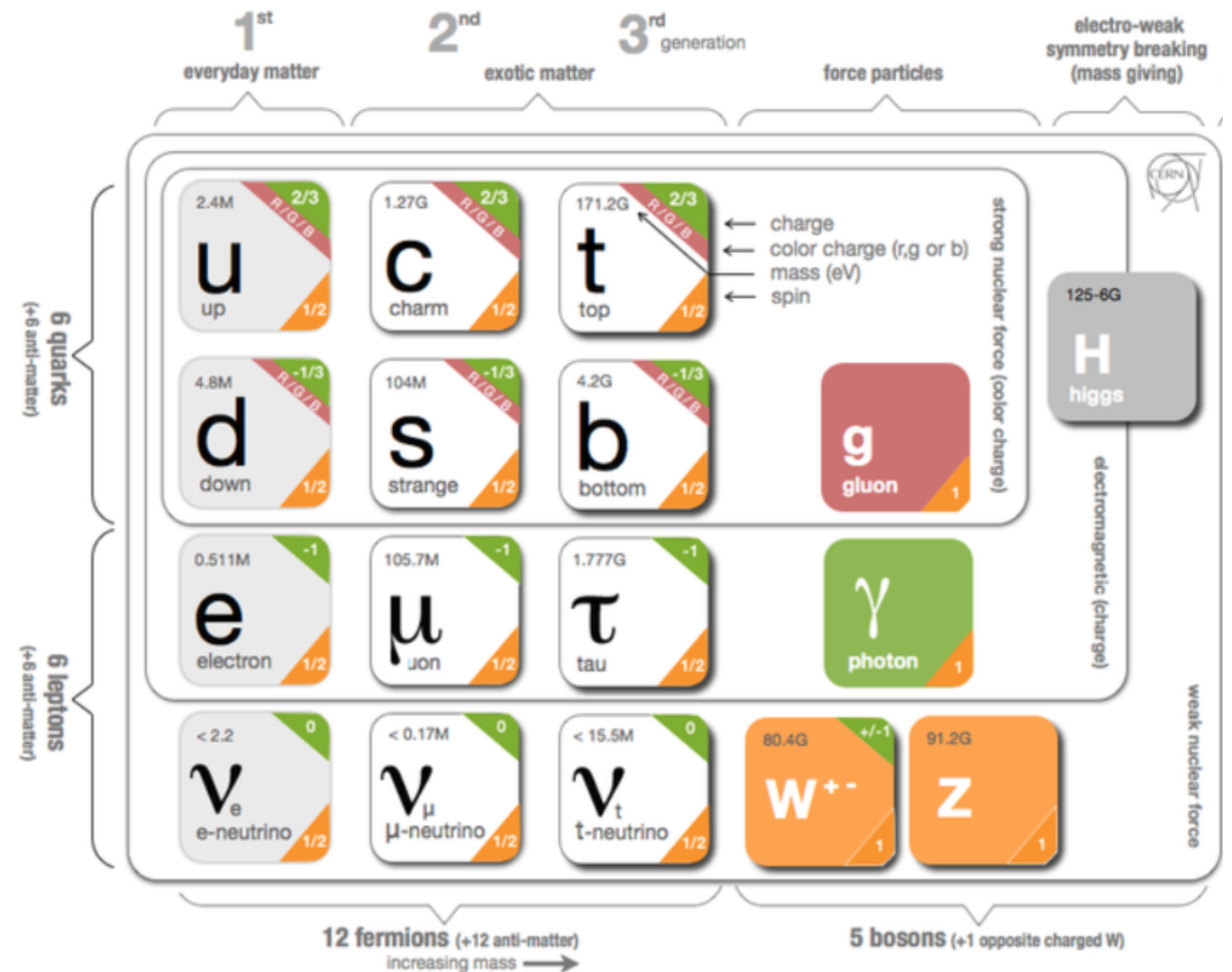
Projects in Preparation

1. D. Raut, Q. Shafi and **A. Thapa**, “Monopoles in Minimal Trinification,” [arXiv: 2107.xxxxx].
2. K. S. Babu, S. Jana, R. N. Mohapatra and **A. Thapa**, “Muon $g-2$ in Left-Right Symmetric Model,” [arXiv: 2107.xxxx].
3. K. S. Babu, S. Jana and **A. Thapa**, “Vector Boson Dark Matter from Trinification,” [arXiv: 2107.xxxx].
4. K. S. Babu, A. Ismail and **A. Thapa**, “ $SU(3)_C \times SU(3)_L \times U(1)_X$ Family Universal Model for Dark Matter”[arXiv: 2108.xxxx].
5. S. Saad, S. Jana and **A. Thapa**, “Common Origin for Lepton $g-2$, B-Anomalies, Neutrino Masses and Nonstandard Neutrino Interaction,” [arXiv:2108.xxxx].
6. K. S. Babu, P. S. B. Dev, G. Chauhan, R. N. Mohapatra and **A. Thapa**, “Oscillations and Baryogenesis in Post-Sphaleron Era”.
7. K. S. Babu, P. S. B. Dev, S. Jana and **A. Thapa**, “Muon $g-2$ in Zee Model”.

- Motivation
- Radiative Neutrino Mass Models
 - Non-standard Neutrino Interaction
 - Unified framework for B-anomalies, muon $g-2$ and neutrino masses
 - Left-Right Symmetric Model without Higgs Triplet
- Conclusion
- Future Direction

Sketch of Standard Model

	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Matter	$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3, 2, 1/3)$ $\psi_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, -1)$ $e_R \sim (1, 1, -2), \quad u_R \sim (3, 1, 4/3)$ $d_R \sim (3, 1, -2/3)$
Higgs	$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (1, 2, 1)$



Lagrangian

$$\underbrace{-\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu}}_{\text{Gauge interaction}} + \underbrace{i\bar{\psi}\not{D}\psi + h.c.}_{\text{Matter fermions}} + \underbrace{\bar{\psi}_i y_{ij} \psi_j \phi + h.c.}_{\text{Yukawa Interactions}} + \underbrace{|D_\mu \phi|^2 - V(\phi)}_{\text{Higgs Interaction}}$$

$$M_\nu = 0$$

ν mass

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

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

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

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \rightarrow 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \rightarrow 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \rightarrow 35.87$
$\sin^2 \theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \rightarrow 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \rightarrow 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \rightarrow 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \rightarrow 52.0$
$\sin^2 \theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \rightarrow 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \rightarrow 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \rightarrow 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \rightarrow 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \rightarrow 403$	286^{+27}_{-32}	$192 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.04$
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \rightarrow +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \rightarrow -2.412$

I Estaban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, A. Zhou (2020)

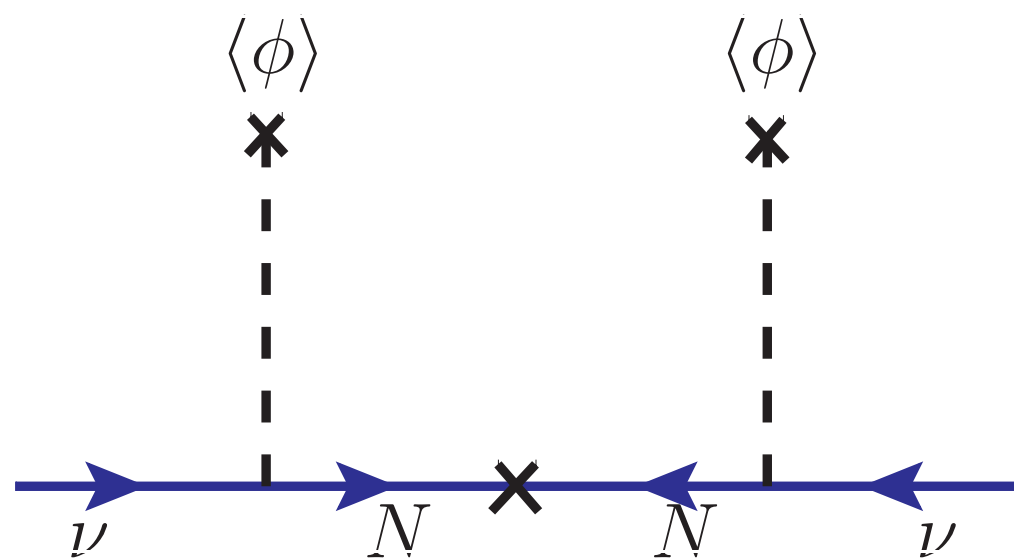
- **Simplest possibility:** Introduce ν_R to the SM allowing

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

- $m_\nu \sim 0.1 \text{eV}$, 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 $m_\nu \ll m_q$ or m_ℓ
- Schemes for neutrino masses and mixings
 - **Tree-level Seesaw** mechanism
 - **Radiative** schemes

Seesaw Paradigm

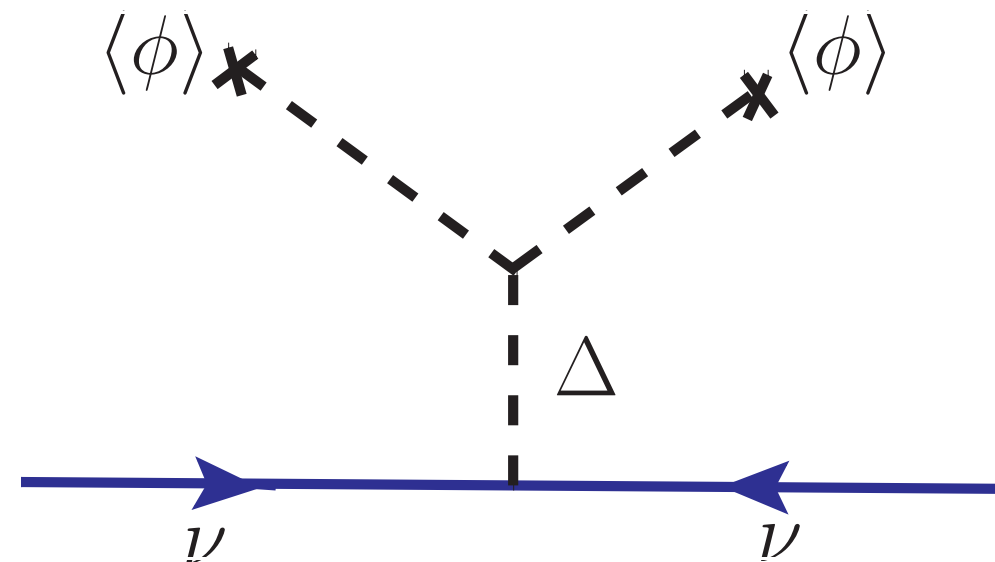
- Light neutrino mass is induced via **Weinberg's dim-5 operator**, $LL\phi\phi$
- Large **Majorana mass scale** Λ to suppress the neutrino mass via $\frac{\langle\phi\rangle^2}{\Lambda}$



Type I / Type III :

ν - mass induced from **fermion exchange**

$$N^1 \sim (1,1,0) \quad N^3 \sim (1,3,0)$$



Type II :

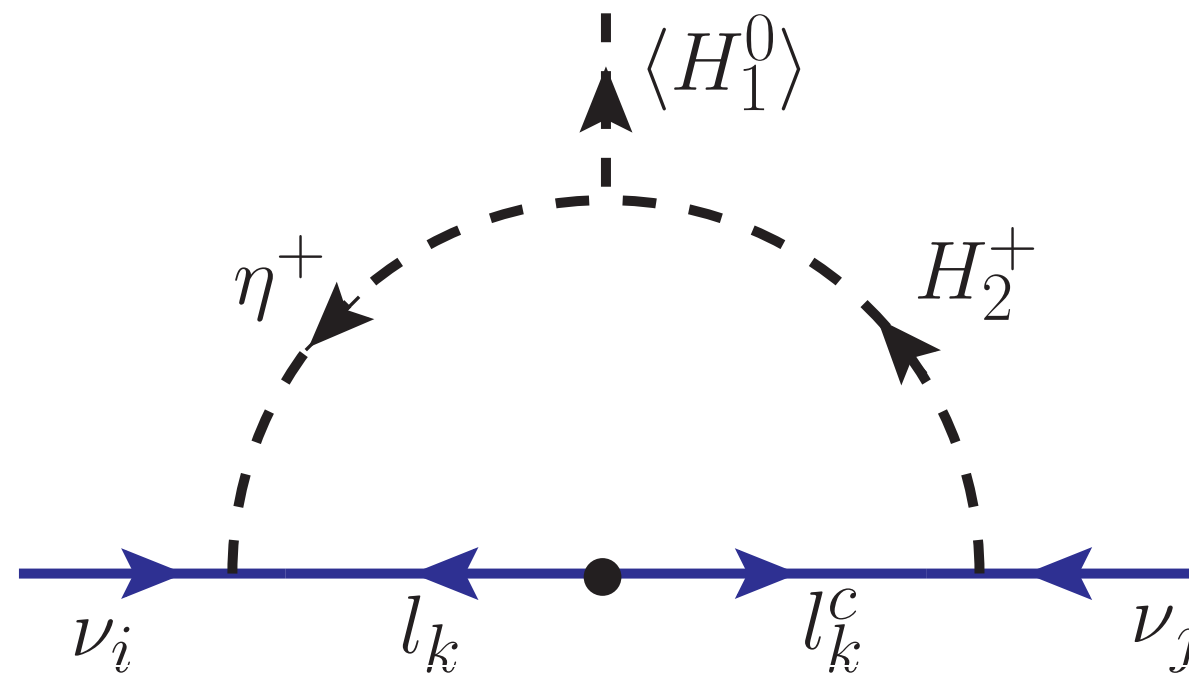
ν - mass induced from scalar **exchange**

$$\Delta \sim (1,3,1)$$

- The scale of new physics can be **rather high** $\sim 10^{14}$ GeV

Radiative ν mass generation

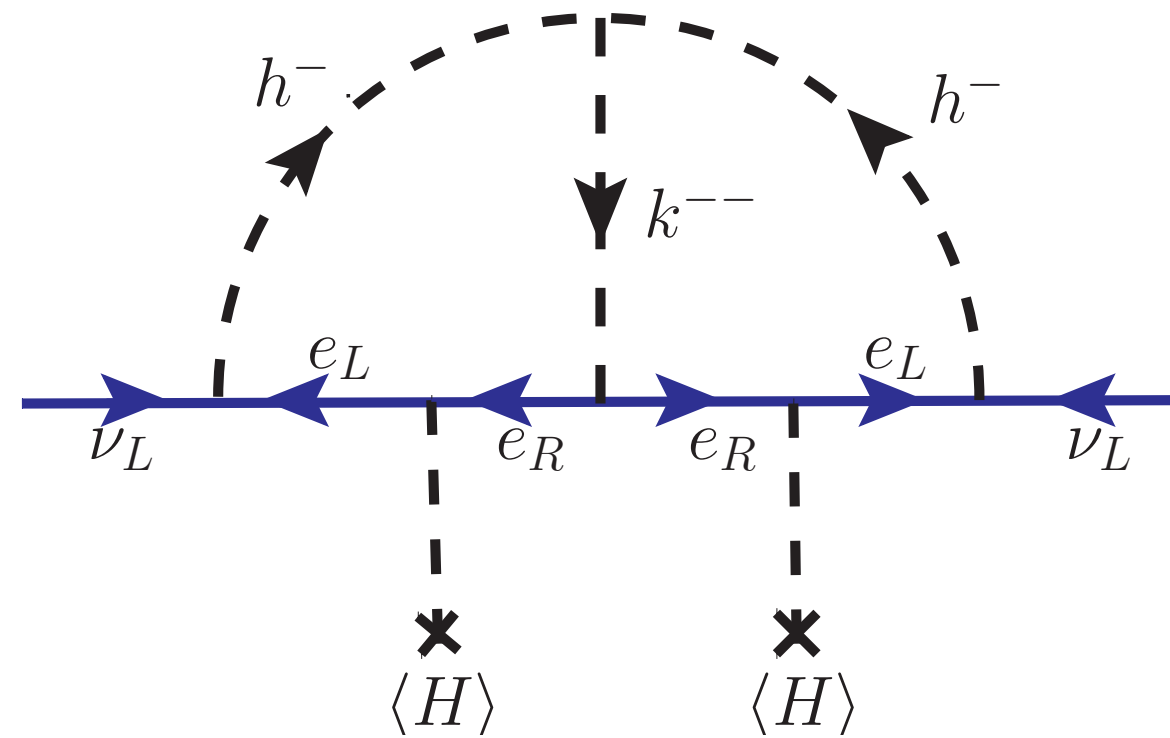
- Neutrino masses are **zero at tree level**: ν_R may be absent
- Small, finite masses are generated as **quantum corrections**
- Typically involves exchange of two scalars **leading to lepton number violation**
- Simple realization is the **Zee Model**, which has a second **Higgs doublet** and a **charged 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 $d = 7, 9, 11 \dots$ 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

