

# Unified Framework for $B$ Anomalies, muon $g - 2$ , Neutrino Masses

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In collaboration with  
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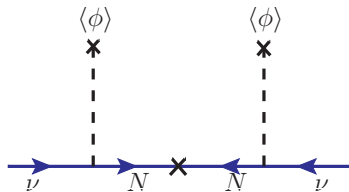


# Outline

- 1 Radiative  $\nu$  Mass generation
- 2  $B$ -physics anomalies and Muon anomalous magnetic moment
- 3 Constraints
- 4 Numerical Fit
- 5 Collider Implications
- 6 Conclusion

# $\nu$ mass generation: Seesaw Paradigm

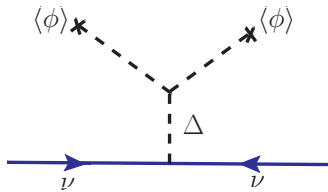
- Light neutrino mass is induced via Weinberg's dim-5 operator,  $LL\phi\phi$ .
- Large Majorana mass scale  $\Lambda$  to suppress the neutrino mass via  $\frac{\langle\phi\rangle^2}{\Lambda}$ .
- Different schemes:



**Type I/ Type III seesaw:**

$\nu$ -mass induced from **fermion exchange**:

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



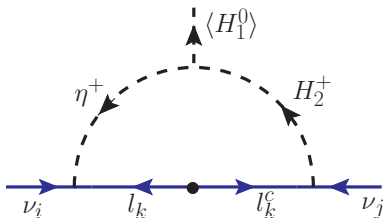
**Type II seesaw:**

$\nu$ -mass induced from **scalar boson exchange**  $\Delta \sim (1, 3, 1)$

- The scale of new physics can be **rather high**

# Radiative $\nu$ mass generation

- Neutrino masses are **zero at tree level** as SM:  $\nu_R$  may be absent.
- Small, finite Majorana masses are generated at the **quantum level**.
- Typically involves exchange of scalars that **violates lepton number**.
- Simple realization is the **Zee Model**, which has a second Higgs **doublet** and a charged **singlet**.



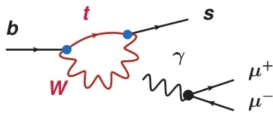
- Smallness of neutrino mass is explained via **loop** and **chiral suppression**.
- New physics in this framework may lie at the **TeV scale**.

# Goal

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

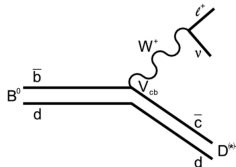
- $R_K$  and  $R_{K^*}$

$$\sim 3.1\sigma$$



- $R_D$  and  $R_{D^*}$

$$\sim 3.0\sigma$$



- $(g-2)_\mu$

$$\sim 4.2\sigma$$

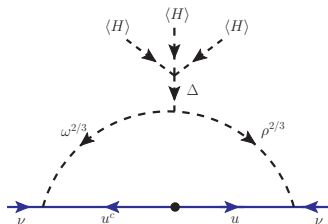
If confirmed: Implications for **New Physics**

- Nonstandard neutrino interaction (**NSI**)
- Collider Phenomenology** with new scalars
- $\Delta a_\mu \iff h \rightarrow \mu\mu$  and  $h \rightarrow \tau\tau$

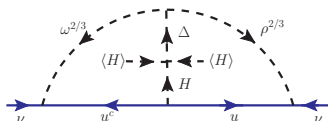
(Crivellin, Mueller, Saturnino, 20)

# 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  $\Delta \sim (1, 4, 3/2)$ .



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



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

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

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

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

# Minimal Yukawa texture

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

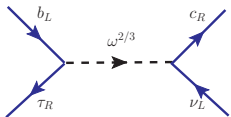
$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & f'_{33} \end{pmatrix}, f = \begin{pmatrix} 0 & 0 & f_{13} \\ 0 & f_{22} & f_{23} \\ 0 & f_{32} & f_{33} \end{pmatrix}, y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ y_{31} & y_{32} & 0 \end{pmatrix}$$

