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

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# $\nu$ mass

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

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

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

- Simplest possibility: Introduce $\nu_R$ to the SM allowing

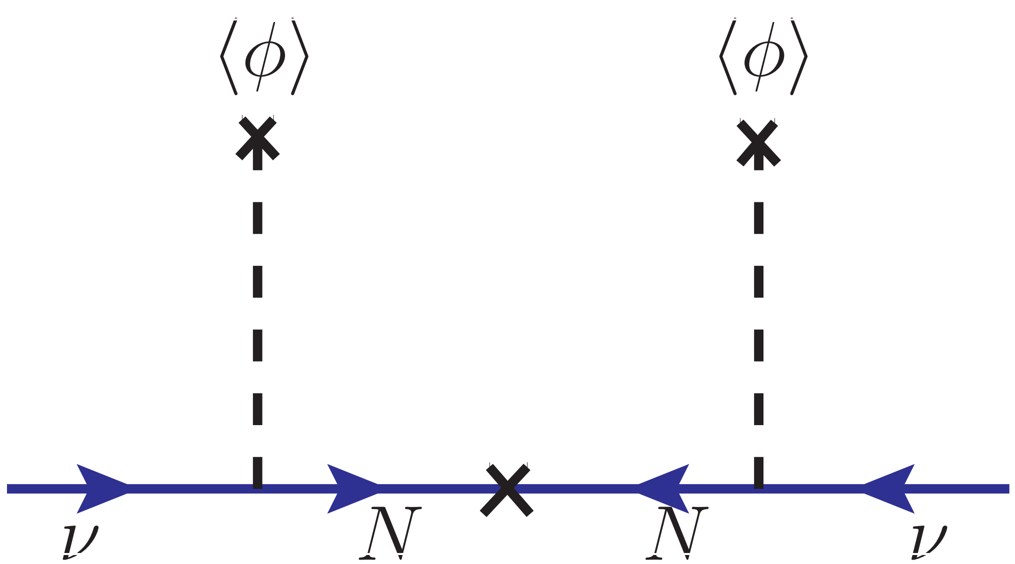
$$\mathcal{L}_Y : y_\nu \bar{\psi}_L \phi \nu_R + h.c.$$

  $m_\nu \sim 0.1$eV, this means Yukawa coupling $y_\nu \sim 10^{-12}!!$

- Schemes for neutrino masses and mixings
  - Tree-level Seesaw mechanism
  - Radiative schemes

# Seesaw Paradigm

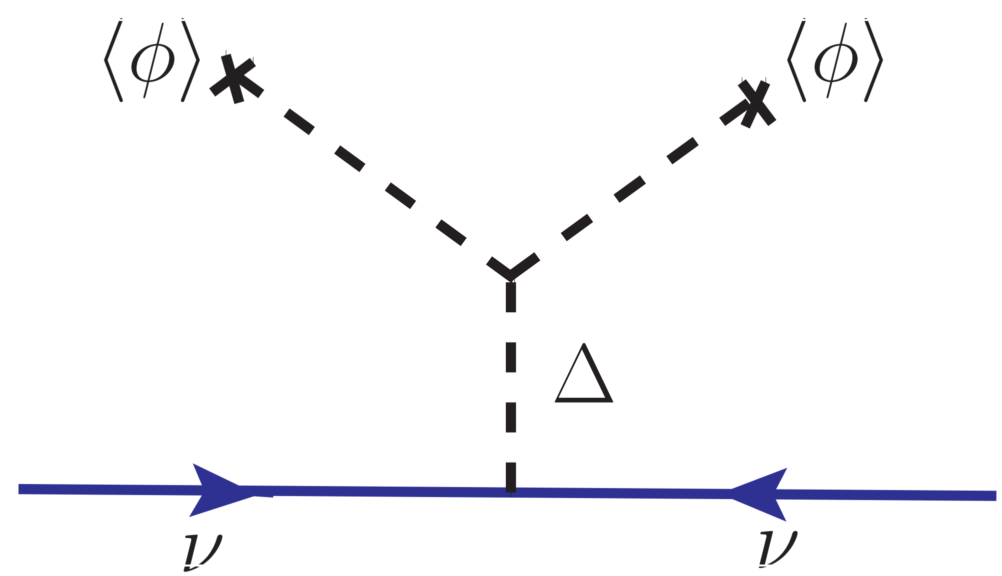
- Light neutrino mass is induced via Weinberg's dim-5 operator, $LL\phi\phi$
- Large Majorana mass scale $\Lambda$ to suppress the neutrino mass via $\frac{\langle\phi\rangle^2}{\Lambda}$




**Type I / Type III :**

$\nu$- mass induced from fermion exchange

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




**Type II :**

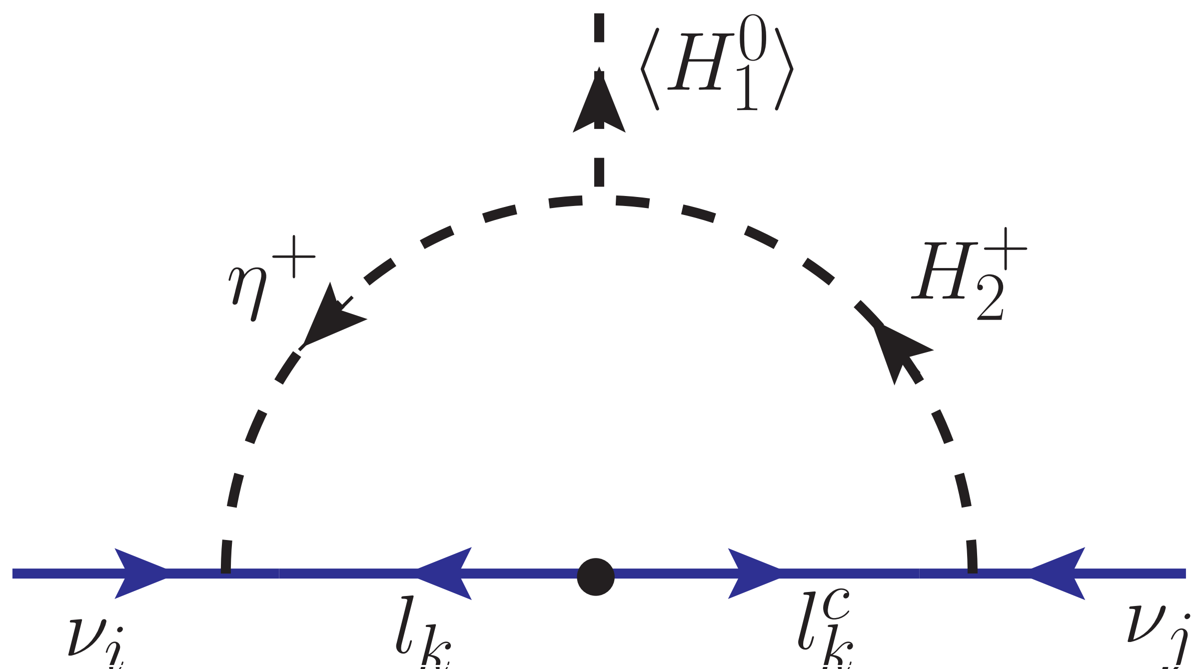
$\nu$- mass induced from scalar exchange