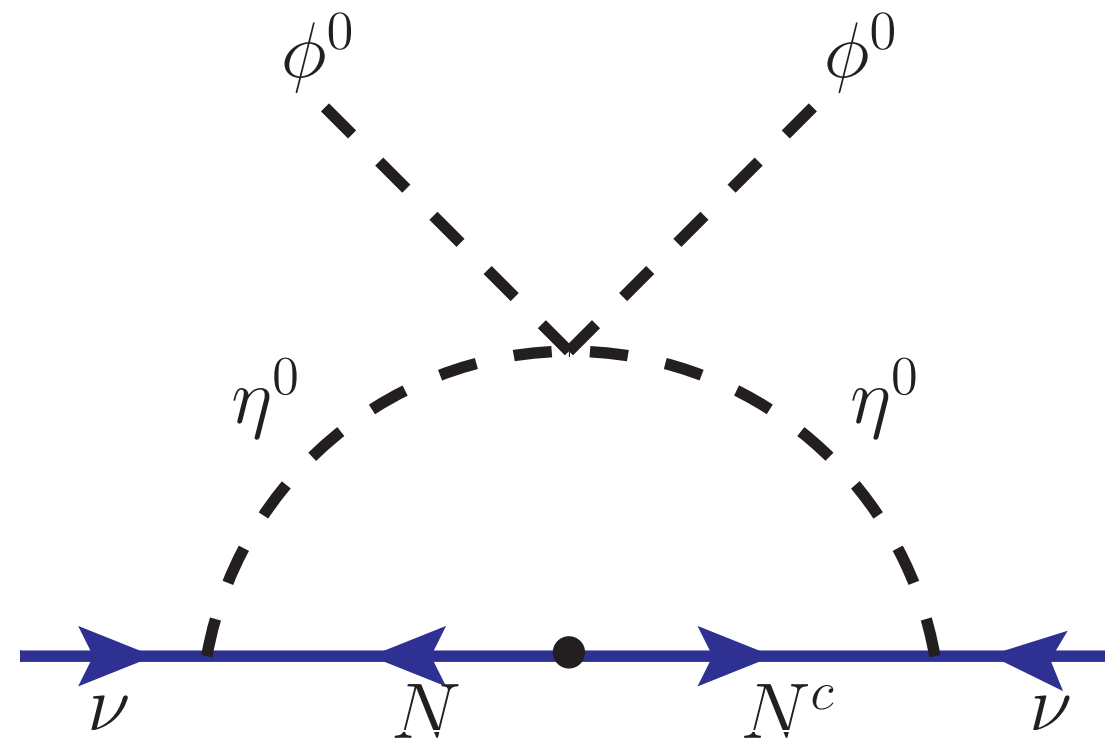
Classification : Babu, Leung (2001)

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

Babu, Dev, Jana, Thapa (2020)

Type II radiative mechanism

- No Standard Model particle inside the loop
- Cannot be cut to generate $d = 7, 9, \dots$ 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)

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Nonstandard Neutrino Interactions

- New physics near **TeV scale** can generate **nonstandard neutrino interactions (NSI)**
- Most important effect of NSI is in neutrino **propagation in matter**
Wolfenstein (1978)

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

- Matter potential

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

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

Esteban, Gonzalez-Garcia, Maltoni (2019)

Zee Model

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

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

- Mixing between η^+ and H_2^+ :

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

where

$$\begin{aligned} h^+ &= \cos \varphi \eta^+ + \sin \varphi H_2^+ \\ H^+ &= -\sin \varphi \eta^+ + \cos \varphi H_2^+ \end{aligned}$$

Neutrino Masses in Zee Model

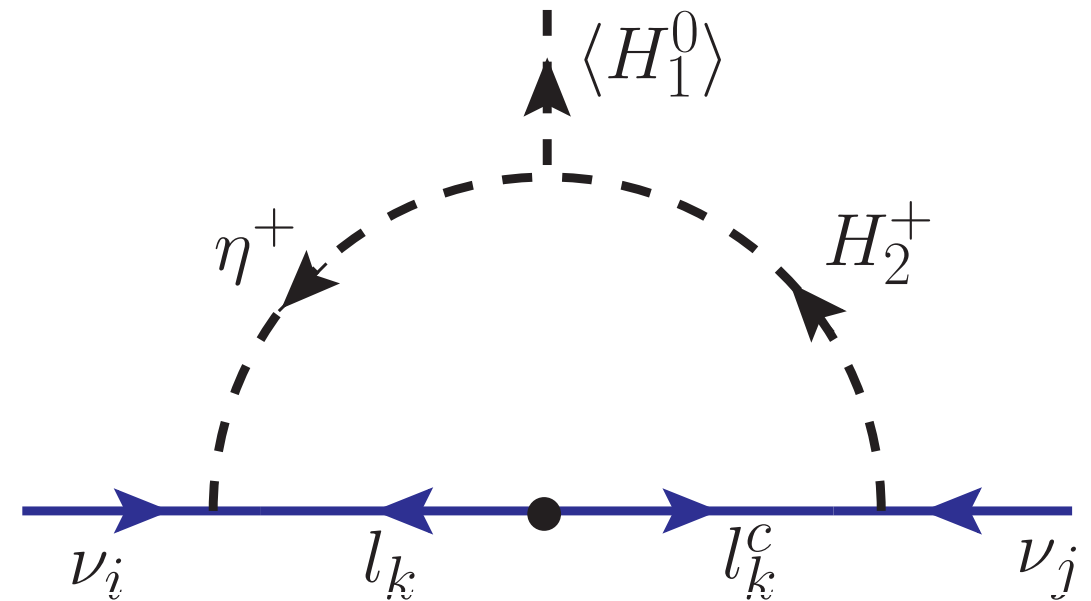
- Yukawa Coupling Matrices

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

- Neutrino Mass

$$M_\nu = \kappa (f M_l Y^T + Y M_l f^T)$$

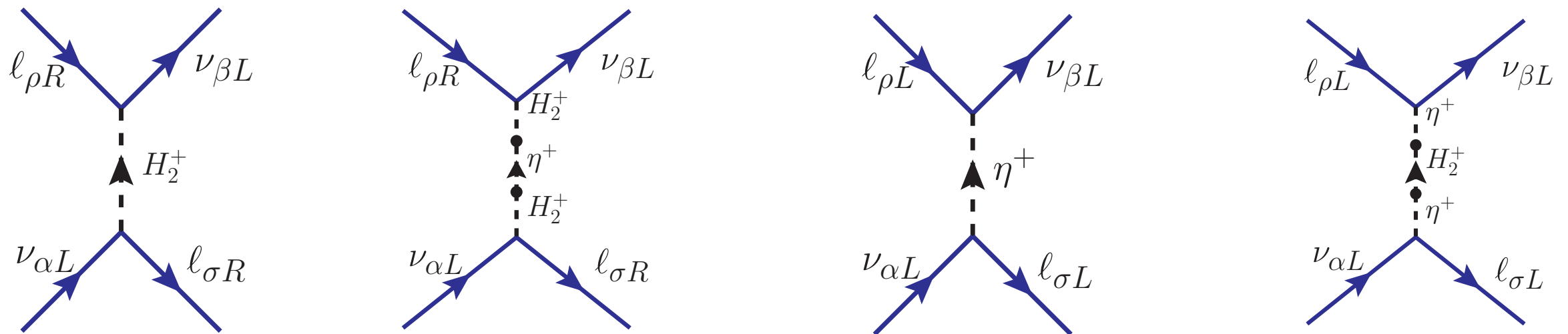
$$\kappa = \frac{1}{16\pi^2} \sin 2\varphi \log \frac{m_{h^+}^2}{m_{H^+}^2}$$



- If $Y \propto M_l$, which happens with a Z_2 , then **model is ruled out**
Wolfenstein (1980)
- In general, Y not proportional to M_l , and the model gives reasonable fit to oscillation data

NSI in Zee Model

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

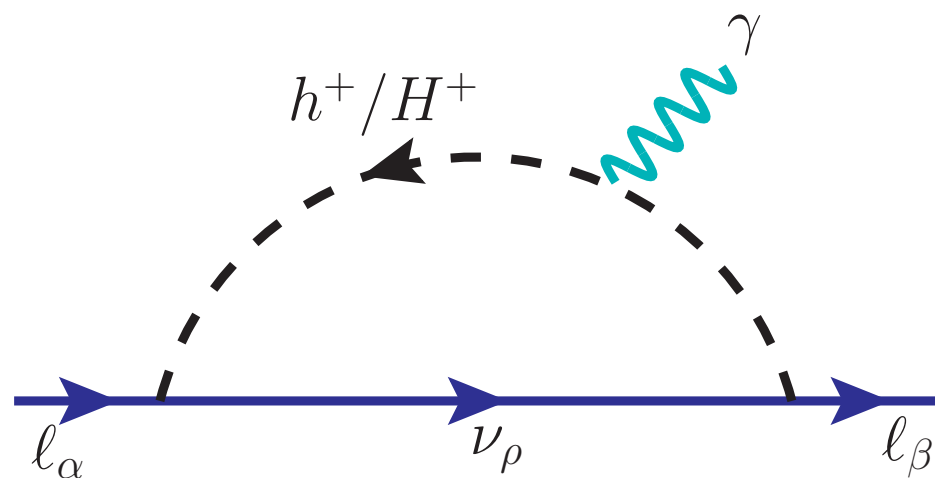


- Considering, $y \sim \mathcal{O}(1)$ and $M_\nu \sim \mathcal{O}(10^{-1})$ eV demands $f \sim 10^{-8}$
 $\Rightarrow$ NSI effect from f is heavily suppressed

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

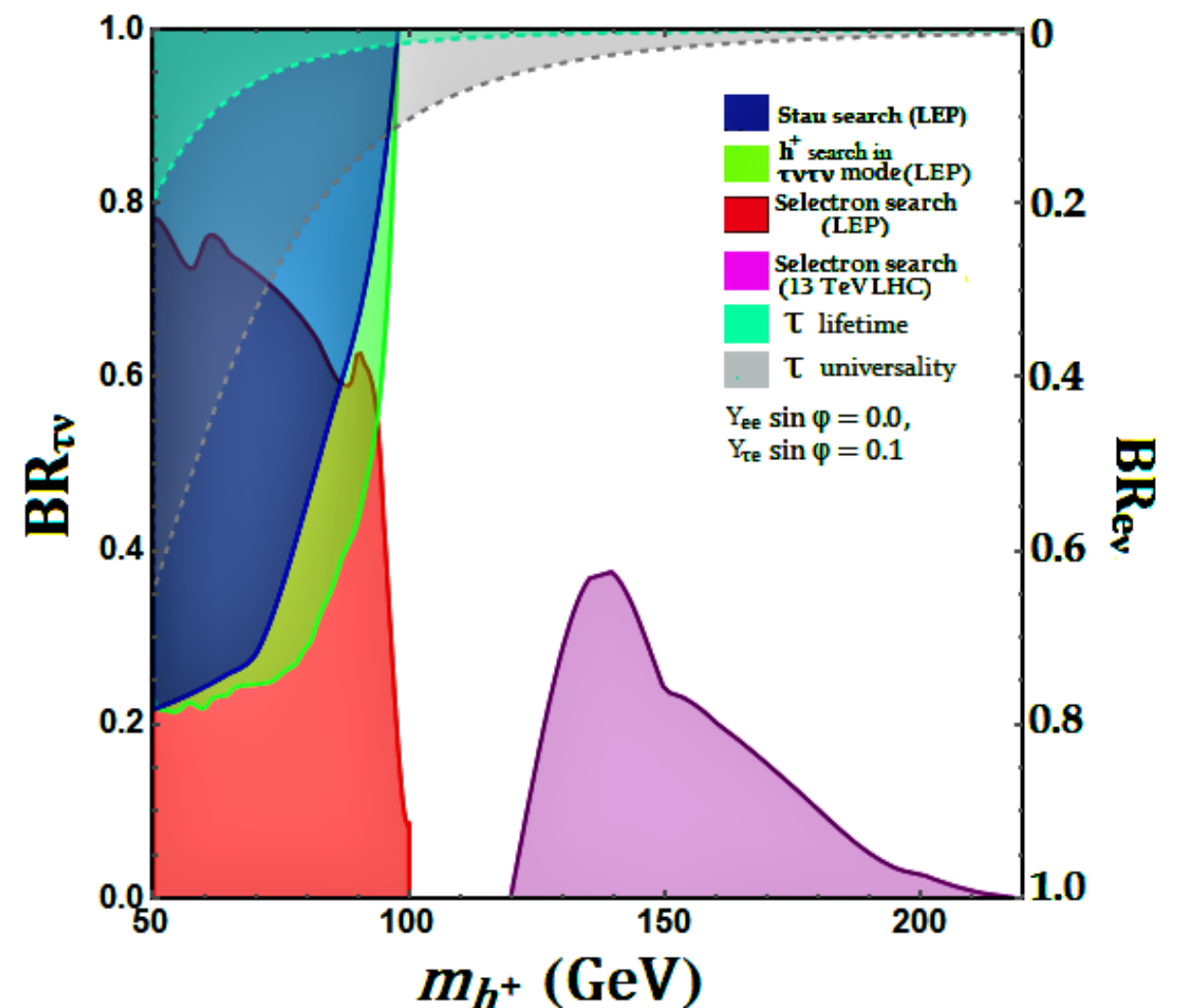
Constraints on Zee Model

- Electroweak T parameter
- $\mu \rightarrow e\gamma, \mu \rightarrow 3e$
- τ lifetime and universality
- Lepton universality in $W^\pm$ decay
- Charge breaking minima
- Higgs precision physics limit
- LEP direct search limits
- Constraints from LHC searches



$$\mu \rightarrow e\gamma \text{ (BR} < 4.2 \times 10^{-13}\text{)}$$

$$|Y_{\mu e}^* Y_{ee}| < 1.05 \times 10^{-3} \left(\frac{m_H}{700 \text{ GeV}} \right)^2$$



