Neutrino mass and flavor anomalies

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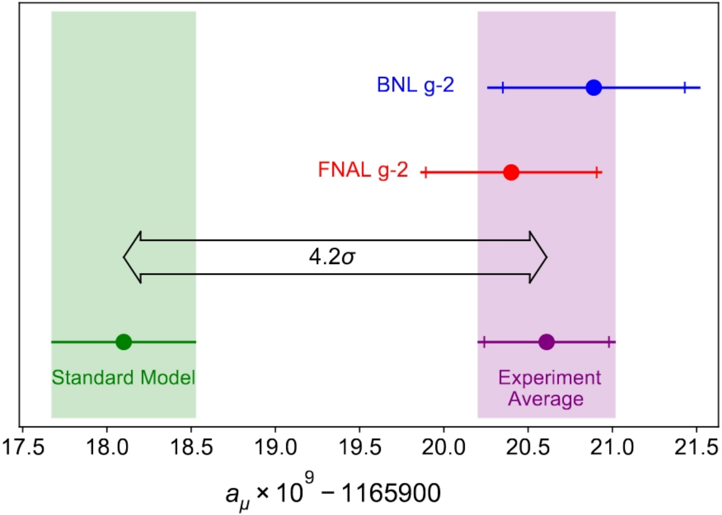
arXiv:2202.10479, arXiv:2203.15499 (J. Julio, S. Saad, A. Thapa)

Outline

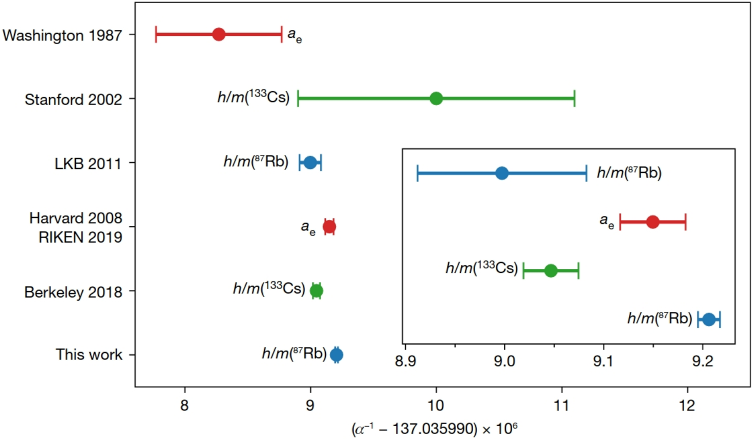
- Flavor anomalies
- Proposed model
- Solutions to flavor anomalies

Anomaly in a_μ



Phys. Rev. Lett. 126, 141801

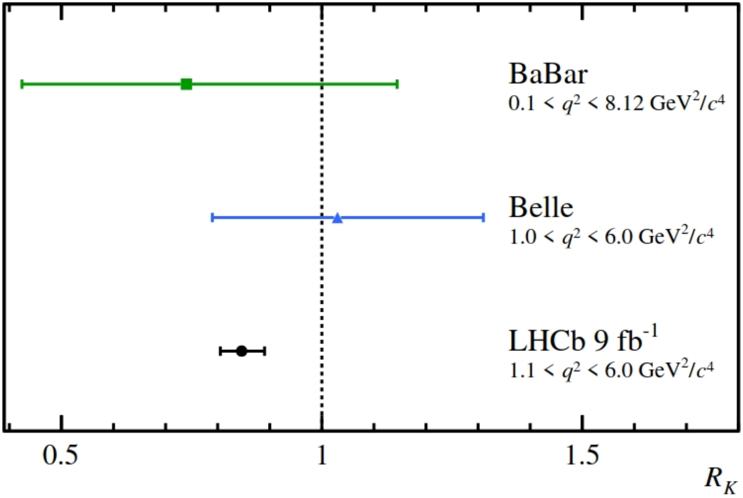
Anomaly in a_e



Berkeley (2018): $\sim -2.5\sigma$

Nature 588 (2020) no.7836, 61-65

Anomaly in R_K



Nature Phys. 18 (2022) 3, 277-282

Anomalies in B-meson decays

- LHCb (2021): $R_K^{[1.1,6]} = 0.847 \pm 0.042$ $\sim -3.1\sigma$

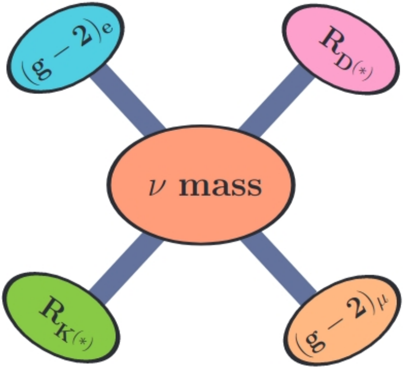
- LHCb (2017): ${R_{K^*}}^{[1.1,6]} = 0.71 \pm 0.10$ $\sim -2.5\sigma$

  ${R_{K^*}}^{[0.045,1.1]} = 0.68 \pm 0.10$ $\sim -2.3\sigma$

- Belle (2019):

  $R_D = 0.340 \pm 0.030,\ R_{D^*} = 0.295 \pm 0.014$ $\sim +3\sigma$

Model Building Motivation

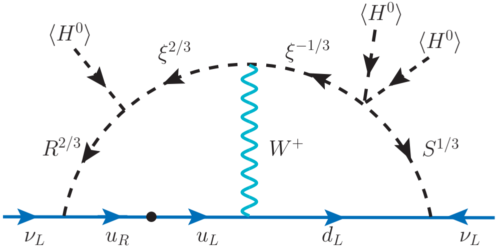


✓ Scalar Leptoquarks !

