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

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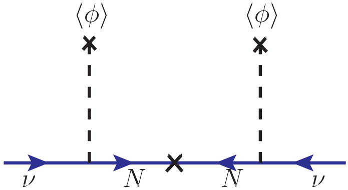
Outline

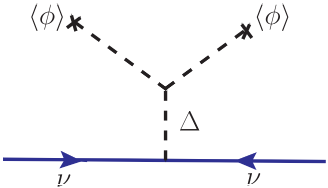
1. Radiative ν Mass generation
2. B-physics anomalies and Muon anomalous magnetic moment
3. Constraints
4. Numerical Fit
5. Collider Implications
6. Conclusion

ν mass generation: 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 $\frac{\langle\phi\rangle^2}{\Lambda}$.
- Different schemes:



Type I/ Type III seesaw:
ν-mass induced from fermion exchange:
$N^1 \sim (1,1,0)$ $N^3 \sim (1,3,0)$

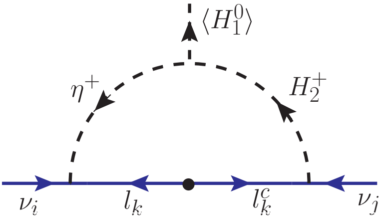


Type II seesaw:
ν-mass induced from scalar boson exchange $\Delta \sim (1,3,1)$

- The scale of new physics can be rather high

Radiative ν mass generation

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

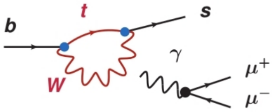


- Smallness of neutrino mass is explained via loop and chiral suppression.
- New physics in this framework may lie at the TeV scale.

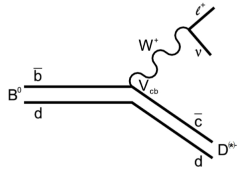
Goal

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

- R_K and R_{K^*} $\sim 3.1\sigma$



- R_D and R_{D^*} $\sim 3.0\sigma$



- $(g-2)_\mu$ $\sim 4.2\sigma$

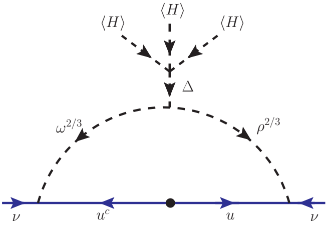
If confirmed: Implications for New Physics

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

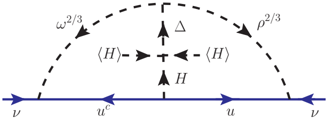
(Crivellin, Mueller, Saturnino, 20)

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



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



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

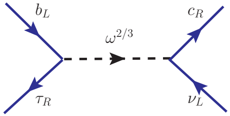
$$M_\nu = (\kappa_1 + \kappa_2)(f^T M_u V^* y + y^T V^\dagger M_u f)$$

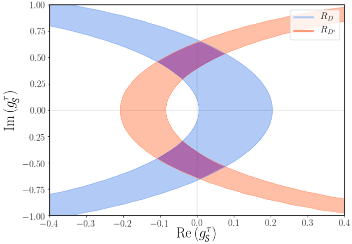
$$\kappa_1 = \frac{1}{16\pi^2} \sin 2\varphi \log \left(\frac{M_2^2}{M_1^2}\right) \qquad \kappa_2 \approx \frac{1}{(16\pi^2)^2} \frac{\lambda_5 \text{v} \mu}{M_{1,2}^2}$$

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

New Physics for anomalies

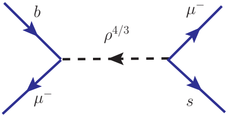
$R_2 \sim (3, 2, 7/6)$

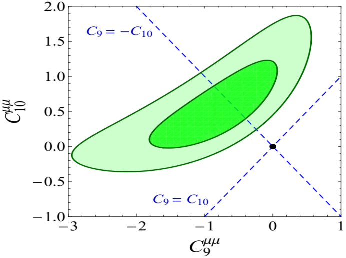




$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + g_V) \left(\bar{\tau}_L \gamma^\mu \nu_L \right) \left(\bar{c}_L \gamma_\mu b_L \right) + g_S \left(\bar{\tau}_R \nu_L \right) \left(\bar{c}_R b_L \right) + g_T \left(\bar{\tau}_R \sigma^{\mu\nu} \nu_L \right) \left(\bar{c}_R \sigma_{\mu\nu}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

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

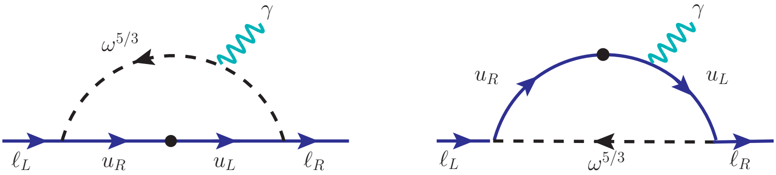




$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{(4\pi)^2} \left\{ C_9 (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu) + C_{10} (\bar{s}\gamma_\mu b)(\bar{\mu}\gamma^\mu \gamma^5 \mu) \right\}$$