- The lowest charged Higgs mass allowed is 96 GeV

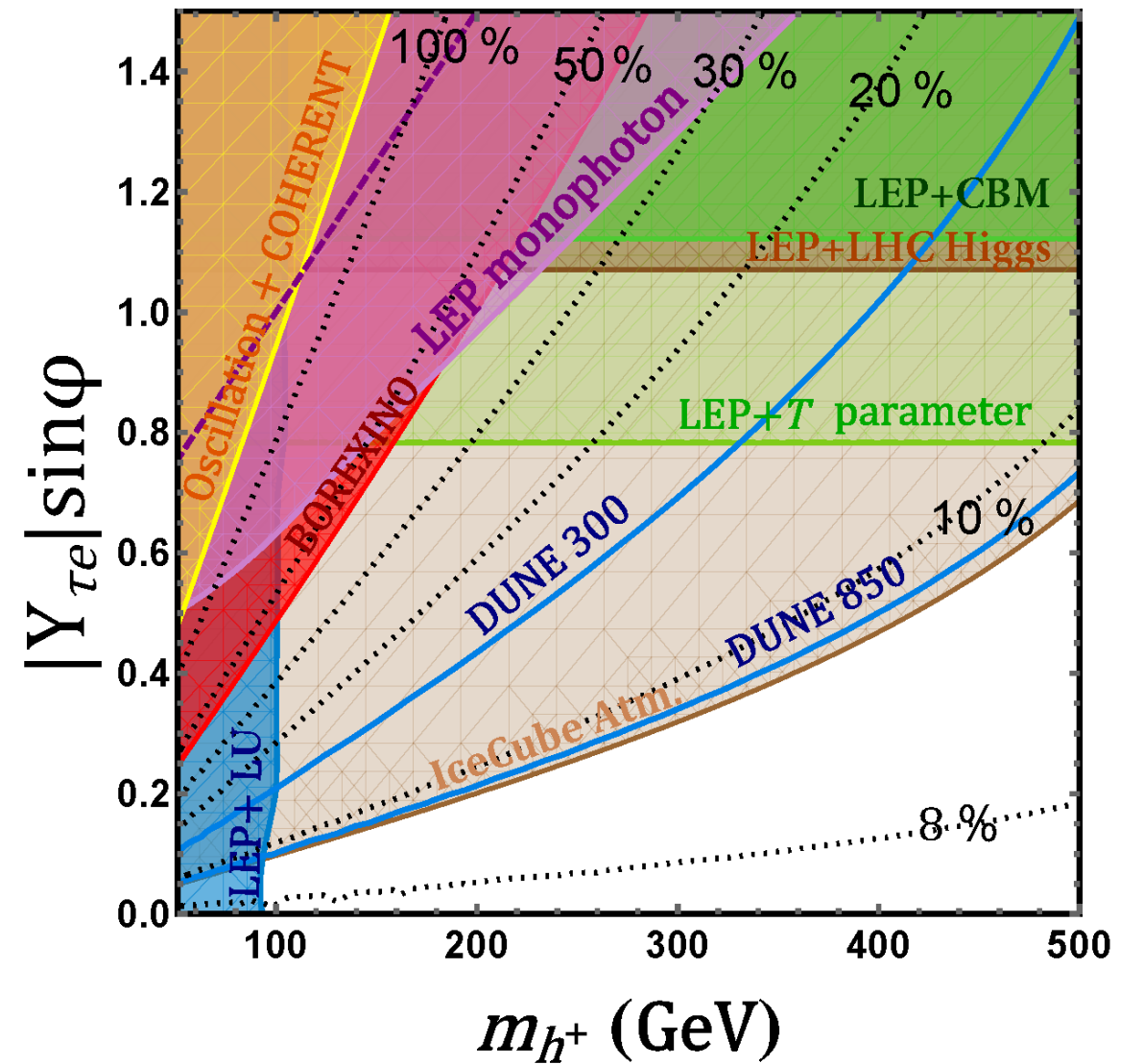
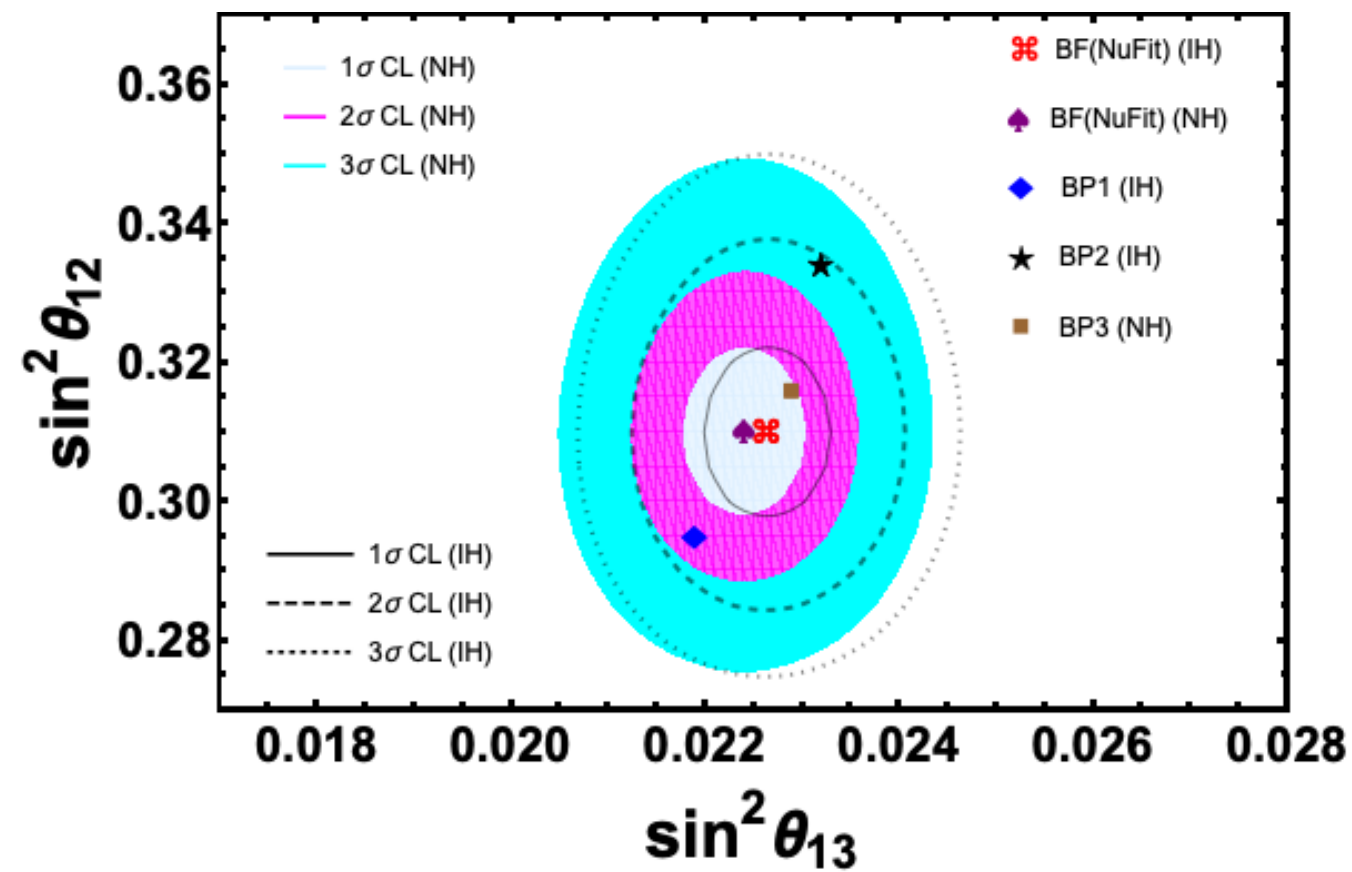
Results

$$\text{BP1:} \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & 0 & Y_{\tau\tau} \end{pmatrix}$$

$$\text{BP2:} \begin{pmatrix} 0 & 0 & Y_{e\tau} \\ Y_{\mu\mu} & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & 0 & Y_{\tau\tau} \end{pmatrix}$$

$$\text{BP3:} \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & 0 & Y_{\tau\tau} \end{pmatrix}$$

$\epsilon_{\tau\tau}$



$$\epsilon_{ee}^{\max} \approx 3.0 \%$$

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

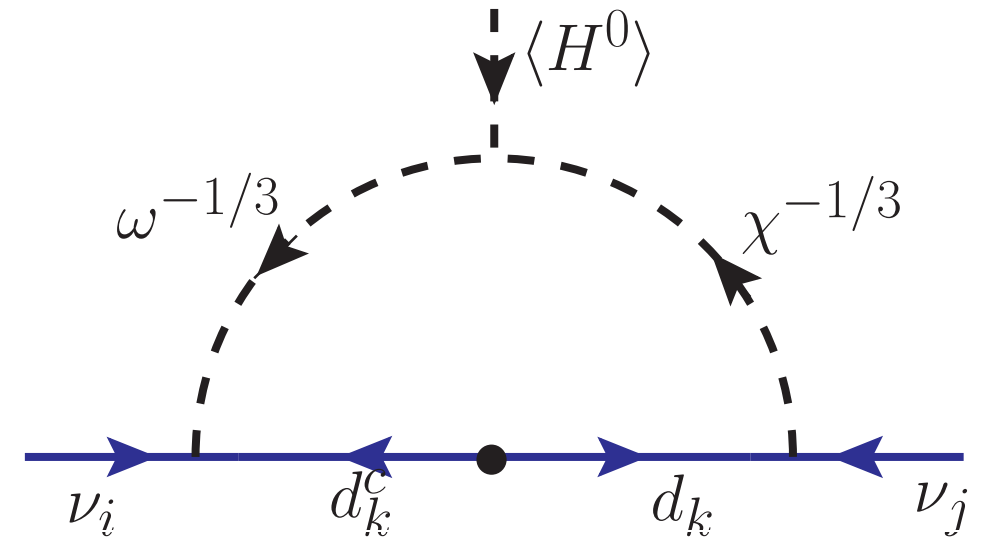
$$\epsilon_{\tau\tau}^{\max} \approx 9.3 \%$$

NSI in Leptoquark: Colored Zee Model

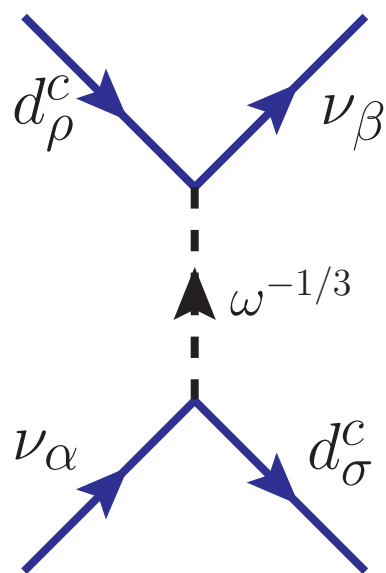
- Two $SU(3)_C$ scalar fields: $\Omega \sim (3, 2, 1/6)$ and $\chi^{-1/3} \sim (3, 1, -1/3)$ are introduced.

$$M_\nu = \kappa(\lambda M_d \lambda'^T + \lambda' M_d \lambda^T)$$

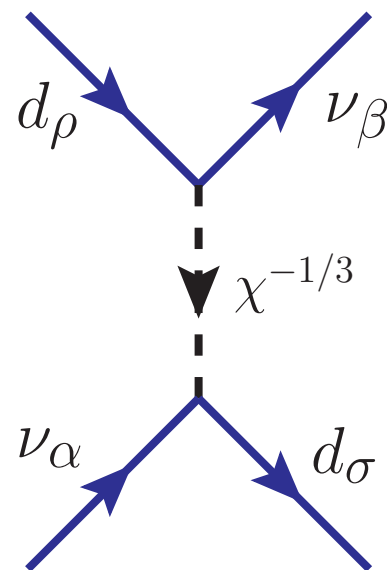
$$\kappa = \frac{3 \sin 2\varphi}{32\pi^2} \log \frac{M_1^2}{M_2^2}$$



- Choosing $\lambda\lambda' \approx 0 \Rightarrow \lambda \sim \mathcal{O}(1)$ or $\lambda' \sim \mathcal{O}(1) \Rightarrow$ satisfies ν -mass constraints