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

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

# Radiative $\nu$ mass generation

- Neutrino masses are zero at tree level: $\nu_R$ 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

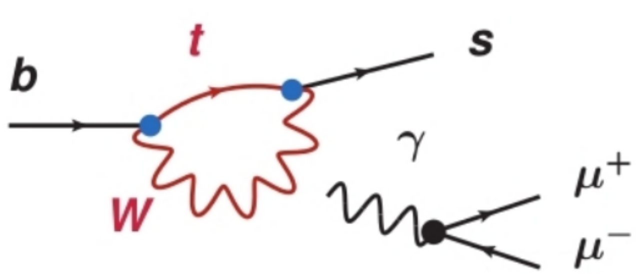



- Smallness of neutrino mass is explained via loop and chiral suppression
- New physics in this framework may lie at the TeV scale

# Motivation

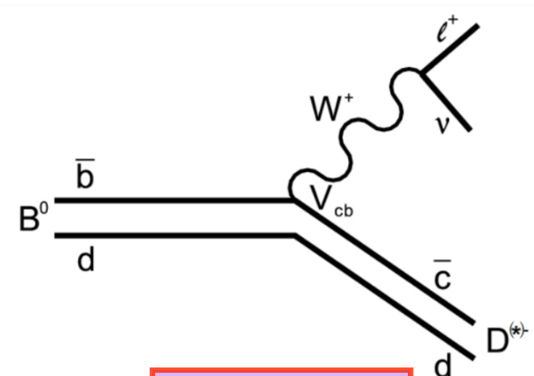
Construct a Neutrino mass model with New Physics at TeV scale that can resolve the following and simultaneously fit neutrino oscillation data: $(\Delta m^2_{21}, \Delta m^2_{31}, \sin^2\theta_{13}, \sin^2\theta_{23}, \sin^2\theta_{12}, \delta_{CP})$

- $R_K$ and $R_{K^\star}$



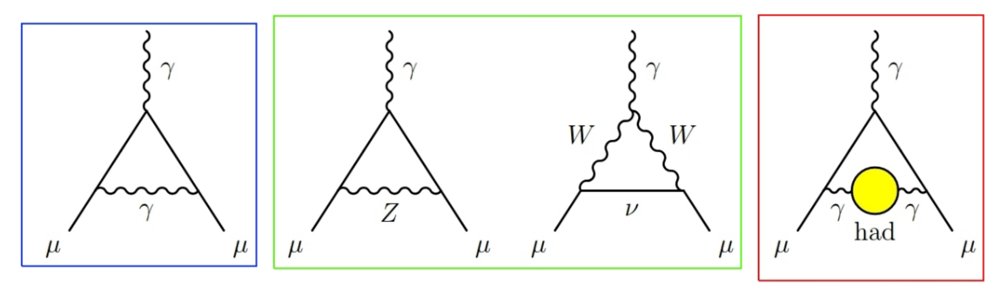

$\sim 3.1\sigma$

- $R_D$ and $R_{D^\star}$




$\sim 3.4\sigma$

- $(g-2)_\mu$




$\sim 4.2\sigma$

If confirmed: Implications for New Physics

- Collider Phenomenology with new scalars
- $\Delta a_\mu \Longleftrightarrow h \to \mu\mu$ and $h \to \tau\tau$

(Crivellin, Mueller, Saturnino, 2020)

# Framework for Anomalies

| Model | $R_{K^{(*)}}$ | $R_{D^{(*)}}$ | $R_{K^{(*)}}$ & $R_{D^{(*)}}$ |
|---|---|---|---|
| $S_3$ $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ | ✓ | ✗ | ✗ |
| $S_1$ $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ | ✗ | ✓ | ✗ |
| $R_2$ $(\mathbf{3}, \mathbf{2}, 7/6)$ | ✗ | ✓ | ✗ |

A. Angelescu et. al., 21.

- LQ $R_2$ explains $R_{D(\star)}$ , $S_3$ explains $R_{K(\star)}$
- The same $R_2$ LQ also induce muon $(g-2)_\mu$
- A pair of leptoquark scalars ($R_2$ and $S_3$) can generate neutrino masses radiatively
- Flavor structure to achieve these is very constrained
- Framework can be tested at LHC as well as in processes such as $\tau \to \mu\gamma$

# Unified Model

The model is based on $SU(3)_C \times SU(2)_L \times U(1)_Y$, with an extended scalar sector.

$$R_2 = \begin{pmatrix} \omega^{5/3} \\ \omega^{2/3} \end{pmatrix} \sim (3,2,7/6) \qquad S_3 = (\rho^{4/3}, \rho^{1/3}, \rho^{-2/3}) \sim (\bar{3},3,1/3)$$