Angelescu et al., 18

Anomalous Magnetic Moment



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

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

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

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

Minimal Yukawa texture

$$\mathcal{L}'_{Yuk} = f_{ab} u^c_a \psi^i_b R^j_2 \epsilon^{ij} - f'_{ab} Q^i_a e^c_b \widetilde{R}^j_2 \epsilon^{ij} + y_{ab} Q_a \tau_\alpha \psi_b S_{3\alpha} + \text{H.c}$$

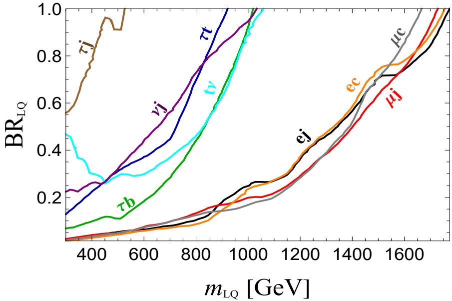
$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & f'_{33} \end{pmatrix}, \; f = \begin{pmatrix} 0 & 0 & f_{13} \\ 0 & f_{22} & f_{23} \\ 0 & f_{32} & f_{33} \end{pmatrix}, \; y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ y_{31} & y_{32} & 0 \end{pmatrix}$$

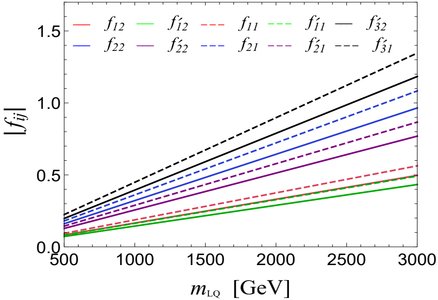
f_{ab} ($a \to$ quark flavor, $b \to$ lepton flavor)

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

Constraints

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

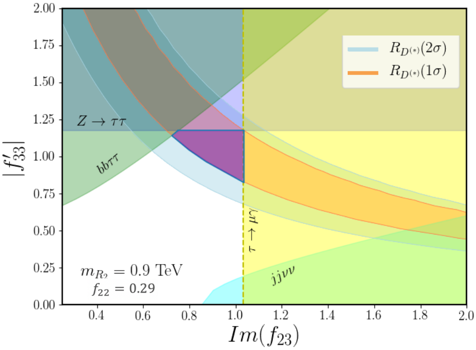




Fit

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

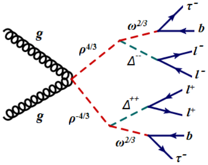
Oscillation Parameter	s_{12}^2	s_{13}^2	s_{23}^2	Δm_{21}^2 eV^2	Δm_{23}^2 eV^2	$\delta/\ ^\circ$
Model Fit	0.29	0.023	0.47	$7.39 \cdot 10^{-5}$	$2.54 \cdot 10^{-3}$	320

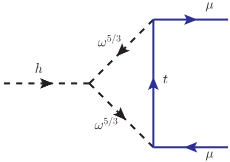


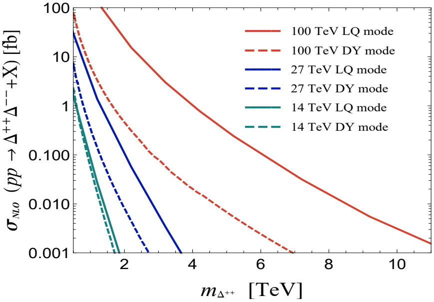
Observable	R_D	R_D^*	$C_9 = -C_{10}$	$(g-2)_\mu$
Model Fit	0.34	0.282	-0.52	$2.97 \cdot 10^{-9}$

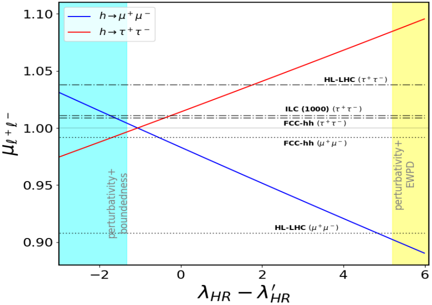
Collider Implications

- 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 $h \to \mu\mu$ and $h \to \tau\tau$.









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 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.
- The model is consistent with observed neutrino oscillation data.

Thank You

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

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

- The neutral member of Δ acquires an induced vacuum expectation value

$$\boxed{\mathrm{v}_\Delta \sim \frac{-\lambda_5 \mathrm{v}^3}{m_\Delta^2}}$$

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

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