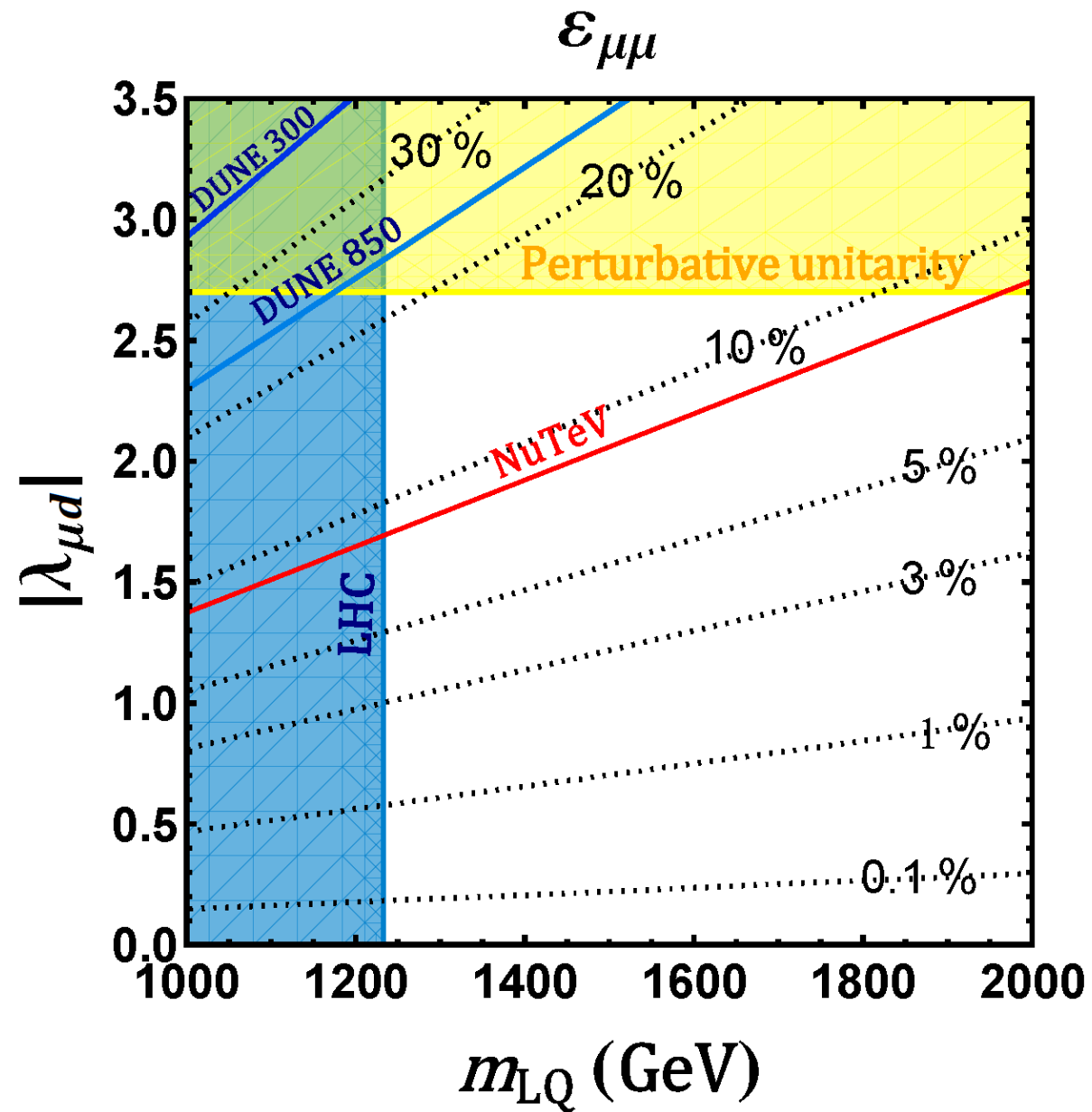
$$\lambda \sim \mathcal{O}(1)$$



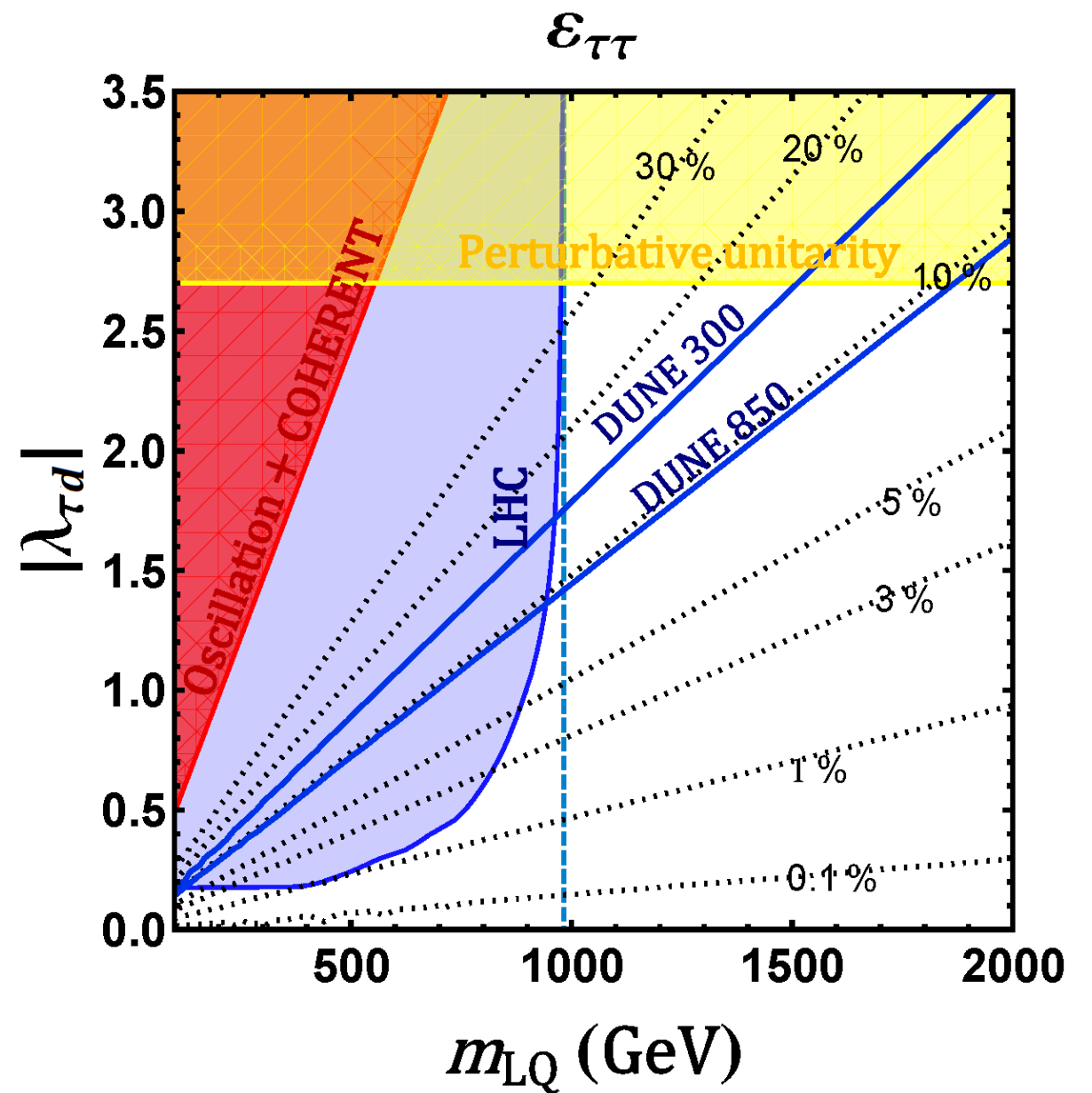
$$\lambda' \sim \mathcal{O}(1)$$

$$\epsilon_{\alpha\beta}^d = \frac{1}{4\sqrt{2} G_F} \left(\frac{\lambda_{\alpha d}^* \lambda_{\beta d}}{m_\omega^2} + \frac{\lambda_{\alpha d}'^* \lambda_{\beta d}'}{m_\chi^2} \right)$$

NSI prediction



$$\epsilon_{\mu\mu}^{\max} \approx 21.6 \%$$

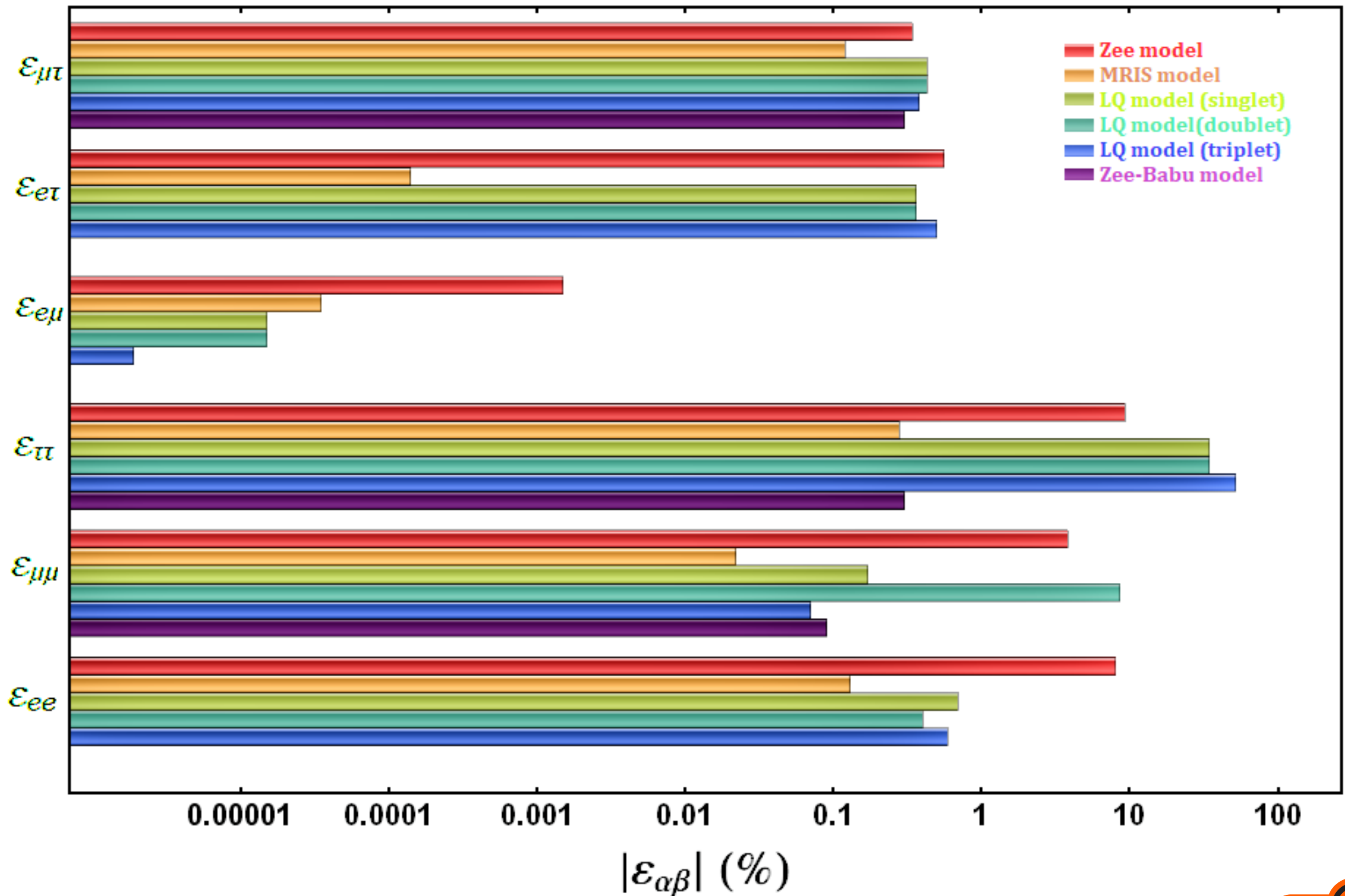


$$\epsilon_{\tau\tau}^{\max} \approx 34.3 \%$$

Summary of type-I Models

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

Summary

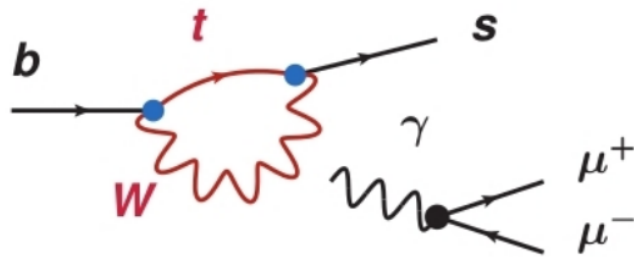


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 - **Unified framework for B-anomalies, muon $g-2$ and neutrino masses**
 - Left-Right Symmetric Model without Higgs Triplet
- Conclusion
- Future Direction

Goal

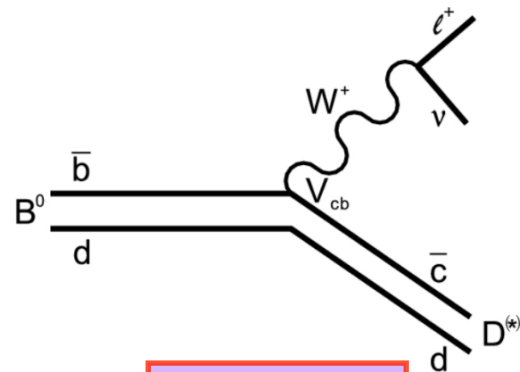
Construct a **Neutrino mass model** with **New Physics at TeV scale** that can resolve the following and simultaneously fit neutrino oscillation data: $(\Delta m_{21}^2, \Delta m_{31}^2, \sin^2 \theta_{13}, \sin^2 \theta_{23}, \sin^2 \theta_{12}, \delta_{CP})$

- R_K and R_{K^*}



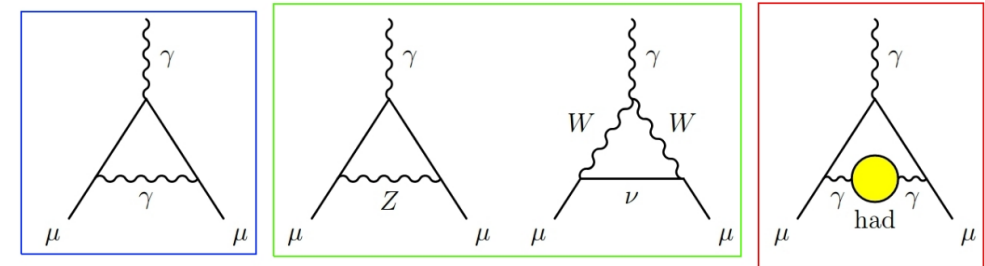
$\sim 3.1\sigma$

- R_D and R_{D^*}



$\sim 3.0\sigma$

- $(g - 2)_\mu$



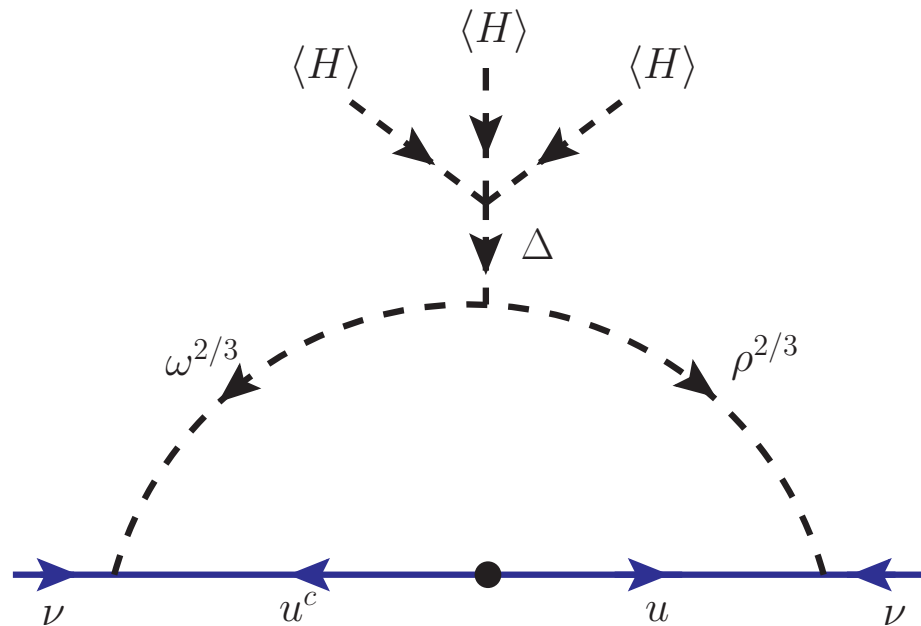
$\sim 4.2\sigma$

If confirmed: Implications for **New Physics**

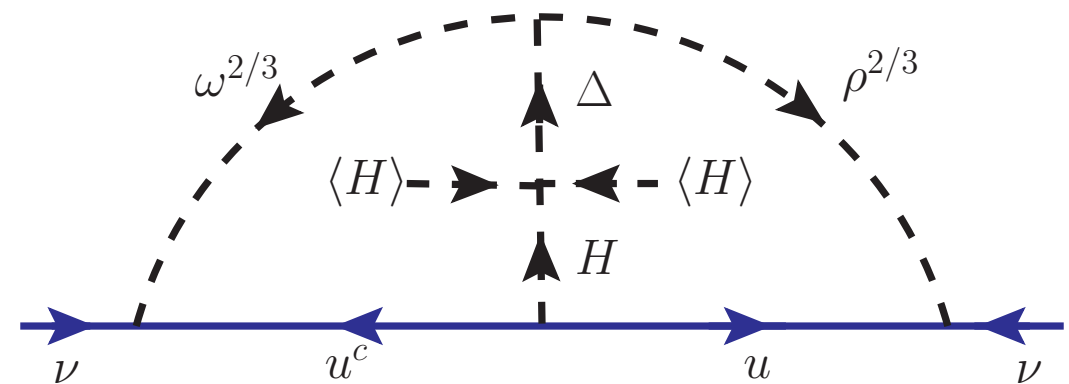
- Collider Phenomenology** with new scalars
- $\Delta a_\mu \iff h \rightarrow \mu\mu$ and $h \rightarrow \tau\tau$
(Crivellin, Mueller, Saturnino, 2020)

Model

The model is based on $SU(3)_C \times SU(2)_L \times U(1)_Y$, with an extended scalar sector $R_2 \sim (3, 2, 7/6)$, $S_3 \sim (\bar{3}, 3, 1/3)$ and $\Delta \sim (1, 4, 3/2)$



$$\mathcal{O}_{\text{eff}}^{d=7} = \psi\psi HHH^\dagger H$$



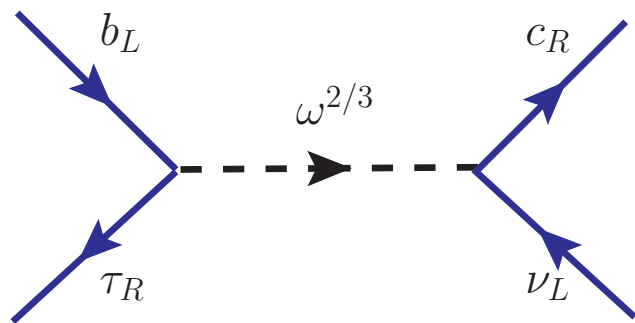
$$\mathcal{O}_{\text{eff}}^{d=5} = \psi\psi HH$$

$$M_\nu = (\kappa_1 + \kappa_2)(f^T M_u V^\star y + y^T V^\dagger M_u f)$$

$$\kappa_1 = \frac{1}{16\pi^2} \sin 2\varphi \log\left(\frac{M_2^2}{M_1^2}\right) \quad \kappa_2 \approx \frac{1}{(16\pi^2)^2} \frac{\lambda_5 v \mu}{M_{1,2}^2}$$