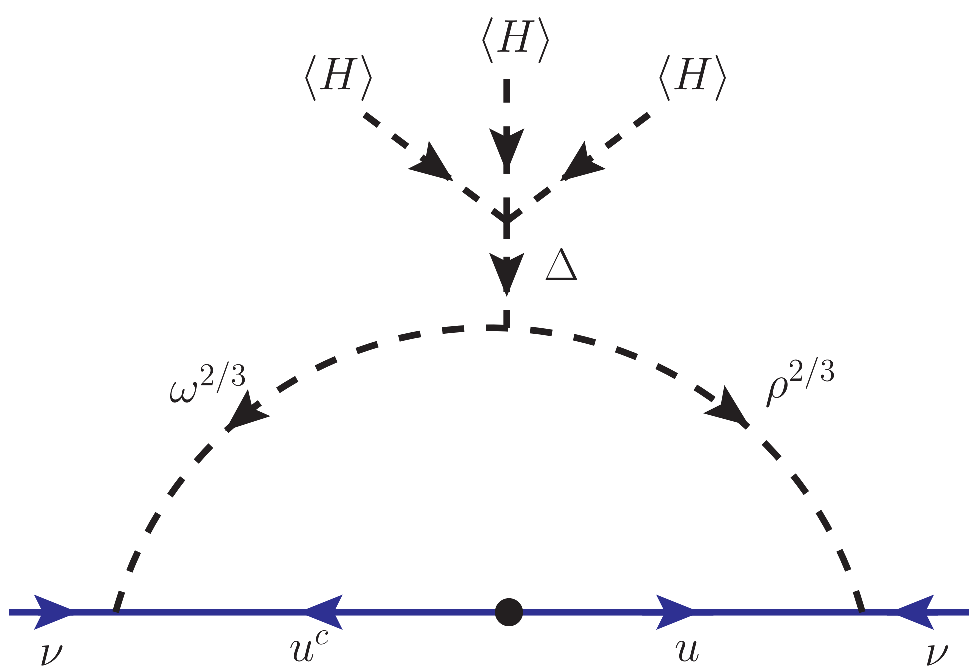
$$\boxed{\Delta = \left(\Delta^{+++}, \Delta^{++}, \Delta^{+}, \Delta^{0}\right)^T \sim (1,4,3/2) \qquad \text{Model I}}$$

$$\boxed{\chi^{2/3} \sim (3,1,2/3) \qquad \text{Model II}}$$

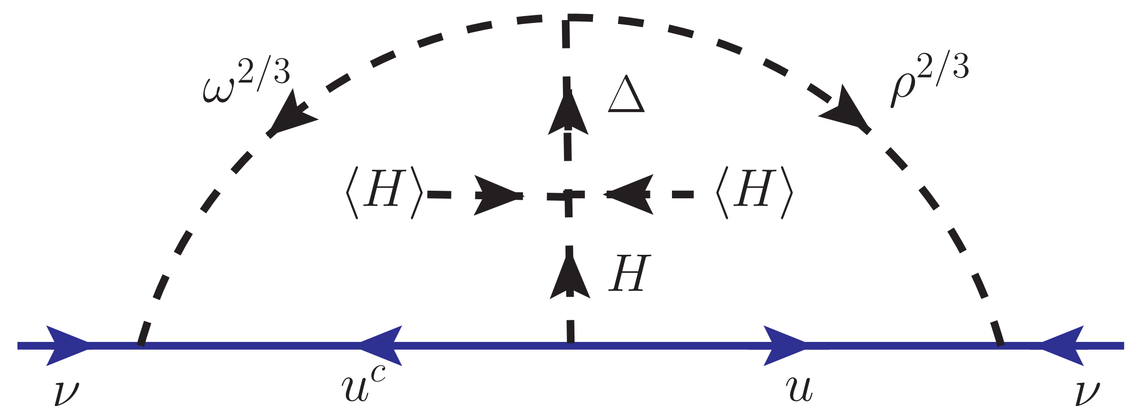
The Yukawa couplings are given by

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

# Neutrino Mass Generation (Model I)




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




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

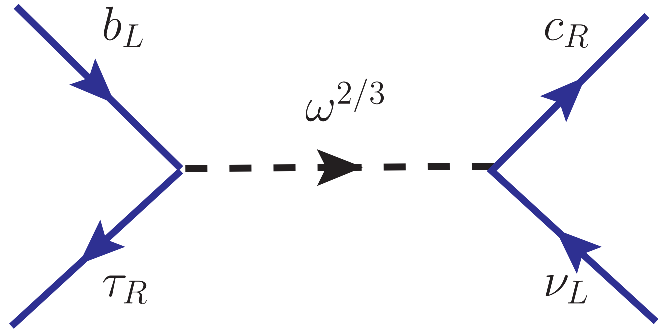
$$M_\nu = (\kappa_1 + \kappa_2)(f^T M_u V^\star y + y^T V^\dagger M_u f)$$

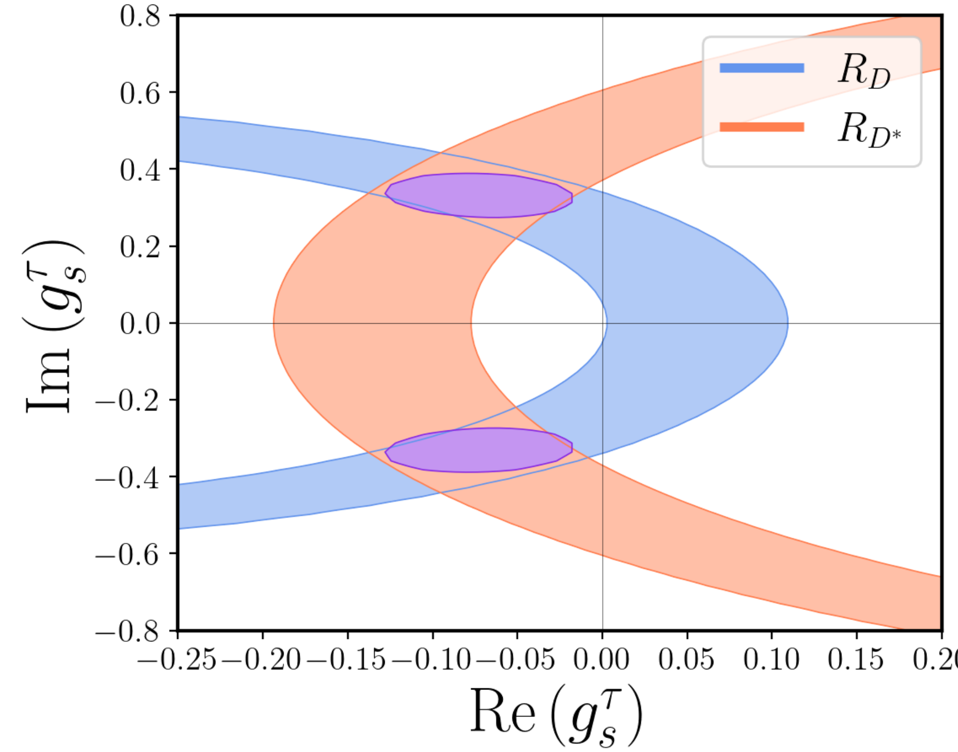
$$\kappa_1 = \frac{1}{16\pi^2} \sin 2\varphi \log\left(\frac{M_2^2}{M_1^2}\right) \qquad \kappa_2 \approx \frac{1}{(16\pi^2)^2} \frac{\lambda_5 v \mu}{M_{1,2}^2}$$