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

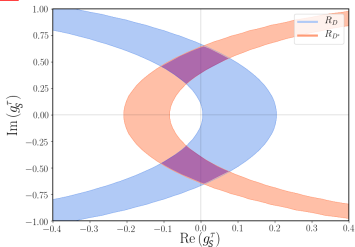
- $f'_{32} f_{32} : (g - 2)_\mu$
- $f'_{33} f_{23} + f'_{33} f_{22} : R_D - R_{D^*}$
- $f_{33} : \text{mild fine-tuning to suppress } \tau \rightarrow \mu \gamma$
- $y_{22} y_{32} : R_K - R_{K^*}$
- $y_{31}, y_{23} : \nu$  fit  $(\Delta m_{21}^2, \Delta m_{31}^2, \sin^2 \theta_{13}, \sin^2 \theta_{23}, \sin^2 \theta_{12}, \delta_{CP})$
- $f_{1\alpha} : \text{NSI}$

# New Physics for anomalies

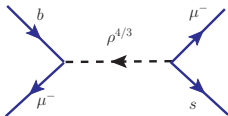
$$R_2 \sim (3, 2, 7/6)$$



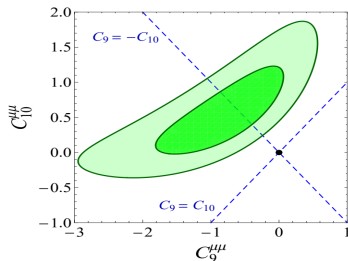
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + g_V) (\bar{\tau}_L \gamma^\mu \nu_L) (\bar{c}_L \gamma_\mu b_L) + g_S (\bar{\tau}_R \nu_L) (\bar{c}_R b_L) + g_T (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) (\bar{c}_R \sigma_{\mu\nu} b_L)]$$



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



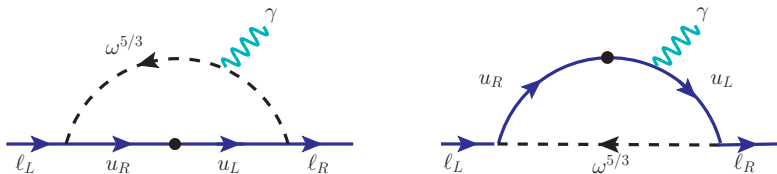
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{(4\pi)^2} \left\{ C_9 (\bar{s} \gamma_\mu P_L b) (\bar{\mu} \gamma^\mu P_L \mu) + C_{10} (\bar{s} \gamma_\mu b) (\bar{\mu} \gamma^\mu \gamma^5 \mu) \right\}$$



Angelescu et al., 18



# Anomalous Magnetic Moment



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

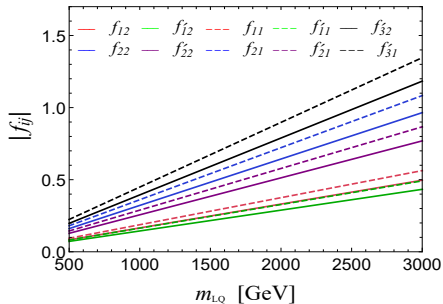
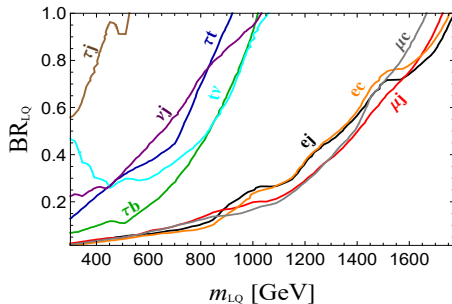
$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & 0 \end{pmatrix}, \quad f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f_{32} & 0 \end{pmatrix}$$