Babu, Dev, Jana, Thapa, 20
Popov, Schmidt, White, 19

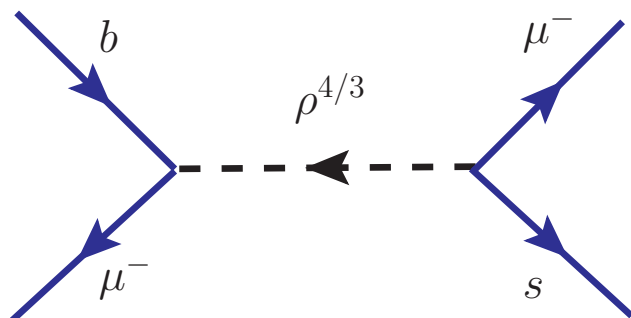
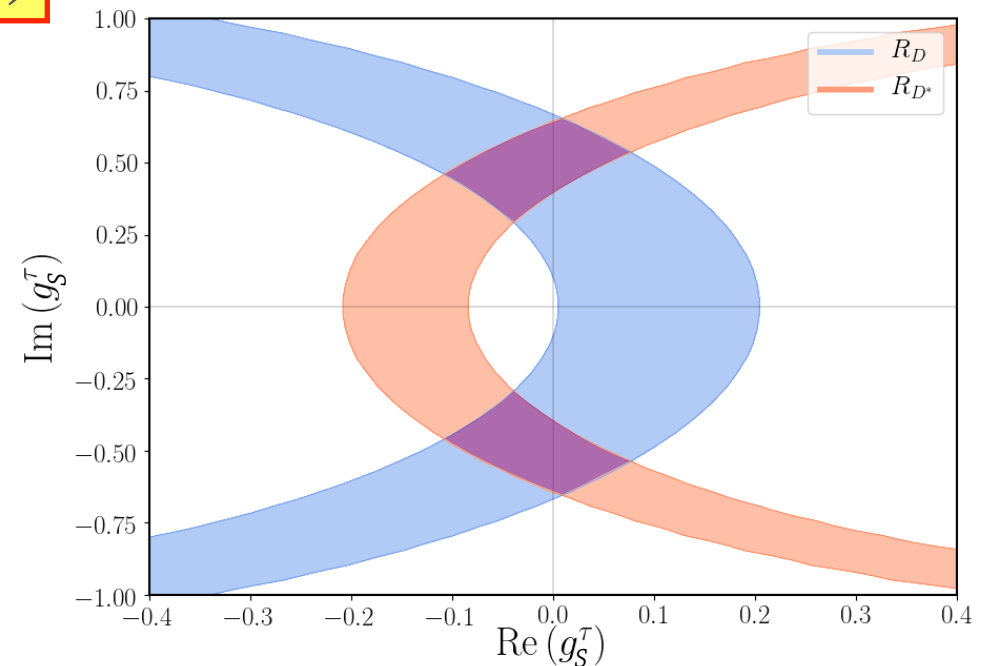
New Physics for anomalies



$$R_2 \sim (3, 2, 7/6)$$

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + g_V)(\bar{\tau}_L \gamma^\mu \nu_L) (\bar{c}_L \gamma_\mu b_L)]$$

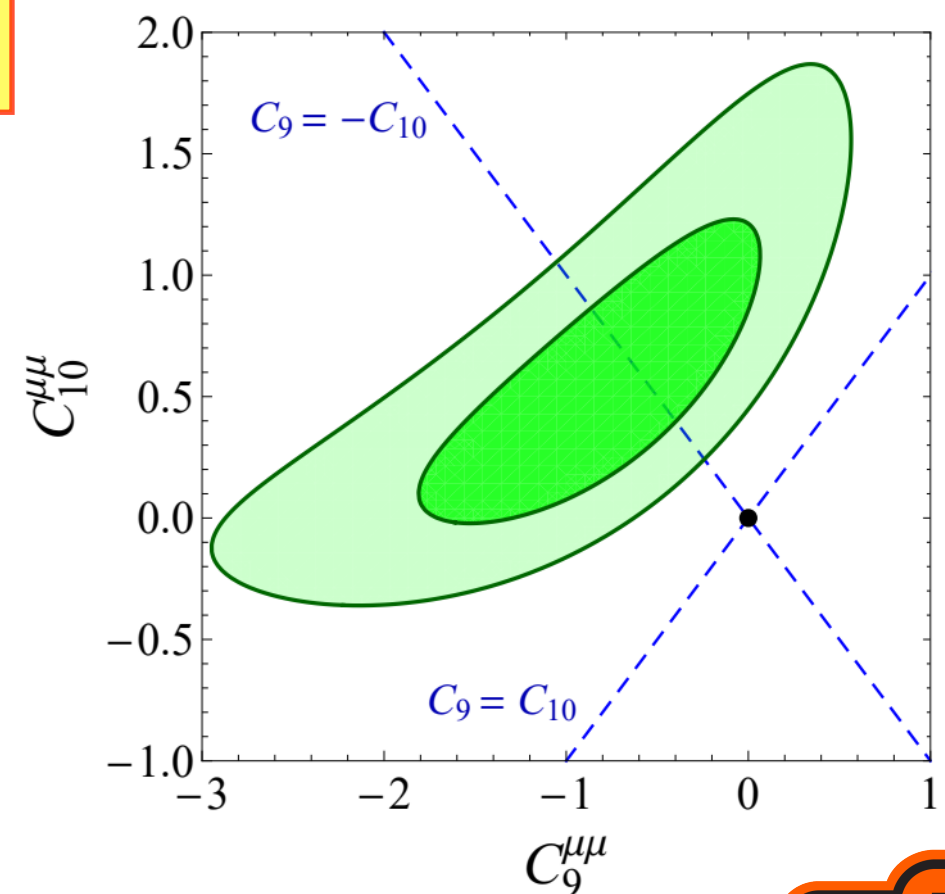
$$g_S (\bar{\tau}_R \nu_L)(\bar{c}_R b_L) + g_T (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) (\bar{c}_R \sigma_{\mu\nu} b_L)$$



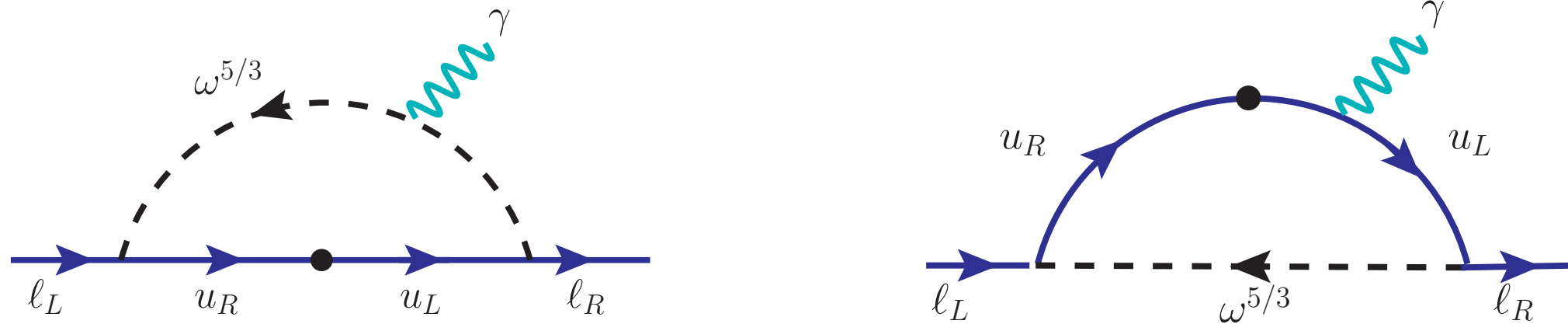
$$S_3 \sim (\bar{3}, 3, 1/3)$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{(4\pi)^2}$$

$$\{ C_9 (\bar{s} \gamma_\mu P_L b)(\bar{\mu} \gamma^\mu P_L \mu) + C_{10} (\bar{s} \gamma_\mu b)(\bar{\mu} \gamma^\mu \gamma^5 \mu) \}$$



Anomalous Magnetic Moment



$$\mathcal{L}_{\omega^{5/3}} = \bar{u}(fP_L + f'P_R)e\omega^{5/3} + \text{H.c.}$$

$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & 0 \end{pmatrix}$$

$$f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f_{32} & 0 \end{pmatrix}$$

- For 1TeV LQ mass, the required product of Yukawa is

$$(g - 2)_\mu : \quad f_{32}f'_{32} = -0.0019$$

Minimal Yukawa texture

$$\mathcal{L}'_{Yuk} = f_{ab} u_a^c \psi_b^i R_2^j \epsilon^{ij} - f'_{ab} Q_a^i e_b^c \tilde{R}_2^j \epsilon^{ij} + y_{ab} Q_a \tau_\alpha \psi_b S_{3\alpha} + \text{H.c}$$

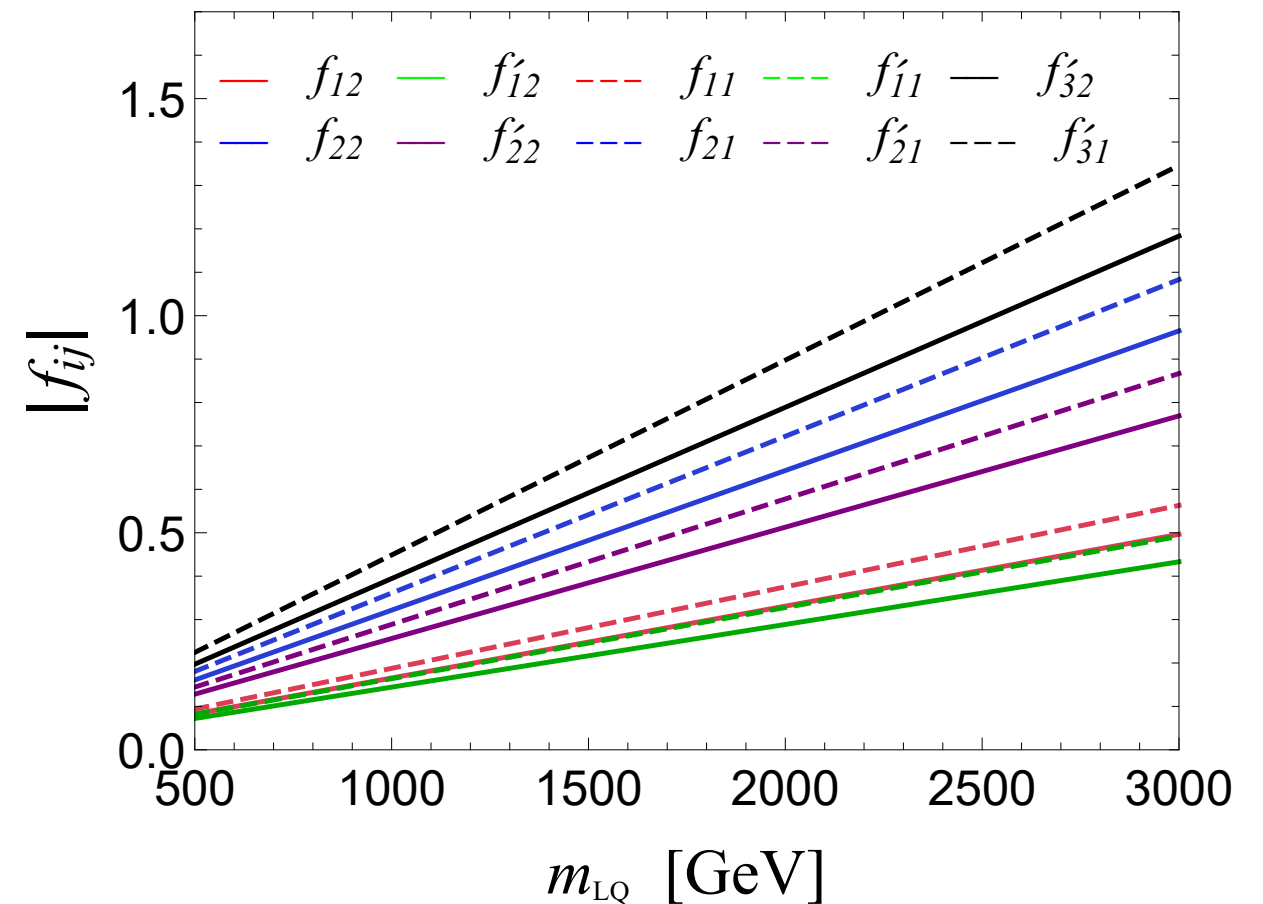
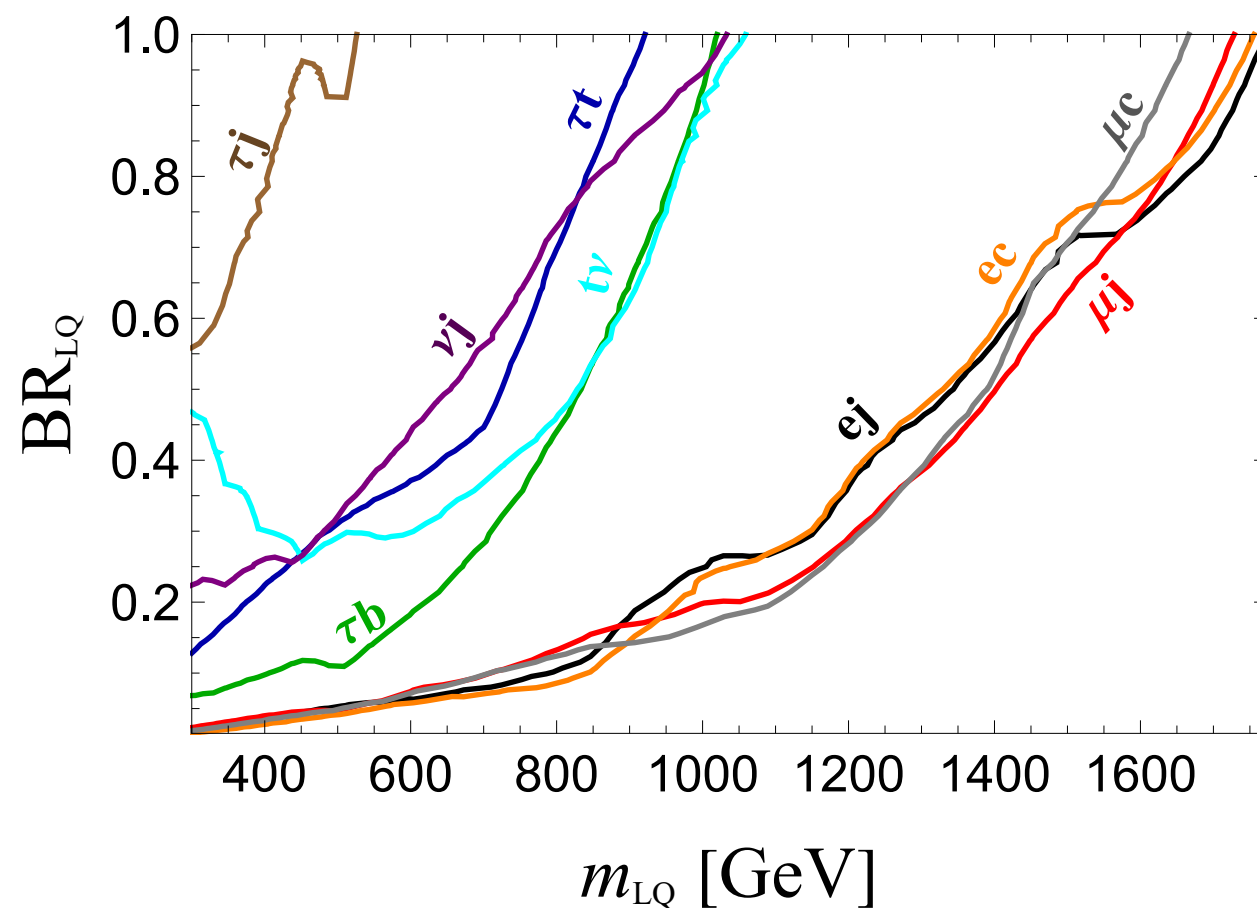
$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & f'_{33} \end{pmatrix} \quad f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & f_{22} & f_{23} \\ 0 & f_{32} & f_{33} \end{pmatrix} \quad y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ y_{31} & y_{32} & 0 \end{pmatrix}$$

f_{ab} (a $\rightarrow$ quark flavor, b $\rightarrow$ lepton flavor)