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

# New Physics for anomalies

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

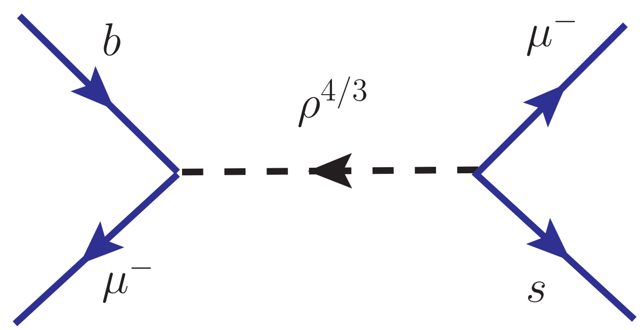



$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ g_s \, (\bar{\tau}_R \nu_L)(\bar{c}_R b_L) + g_T \, (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \, (\bar{c}_R \sigma_{\mu\nu} b_L) \right]$$

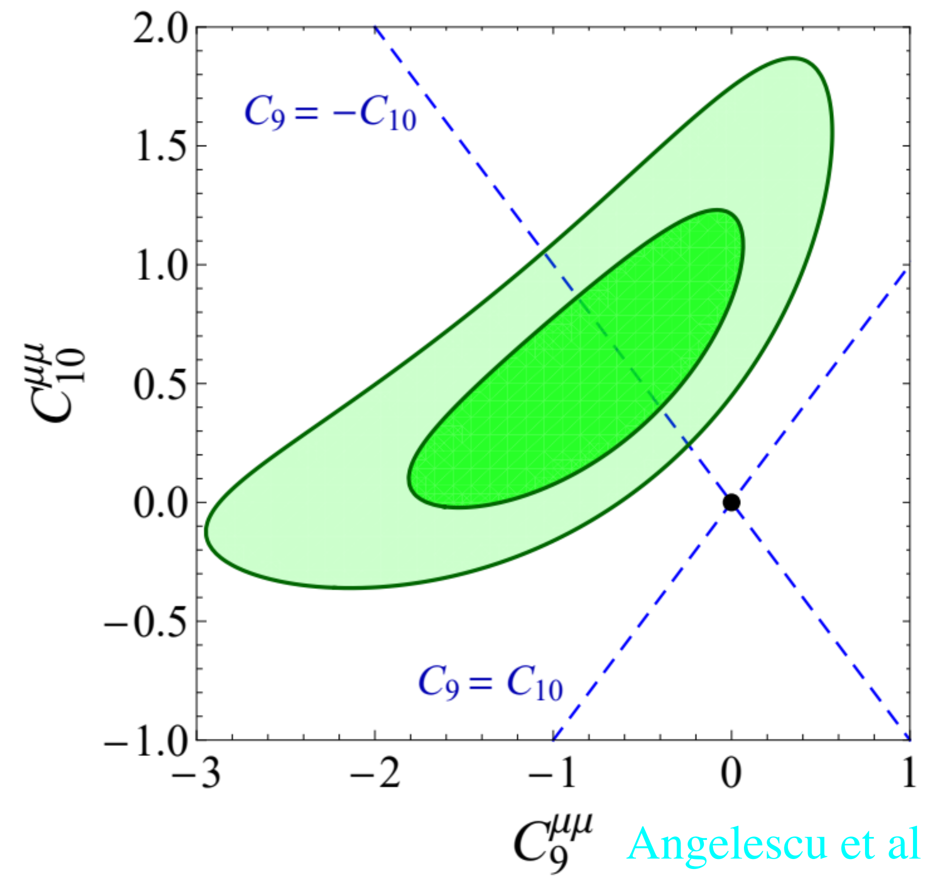
$$\boxed{g_S\left(\mu = m_{R_2}\right) = 4 g_T \left(\mu = m_{R_2}\right) = \frac{f_{2\alpha} f_{33}'^{\star}}{4\sqrt{2} m_{R_2}^2 G_F V_{cb}}}$$

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




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

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

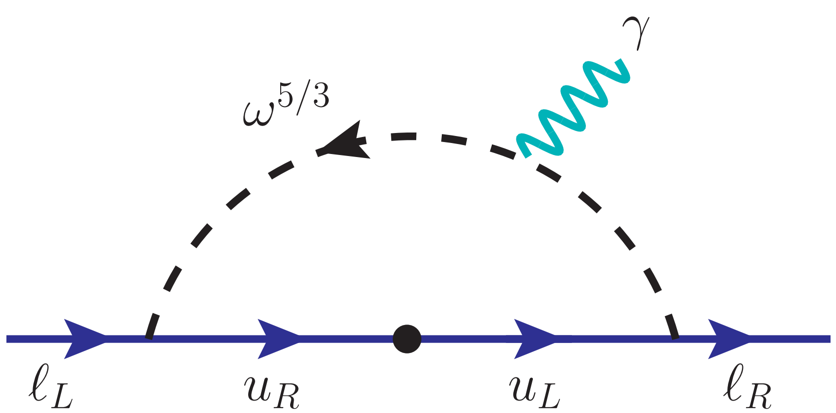


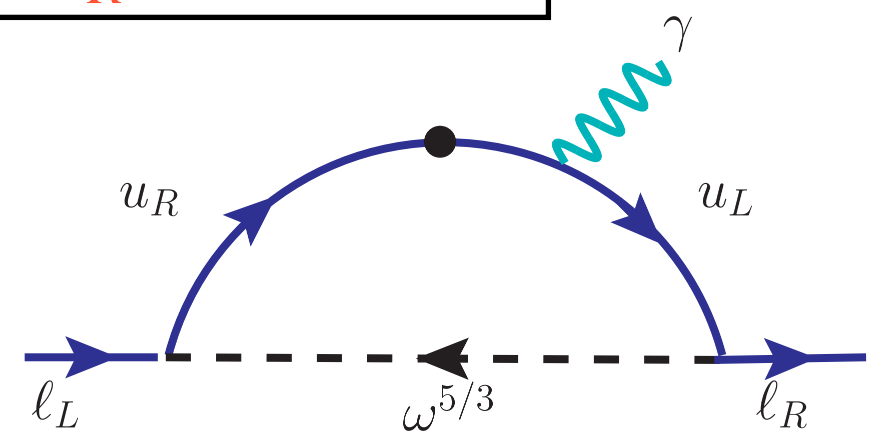

Angelescu et al., 18

$$\boxed{C_9 = -C_{10} = \frac{\pi v^2}{V_{tb} V_{ts}^{\star} \alpha_{\text{em}}} \frac{y_{22} y_{32}^{\star}}{m_{S_3}^2}}$$