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

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

# Constraints

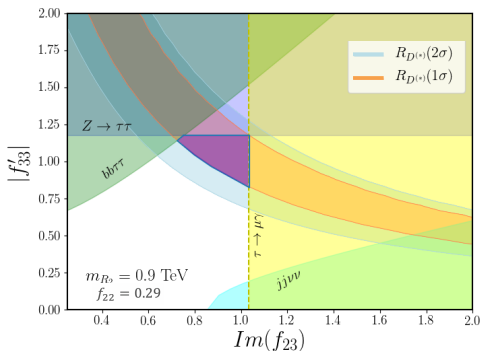
- $\ell_i \rightarrow \ell_j \gamma$
- $\mu - e$  conversion
- $Z \rightarrow \tau\tau$  decay
- Rare  $D$ -meson Decay
- $D^0 - \bar{D}^0$  mixing
- Bounds from kaons
- Collider constraints
  - Pair-production Bounds
  - Dilepton Bounds



# Fit

$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.29 & 1.06 \end{pmatrix}, \quad f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.29 & 0.89i \\ 0 & 0.006 & 0.023 \end{pmatrix}, \quad y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.124 & 0.064 \\ -0.016 & 0.028 & 0 \end{pmatrix}$$

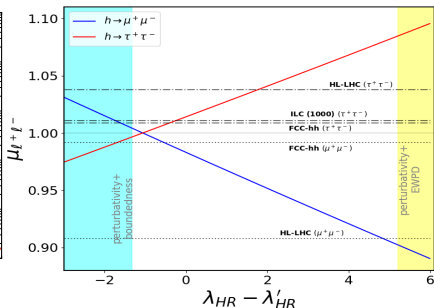
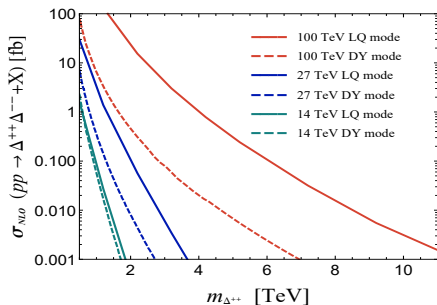
Oscillation Parameter	$s_{12}^2$	$s_{13}^2$	$s_{23}^2$	$\Delta m_{21}^2 \text{ eV}^2$	$\Delta m_{23}^2 \text{ eV}^2$	$\delta / ^\circ$
Model Fit	0.29	0.023	0.47	$7.39 \cdot 10^{-5}$	$2.54 \cdot 10^{-3}$	320



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  $\Delta$ -quadruplet coupling to the SM leptons.  $Y_\Delta \sim M_\nu/v_\Delta$ .
- Same  $R_2$  LQ responsible for  $\Delta a_\mu$  give rise  $h \rightarrow \mu\mu$  and  $h \rightarrow \tau\tau$ .



also Ref. to Bhupal Dev talk

# Conclusion

- 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  $\Delta$ , which provides a plethora of implications at the collider experiments.
- Same Yukawa couplings responsible for the chirally-enhanced  $\Delta a_\mu$  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.
- The model is consistent with observed neutrino oscillation data.

Thank You

$$\mathcal{L}_Y = u^{cT} C f \nu \omega^{2/3} - u^{cT} C f e \omega^{5/3} + u^T C (V^* f') e^c \omega^{-5/3} + d^T C f' e^c \omega^{-2/3} \\ - u^T C (V^* y) \nu \rho^{-2/3} + u^T C (V^* y) e \frac{\rho^{1/3}}{\sqrt{2}} + d^T C y \nu \frac{\rho^{1/3}}{\sqrt{2}} + d^T C y e \rho^{4/3}$$

$$V \supset \lambda'_{H\Delta} (H^\dagger \tau_a H) (\Delta T'_a \Delta) + (\mu R_2 S_3 \Delta^* + \lambda_5 \Delta^* H^3 + \text{H.c.})$$

- The neutral member of  $\Delta$  acquires an induced vacuum expectation value

$$v_\Delta \sim \frac{-\lambda_5 v^3}{m_\Delta^2}$$

- In the approximation  $v_\Delta \ll v$ , masses of Higgs quadruplet components

$$m_i^2 = \mu_\Delta^2 - q_i \frac{\lambda'_{H\Delta} v^2}{4}$$