- $f'_{32} f_{32} : (g - 2)_\mu$
- $f'_{33} f_{23} + f'_{33} f_{22} : R_D - R_{D^*}$
- $f_{33} : \text{mild fine-tuning to suppress } \tau \rightarrow \mu\gamma$
- $y_{22} y_{32} : R_K - R_{K^*}$
- $y_{31}, y_{23} : \nu \text{ fit } (\Delta m_{21}^2, \Delta m_{31}^2, \sin^2 \theta_{13}, \sin^2 \theta_{23}, \sin^2 \theta_{12}, \delta_{CP})$

Constraints

- $\ell_i \rightarrow \ell_j \gamma$
- $\mu - e$ conversion
- $Z \rightarrow \tau\tau$ decay
- Rare D -meson Decay
- $D^0 - \bar{D}^0$ mixing
- Bounds from kaons
- Collider constraints
 - Pair-production Bounds
 - Dilepton Bounds



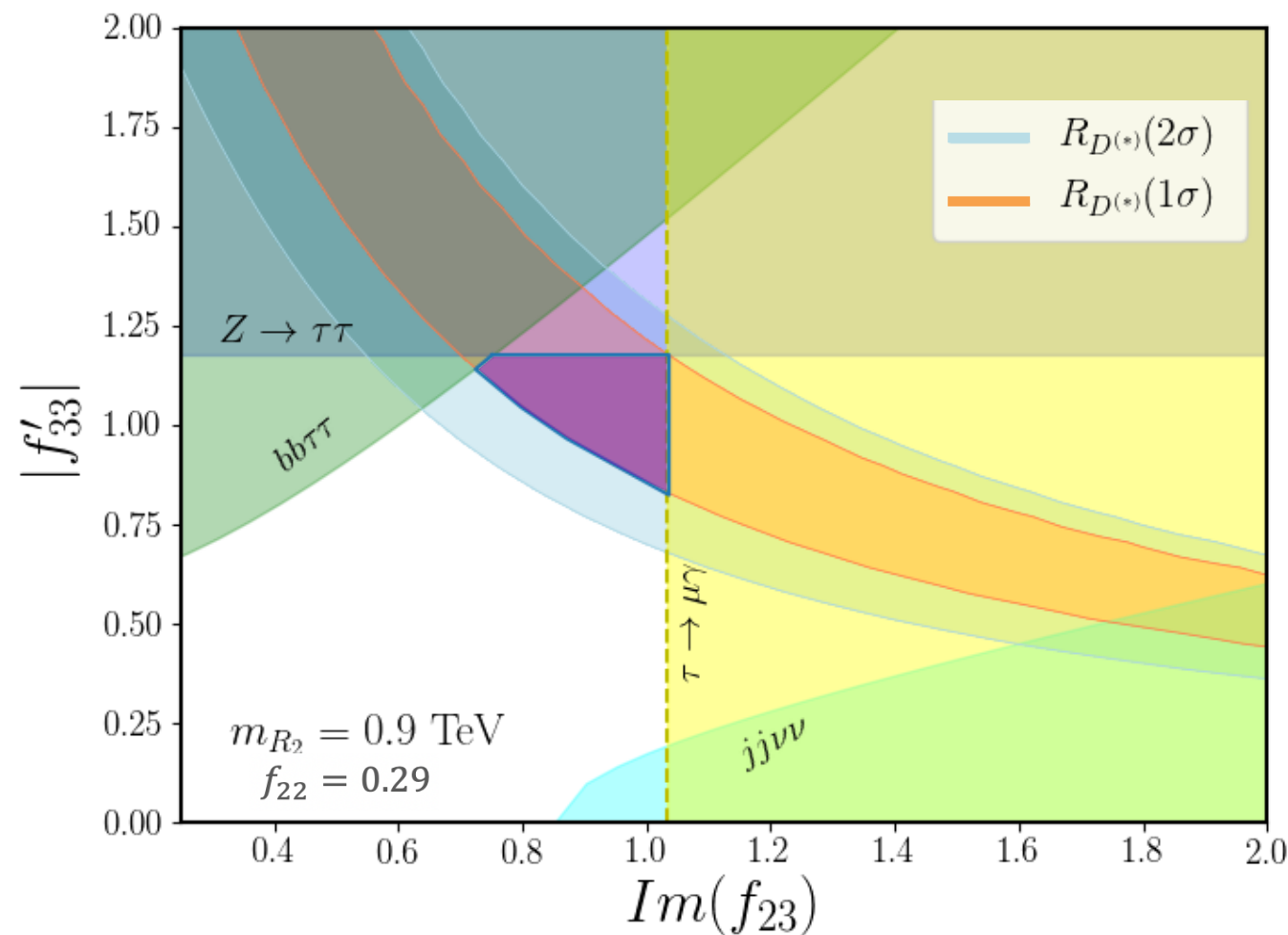
Results

$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.29 & 1.06 \end{pmatrix}$

$f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.29 & 0.89i \\ 0 & 0.006 & 0.023 \end{pmatrix}$

$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.124 & 0.064 \\ -0.016 & 0.028 & 0 \end{pmatrix}$

Oscillation Parameter	s_{12}^2	s_{13}^2	s_{23}^2	$\Delta m_{21}^2 \text{ eV}^2$	$\Delta m_{23}^2 \text{ eV}^2$	$\delta/^\circ$
Model Fit	0.29	0.023	0.47	$7.39 \cdot 10^{-5}$	$2.54 \cdot 10^{-3}$	320

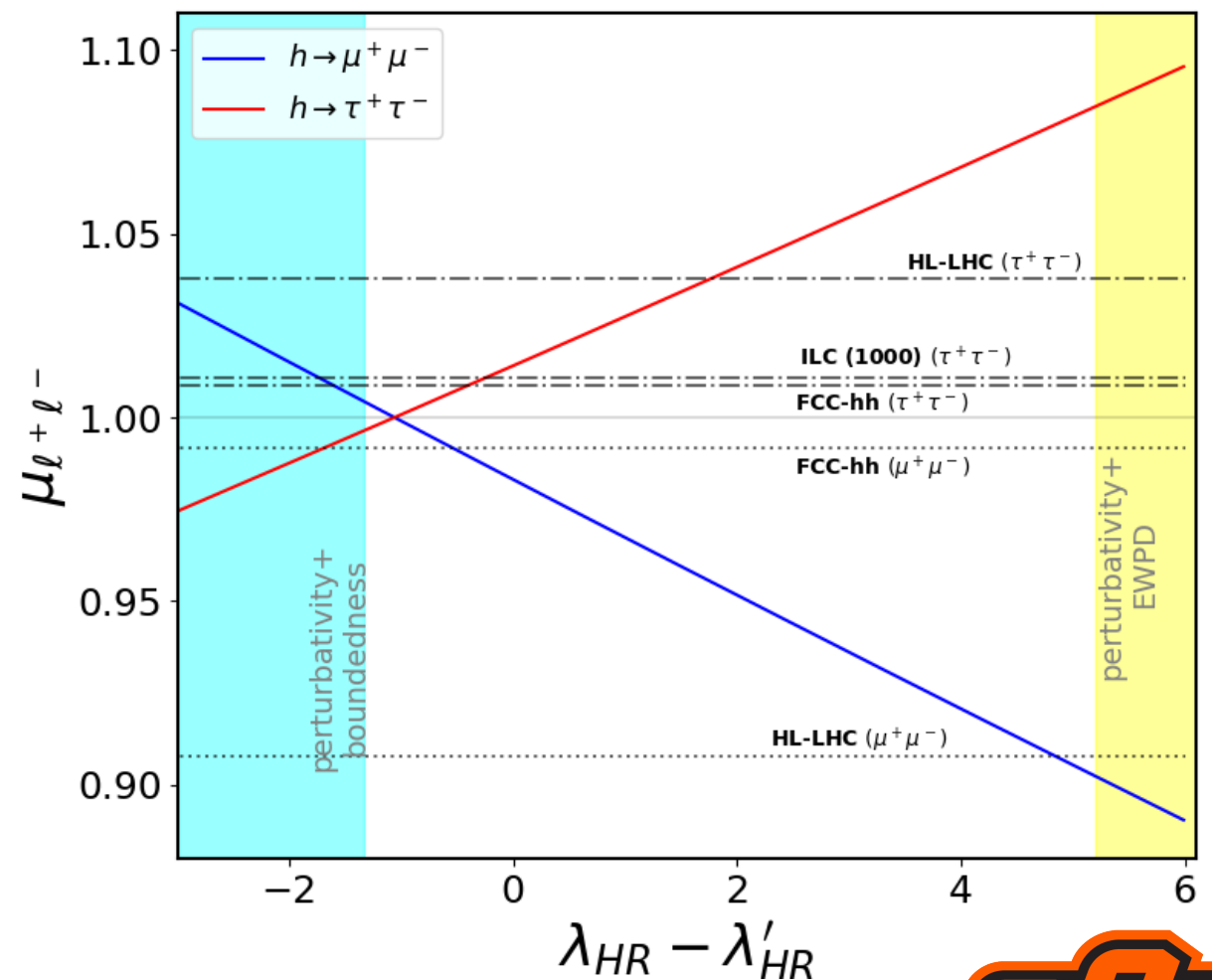
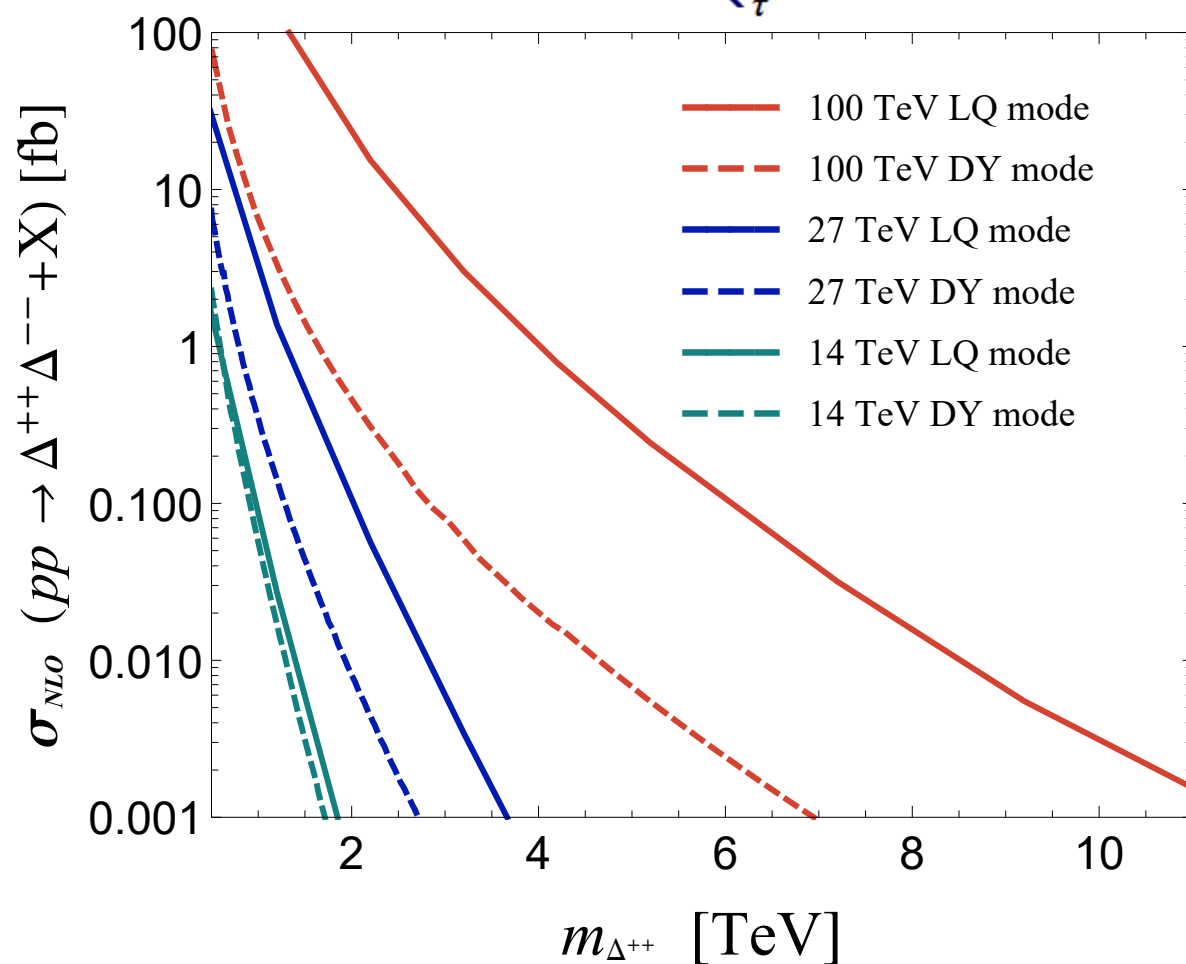
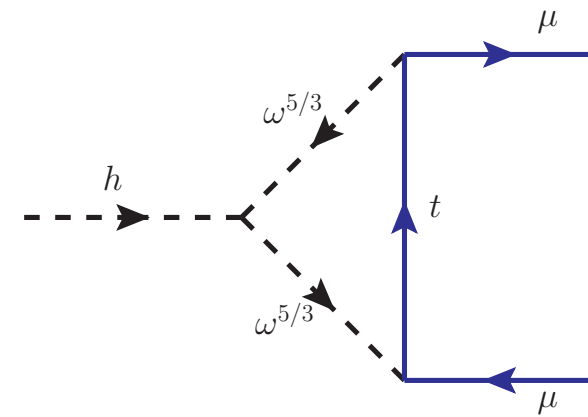
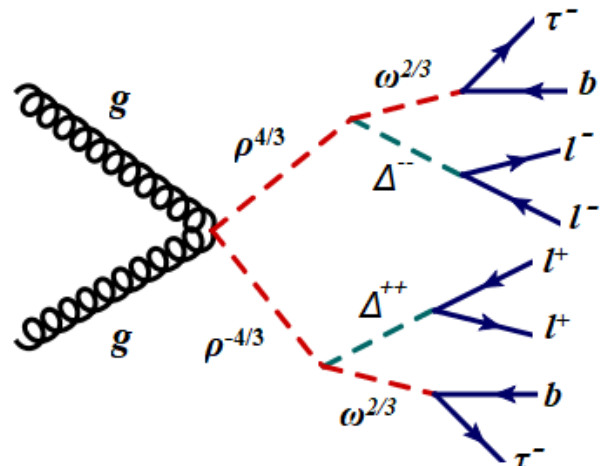


Observable	R_D	R_{D^*}	$C_9 = -C_{10}$	$(g-2)_\mu$
Model Fit	0.34	0.282	-0.52	$2.97 \cdot 10^{-9}$



Collider Implications

- Same operator to neutrino masses also induces an effective Δ -quadruplet coupling to the SM leptons. $Y_\Delta \sim M_\nu/v_\Delta$
- Same R_2 LQ responsible for Δa_μ give rise $h \rightarrow \mu\mu$ and $h \rightarrow \tau\tau$



- Motivation
- Radiative Neutrino Mass Models
 - Non-standard Neutrino Interaction
 - Unified framework for B-anomalies, muon $g-2$ and neutrino masses
 - **Left-Right Symmetric Model without Higgs Triplet**
- Conclusion
- Future Direction

Features

- Parity is explicitly broken in Standard Model.
- Left-right models were introduced primarily to understand the origin of parity violation.
Mohapatra, Pati, Senjanovic: 74-75
- In LRSM hypercharge Y arises more coherently from less arbitrary quantity $B - L$.

$$Q = T_L^3 + T_R^3 + \frac{B - L}{2}$$

- ν_R exists as $SU(2)_R$ multiplet. $SU(2)_R$ breaking gives heavy Majorana right handed neutrino. Thus, smallness of left-handed neutrinos is naturally realized via see-saw mechanisms.