# Anomalous Magnetic Moment

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




$$\Delta a_\ell = -\frac{3}{16\pi^2}\frac{m_\ell^2}{m_{R_2}^2}\sum_q \Big[ \left(|f_{q\ell}|^2 + |(V^\star f')_{q\ell}|^2\right)\left(Q_q F_5(x_q) + Q_S F_2(x_q)\right)$$
$$\boxed{-\frac{m_q}{m_\ell}\mathrm{Re}[f_{q\ell}\,(V^\star f')^\star_{q\ell}]\,\left(Q_q F_6(x_q) + Q_S F_3(x_q)\right)\Big]}$$

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

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

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

# Yukawa texture

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

OR

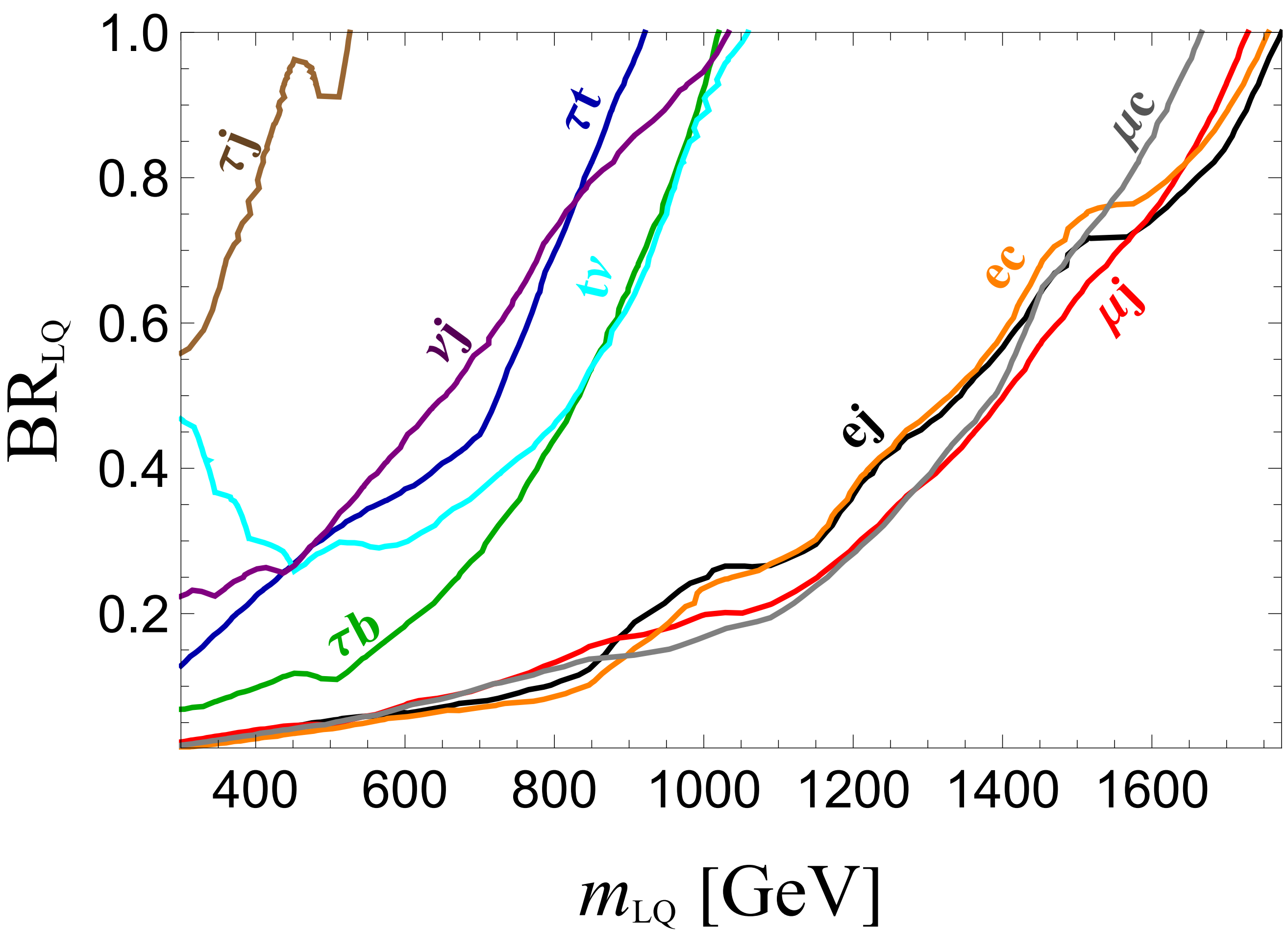
$$\boxed{y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & 0 \\ y_{31} & y_{32} & y_{33} \end{pmatrix}}$$

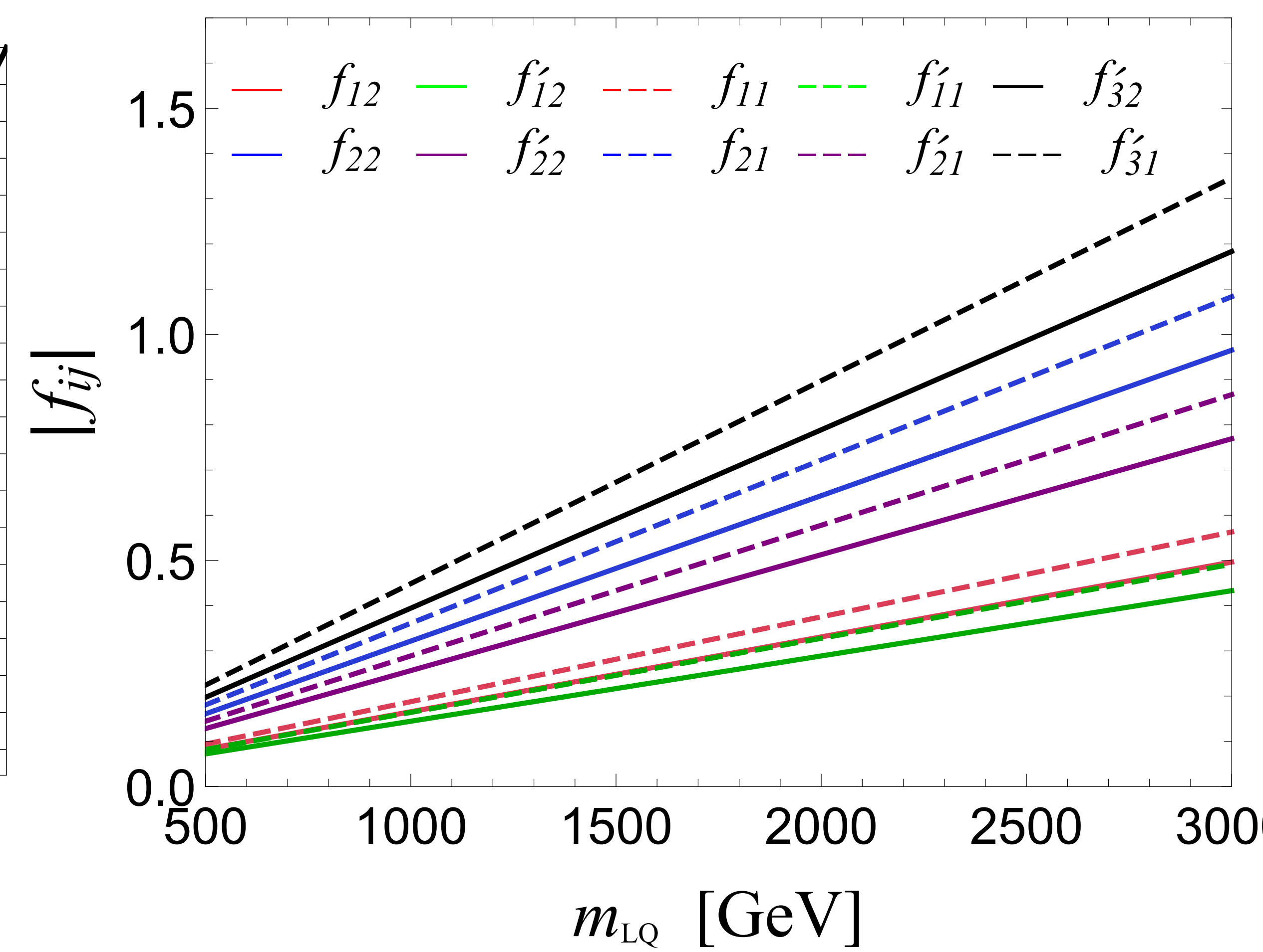
$f_{ab}$ (a $\rightarrow$ quark flavor , b $\rightarrow$ lepton flavor)