LR symmetric Model

- Gauge group: $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

- Fermion Representation :

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \sim (2, 1, 1/3), \quad \begin{pmatrix} u \\ d \end{pmatrix}_R \sim (1, 2, 1/3), \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \sim (2, 1, -1), \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_R \sim (1, 2, -1)$$

- Higgs Representation :

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \quad \eta^+ \quad \chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \quad \chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$$

- Symmetry Breaking :

$$\begin{aligned} \langle \Phi \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha} \end{pmatrix} \\ \langle \chi_L \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_L e^{i\theta_L} \end{pmatrix} \\ \langle \chi_R \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix} \end{aligned}$$

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$



$$SU(2)_L \otimes U(1)_Y$$



$$U(1)_{em}$$

$$\langle \chi_R \rangle \neq 0 \Rightarrow M_{W_R}, M_{Z_R} \neq 0$$

$$\begin{aligned} \langle \Phi \rangle \neq 0 &\Rightarrow M_{W_L}, M_Z \neq 0 \\ \langle \chi_L \rangle &\neq 0 \end{aligned}$$

Fermion Masses

- $\langle \Phi \rangle \neq 0 \Rightarrow$ Quarks, charged leptons and Dirac neutrinos masses:

$$M_u = \frac{1}{\sqrt{2}} (Y \kappa + \tilde{Y} \kappa' e^{-i\alpha}), \quad M_d = \frac{1}{\sqrt{2}} (Y \kappa' e^{i\alpha} + \tilde{Y} \kappa)$$

$$M_\ell = \frac{1}{\sqrt{2}} (y \kappa' e^{i\alpha} + \tilde{y} \kappa), \quad M_{\nu D} = \frac{1}{\sqrt{2}} (y \kappa + \tilde{y} \kappa' e^{-i\alpha}).$$

$$\kappa = \kappa' \Rightarrow M_u = M_d$$

- **Neutrino mass matrix** spanning (ν, ν^c) read:

$$\begin{pmatrix} M_\nu^L & M_{\nu D} \\ M_{\nu D}^T & M_\nu^R \end{pmatrix}$$

- $M_\nu^{\text{light}} = M_\nu^L - M_{\nu D} (M_\nu^R)^{-1} M_{\nu D}^T = M_\nu^{II} - M_\nu^I$

$$M_\nu^I \gg M_\nu^{II} \Rightarrow \text{type-I} \quad M_\nu^{II} \gg M_\nu^I \Rightarrow \text{type-II}$$

$M_\nu^L, M_\nu^R \Rightarrow$ **one-loop** and **two-loop** radiative correction.

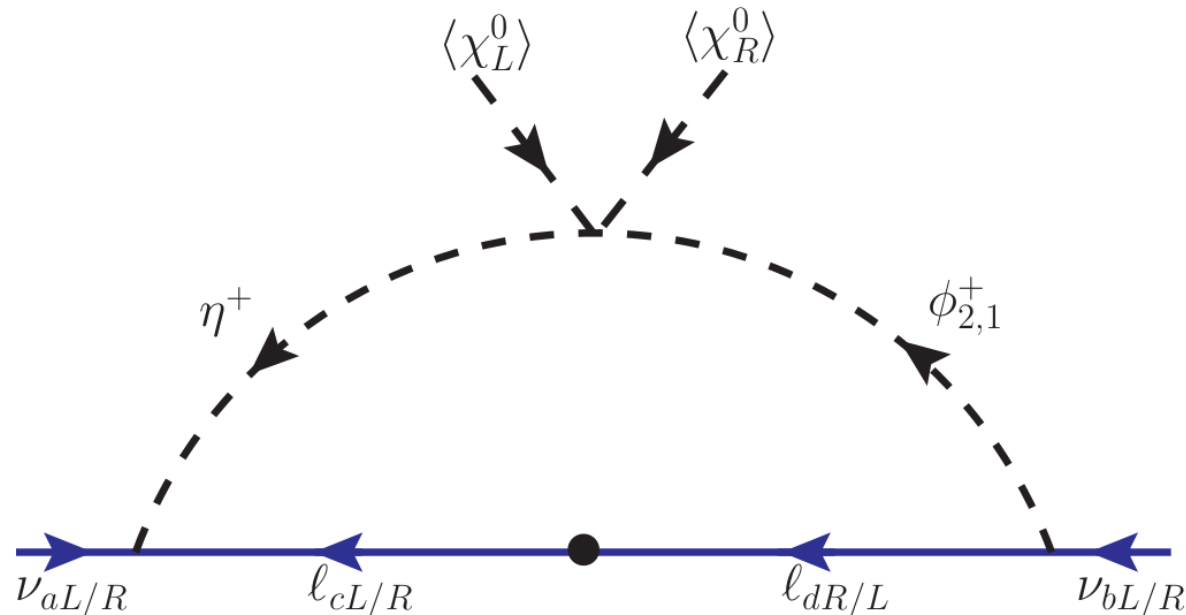
- Neutrino mass matrix is diagonalized by **6×6 unitary matrix**:

$$U^\dagger M_\nu U^\star = \begin{pmatrix} m_{\nu_j} & 0 \\ 0 & M_{N_\alpha} \end{pmatrix} \leftrightarrow U = \begin{pmatrix} U_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix}$$

$U_{\nu\nu}^\star$ is the usual **PMNS matrix** characterizing the **mixing among light neutrinos**.

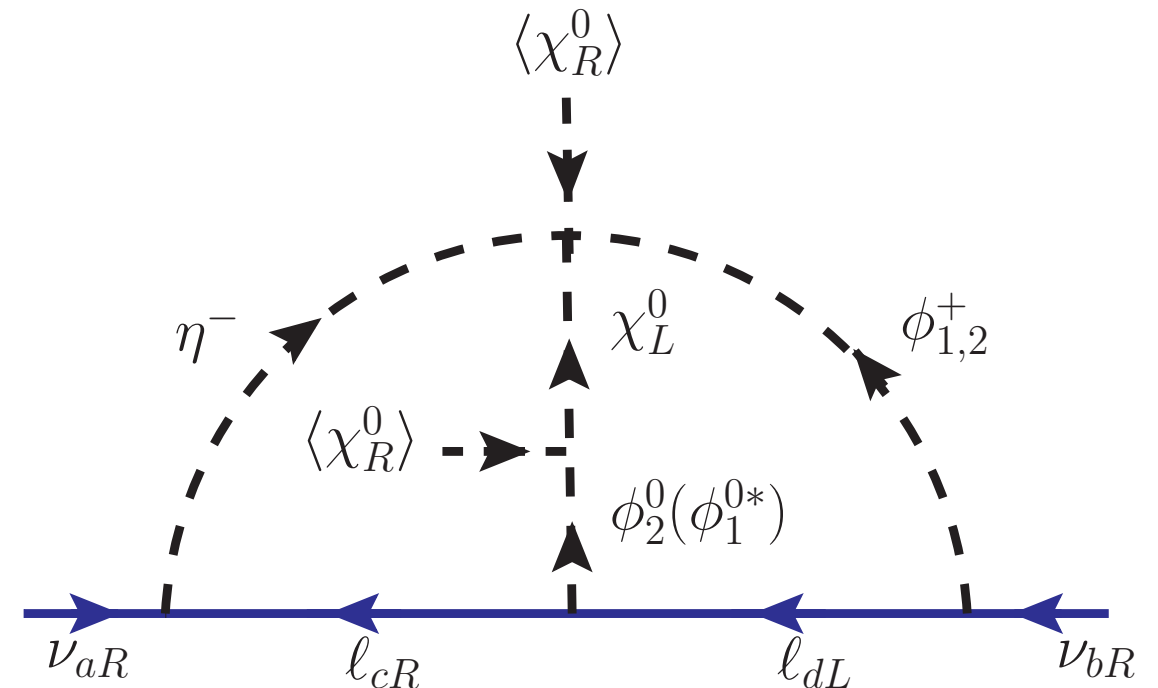
$$s_{12}^2 = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2}, \quad s_{13}^2 = |U_{e3}|^2, \quad s_{23}^2 = \frac{|U_{\mu 3}|^2}{1 - |U_{e3}|^2}$$

Radiative ν_R Mass Generation



$$\mathcal{O}_1 = c_1 \Psi_R \Psi_R (\chi_L^T \Phi \chi_R)$$

$$c_1 \sim \frac{(y_\tau^2 f \alpha_4)}{16\pi^2} \left(\frac{1}{M^2} \right)$$



$$\mathcal{O}_2 = c_2 \Psi_R \Psi_R (\chi_R \chi_R)$$

$$c_2 \sim \frac{(y_\tau^2 f \alpha_4)}{(16\pi^2)^2} \left(\frac{\mu_4}{M^2} \right)$$

- The **two-loop diagrams do not require electroweak symmetry breaking** and dominate over the one-loop diagrams for the entire range of $W_R^\pm$ mass.

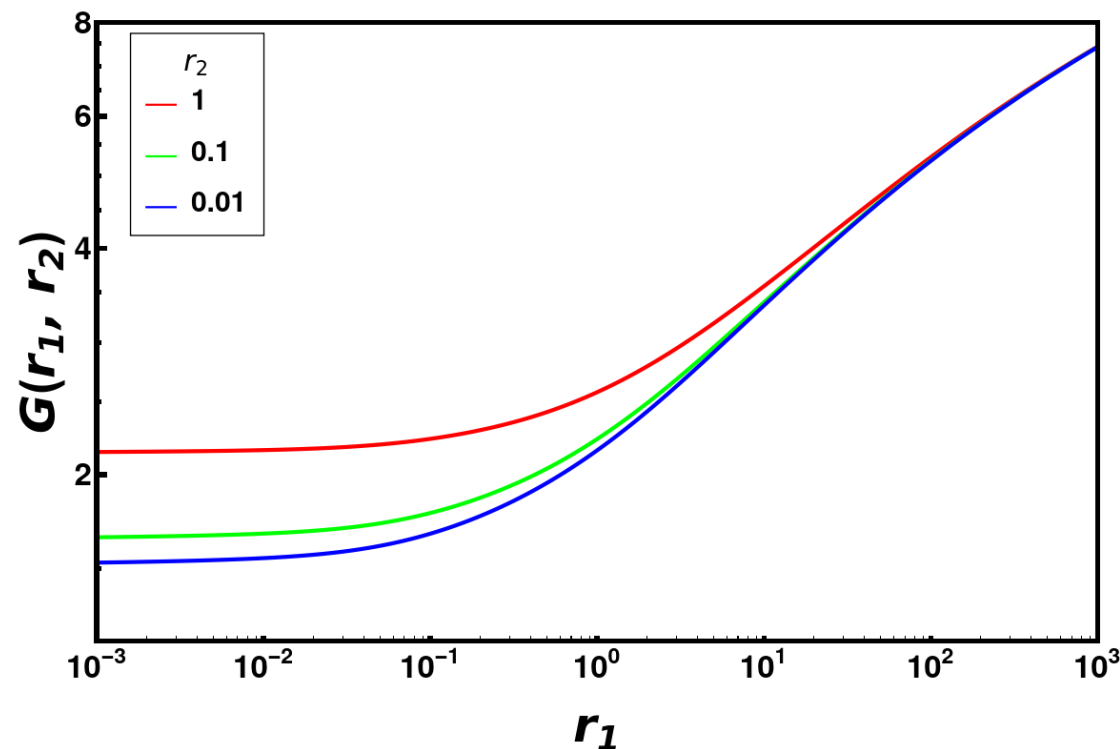
Some More Details

- One-loop radiative corrections:

$$(M_\nu^R)_{ab} = \frac{1}{8\pi^2} \left[f_{a\ell} M_\ell V_{5\beta}^+ (y_{\ell b} V_{1\beta}^{\star+} - \tilde{y}_{\ell b} V_{2\beta}^{\star+}) + (a \leftrightarrow b) \right] \log \left(\frac{m_{H_1^+}^2}{m_{H_\beta^+}^2} \right)$$

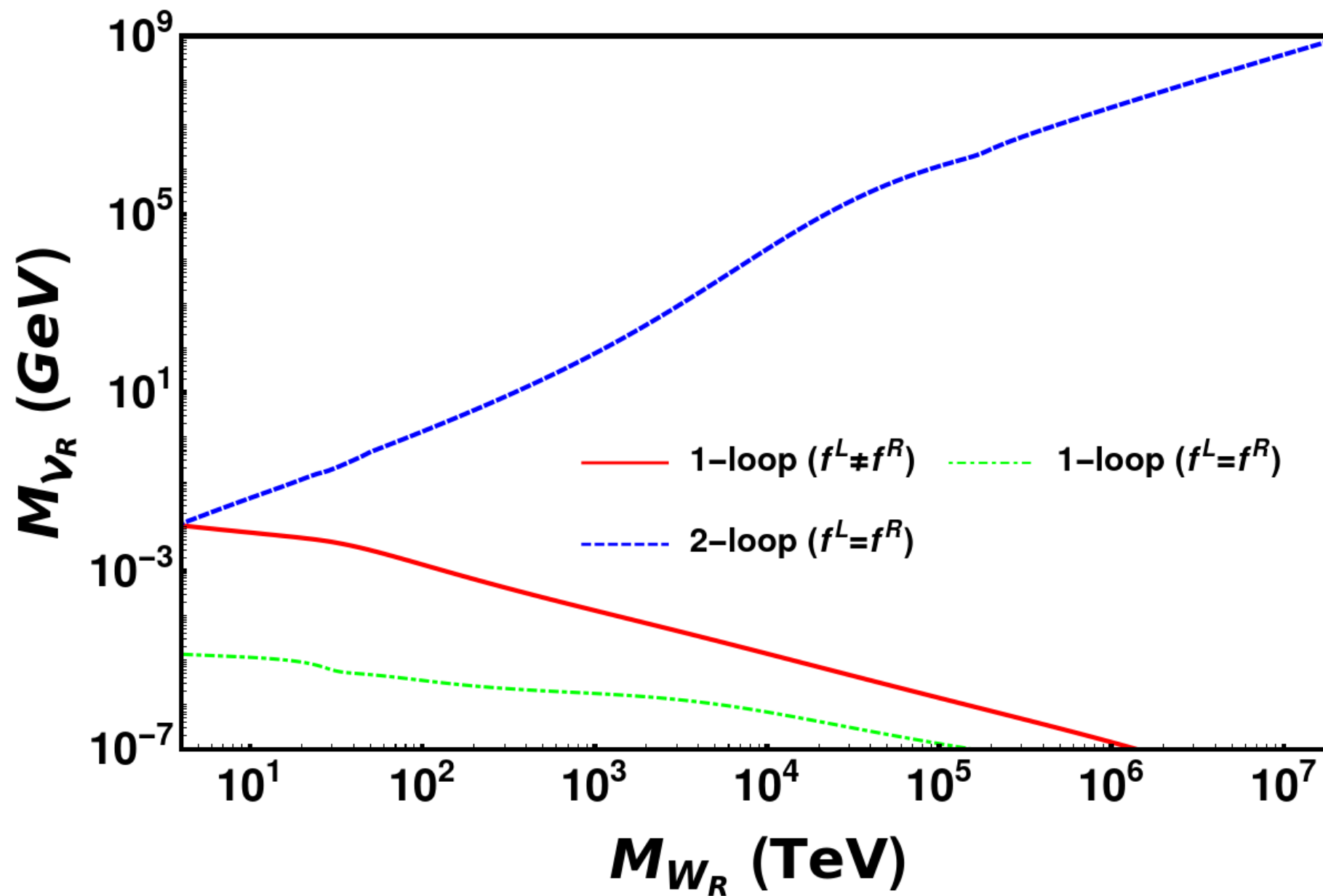
- Case with $M_{\nu D} \ll M_\ell$ (low Scale LR) $\Rightarrow$ Flavor structure simplifies, $y, \tilde{y} \propto M_\ell$

$$(M_{\nu R})_{ab} = \frac{2\sqrt{2} \alpha_4 v_R}{\kappa^2 (1 - \epsilon^2)^2 (16\pi^2)^2} (f M_\ell^2 + M_\ell^2 f^T) \left\{ C_{\beta\gamma} G \left(\frac{m_\eta^2}{m_{H_\gamma^0}^2}, \frac{m_{H_\beta^+}^2}{m_{H_\gamma^0}^2} \right) + C'_{\beta\gamma} G \left(\frac{m_\eta^2}{m_{H_\beta^+}^2}, \frac{m_{H_\gamma^0}^2}{m_{H_\beta^+}^2} \right) \right\}$$



$$G(r_1, r_2) \rightarrow \begin{cases} -\frac{3}{2} - \frac{r}{2} + \frac{7}{4} r \log r & \text{for } r_1 = r_2 = r, r \ll 1 \\ -\frac{1}{2} - \frac{\pi^2}{6} + \frac{1}{4} r_1 \log r_1 & \text{for } r_2 = 1, r_1 \ll 1 \end{cases}$$