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

# Experimental 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

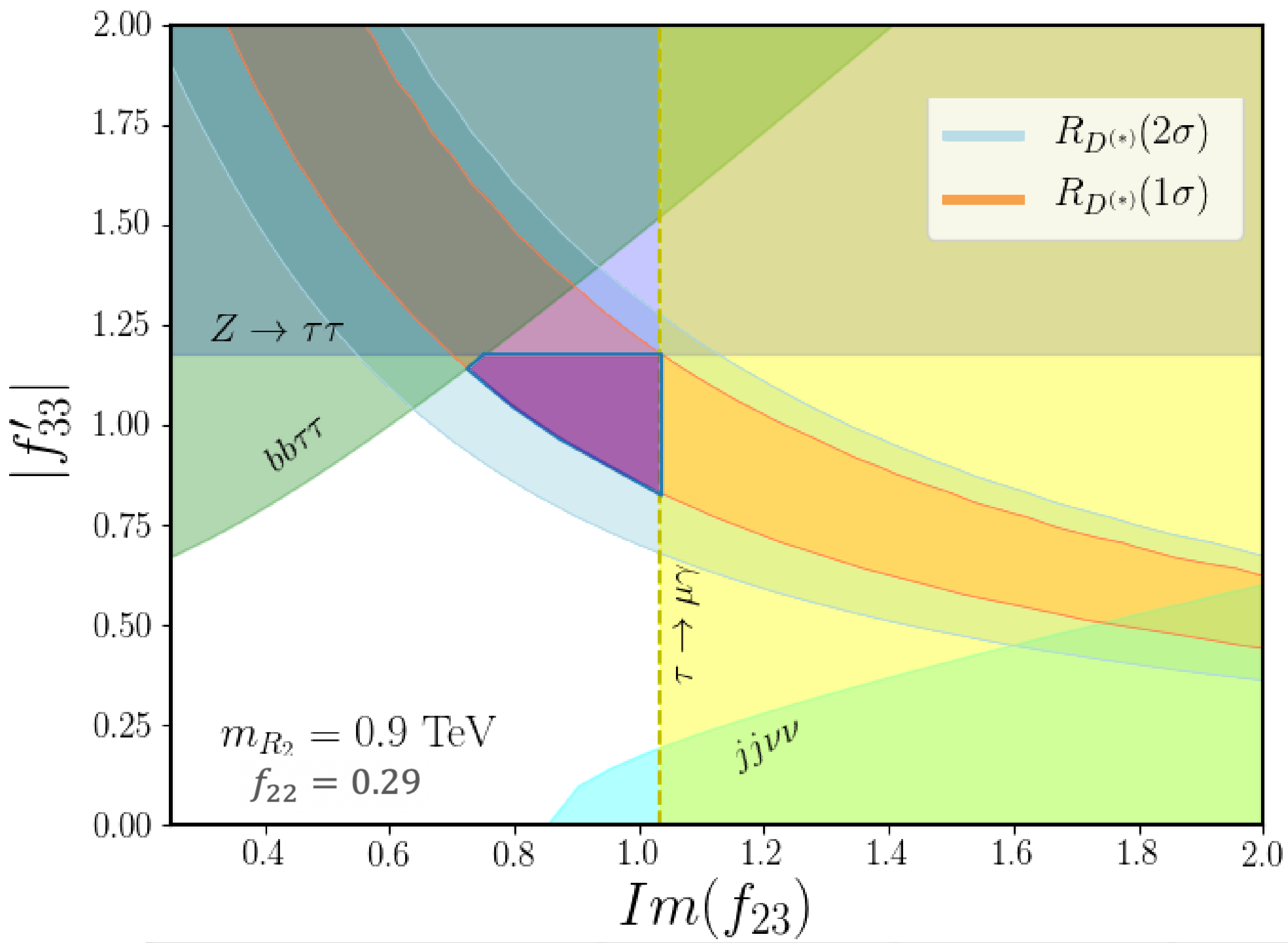


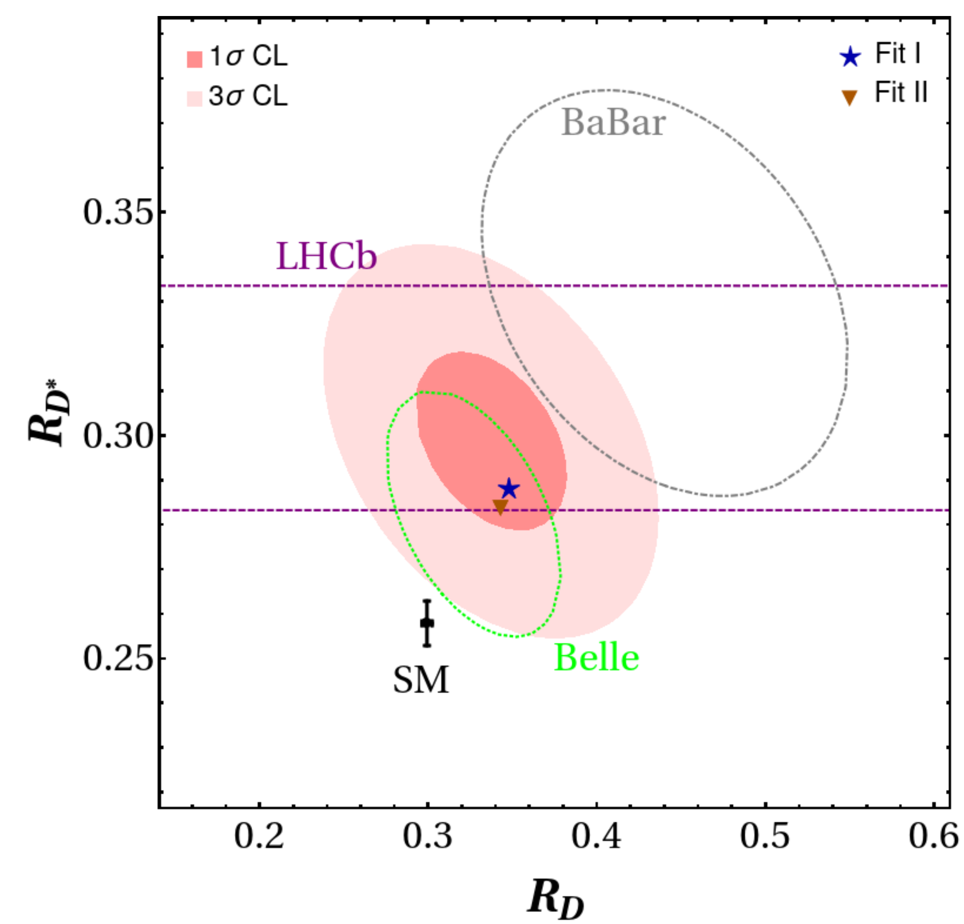



# Results: Numerical Fit

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

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

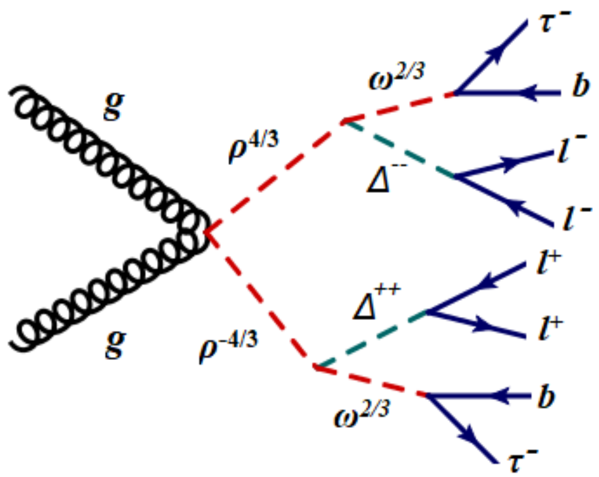


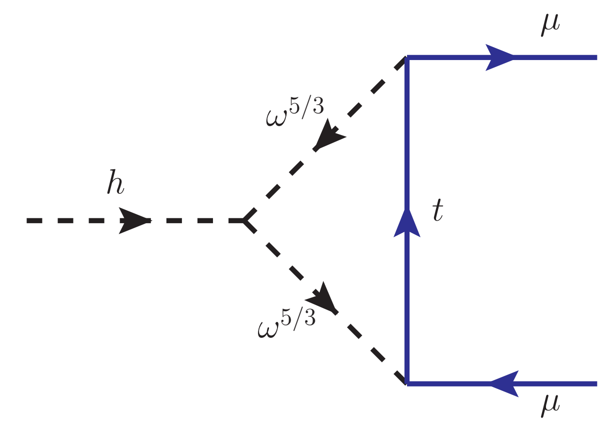



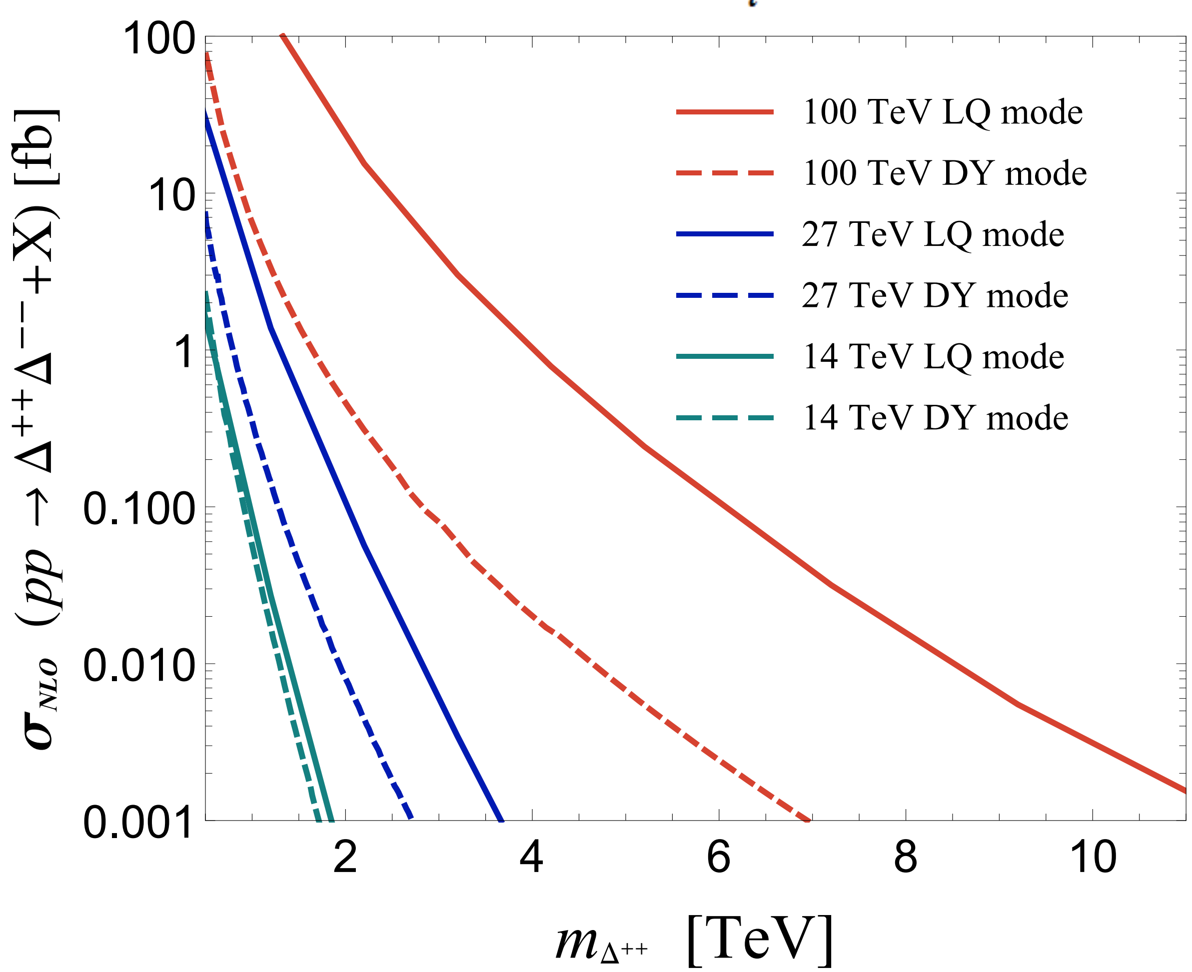

| Observable | $R_D$ | $R_{D^\star}$ | $C_9 = -C_{10}$ | $(g-2)_\mu$ |
|---|---|---|---|---|
| Model Fit | 0.34 | 0.282 | -0.52 | $2.97 \cdot 10^{-9}$ |

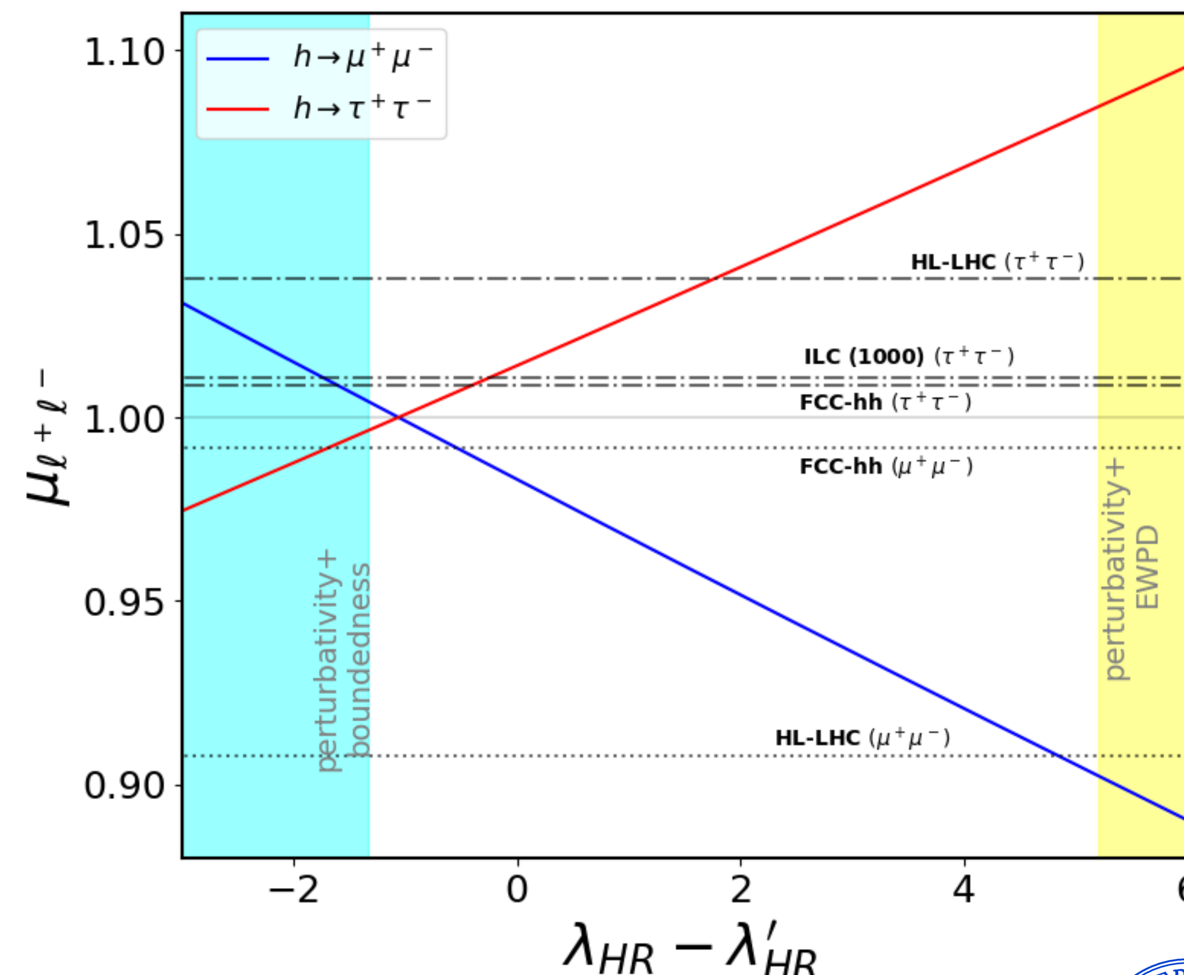
# Collider Implications

- 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 $\Delta a_\mu$ give rise $h \to \mu\mu$ and $h \to \tau\tau$



# 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 interesting new collider signals.

- 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*