One-loop vs Two Loop

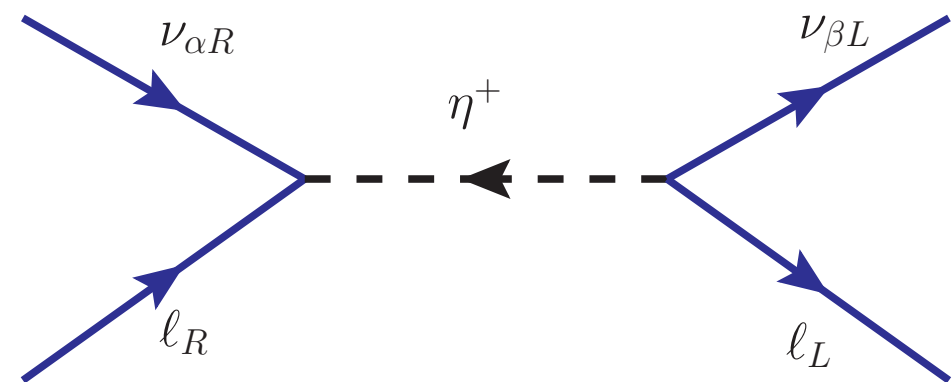
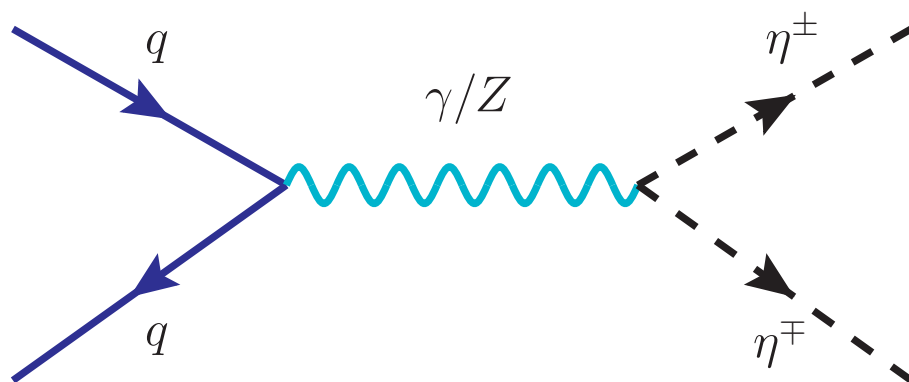


- Maximum contribution to M_{ν_R} for $\alpha_4 = 3.0$ and $f_{e\tau} = 1.0$.

M_{W_R} (TeV)	5	10	15	30	50	100	10^4
M_{ν_R} (GeV)	0.0042	0.010	0.020	0.05	0.11	0.36	4.2×10^3

Collider Implications

- Focus on $\eta^\pm$ and ν_R ; Both can be light $\Rightarrow$ opens possibility of production of ν_R via η^+ .
- $M_{\nu_R} \ll M_{W_R}$ due to two loop suppression. Thus few GeV $M_{\nu_R} \Rightarrow$ very heavy M_{W_R} .
- $\eta^+\eta^-$ can be pair-produced via the Drell-Yan process mediated by the Z and photon.
- The $\eta^+ \rightarrow \ell_R^+ \nu_R, \ell_L^+ \nu_L$. The $\nu_R \rightarrow \ell_R + \ell_L + \nu_L$ through a virtual $\eta^\pm$. This would lead to interesting multi-lepton signals.



Collider Implications

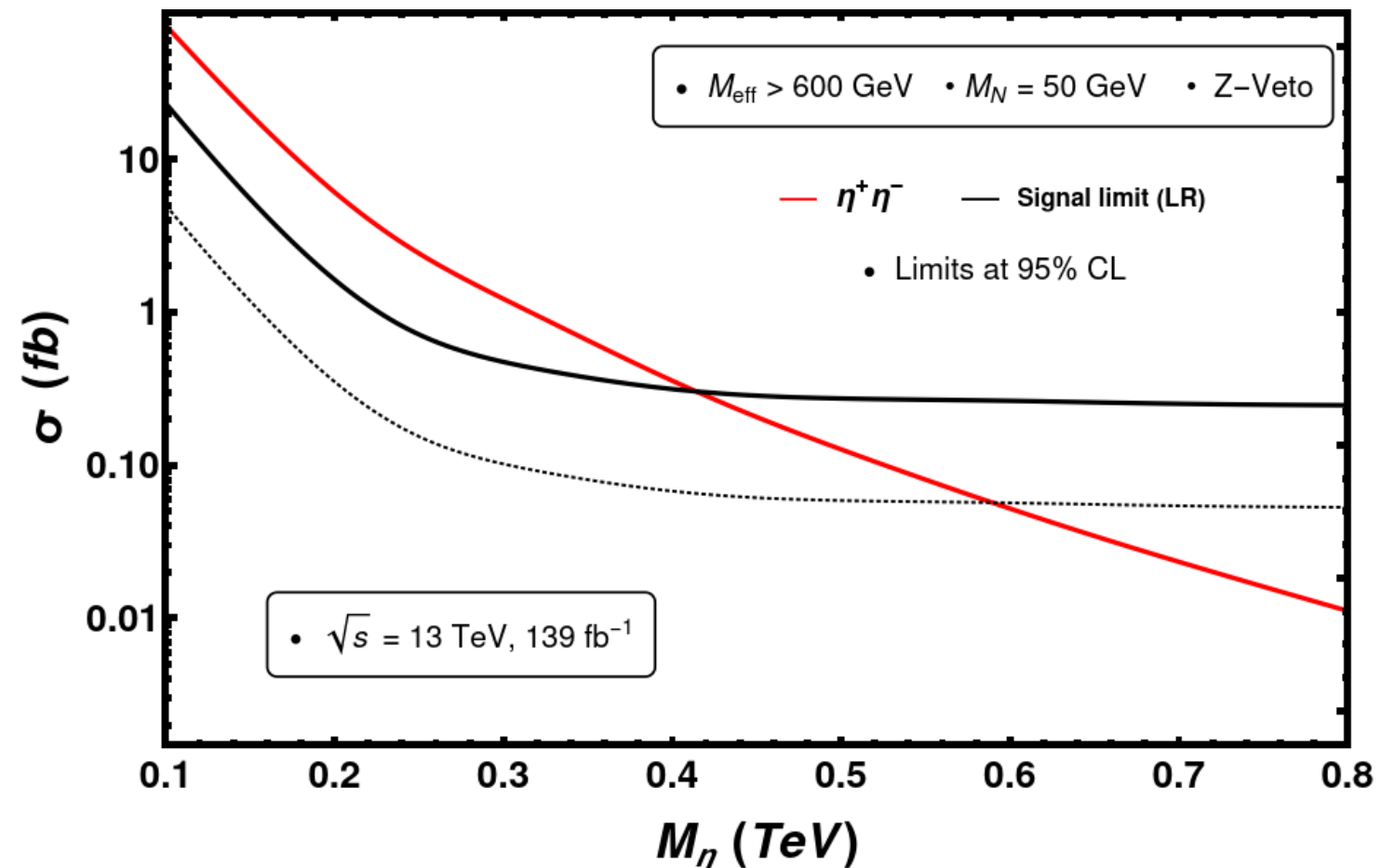
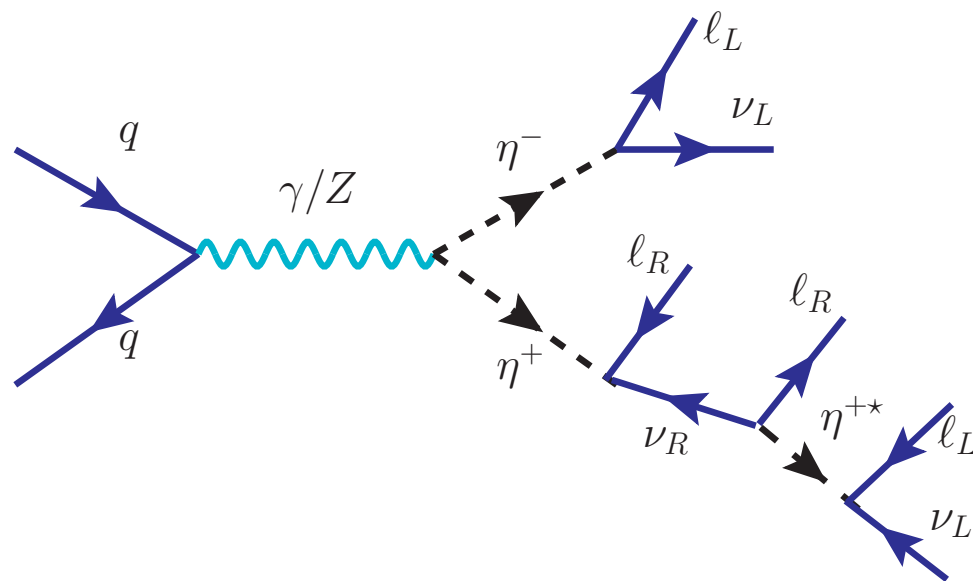
- Three possibilities:

- $pp \rightarrow \ell^+ \ell^- \cancel{E}_T$

- $pp \rightarrow 4l + \cancel{E}_T$

- $pp \rightarrow 6l + \cancel{E}_T$

- $pp \rightarrow 4l + \cancel{E}_T$



The current limit on mass of η^+ is 410 GeV

- $pp \rightarrow 6l + \cancel{E}_T$:

no current searches available. Expect half the number of events with much suppressed background.

Conclusions: NSI

- 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 $(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau})$
- NSI in leptoquark models are studied which allows diagonal NSI $\epsilon_{\tau\tau}$ as large as 51.7 %

Conclusions: B-anomaly and muon $g-2$

- Simple one loop neutrino mass model utilizes TeV scale LQ and explains B -anomalies.
- Same model simultaneously explains observed muon $g - 2$ anomaly.
- The model also utilizes quadruplet Δ , which provides a plethora of implications at the collider experiments.
- Same Yukawa couplings responsible for the chirally-enhanced Δa_μ give rise to SM Higgs decays to muon and tau pairs which could be tested at future hadron colliders, such as HL-LHC and FCC-hh.

Conclusions: LRSM

- A **simple and minimal** left-right symmetric model which **does not use** the **conventional Higgs triplets** have been presented.
- **Majorana masses** for the ν_R are induced through **two-loop diagrams** involving a singly charged scalar field η^+ , which do not rely on **electroweak symmetry breaking**, unlike the one-loop diagrams.
- This model naturally exhibits a **hierarchy in the masses** of ν_R and W_R . If the W_R gauge boson has a mass in the **(5 – 20)TeV** range, the ν_R fields will have masses of a **few tens of MeV**.
- **Collider implications** arising from the production and decays of the η^+ scalar have been studied. The **current limit** on the η^+ mass is **410 GeV**, which can be improved to **585** at the **high luminosity run of the LHC**.

Each model presented has excellent fits to neutrino oscillation parameters.

Future Direction

- Complete the Research in progress
- Explore more on Dark Matter; anomalous magnetic moments.
- Gravitational waves, Collider Physics.....

Open to new ideas and new challenges!

Collaborators



Prof. K.S. Babu



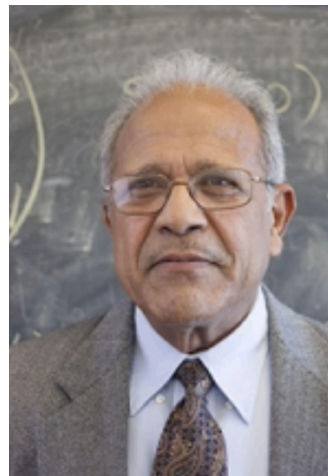
Assoc. Prof. Bhupal Dev



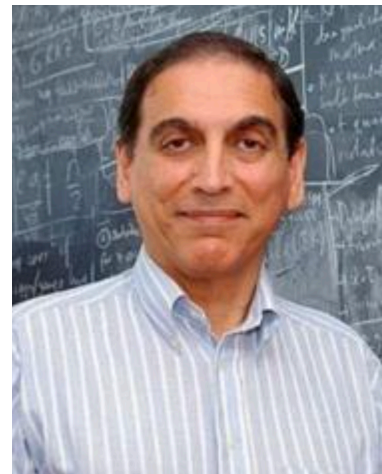
Dr. Sudip Jana



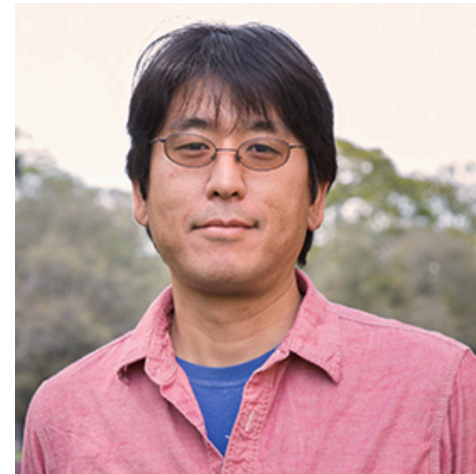
Assist. Prof. Ahmed Ismail



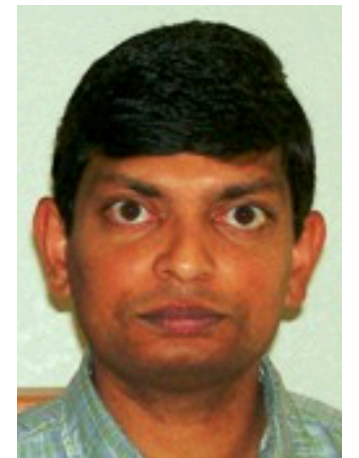
Prof. R. N. Mohapatra



Prof. Qaisar Shafi



Prof. Nobuchika Okada



Prof. Zachary Chacko



Dr. Digesh Raut



Dr. Shaikh Saad