Julio, Saad, Thapa (2022)

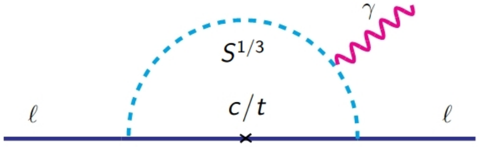
New Proposal

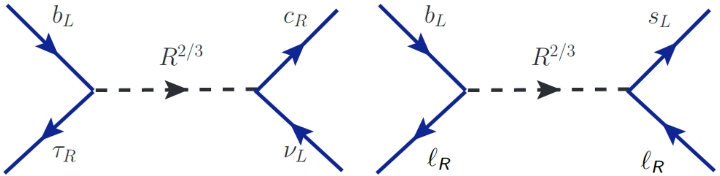
- $R_2(3, 2, 7/6) = \begin{pmatrix} R^{5/3} \\ R^{2/3} \end{pmatrix}$
- $S_1(\overline{3}, 1, +1/3) = S^{1/3}$
- $\xi_3(3, 3, 2/3) = \begin{pmatrix} \frac{\xi^{2/3}}{\sqrt{2}} & \xi^{5/3} \\ \xi^{-1/3} & -\frac{\xi^{2/3}}{\sqrt{2}} \end{pmatrix}$



Julio, Saad, Thapa (2022)

Addressing flavor anomalies





(example diagrams)

Minimal Textures

$$\text{IH-I, NH-I:} \quad f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}, \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}.$$

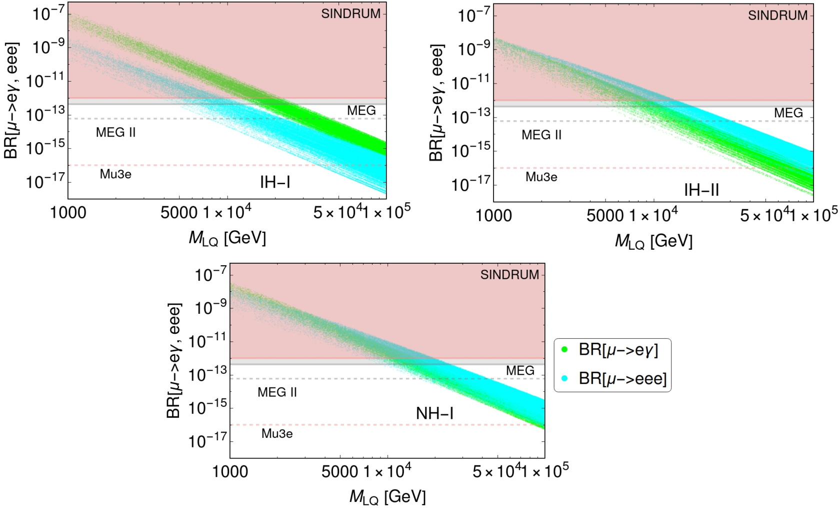
$$\text{IH-II:} \quad f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & 0 & * \end{pmatrix}, \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}.$$

$$\text{NH-II, NH-III:} \quad f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & * \\ 0 & * & * \end{pmatrix}, \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & * \\ * & * & * \end{pmatrix}.$$

NH-II (up-diagonal texture), NH-III (down-diagonal texture)

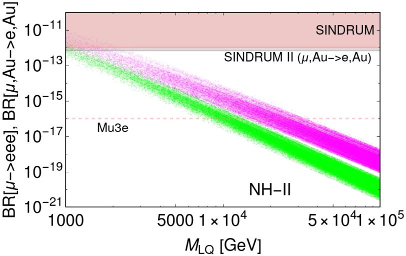
Lepton Flavor Violation

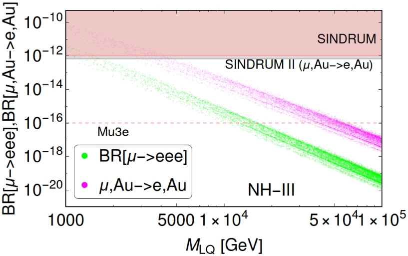
flavor anomalies: $m_{\mathrm{LQ}} \sim \mathcal{O}(1)$ TeV, $y \sim \mathcal{O}(1)$



(minimal textures)

Lepton Flavor Violation





(modified minimally extended textures)

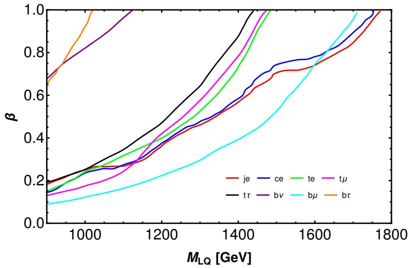
LFV constraints

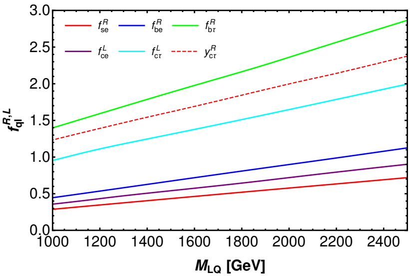
Process	Constraints
$\mu \to e\gamma$	$\lvert f^R_{\alpha e} f^{R*}_{\alpha\mu}\rvert + \lvert f^L_{\alpha e} f^{L*}_{\alpha\mu}\rvert < 4.82 \times 10^{-4} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
	$\left(\lvert f^R_{\alpha e} f^{L*}_{\alpha\mu}\rvert + \lvert f^L_{\alpha e} f^{R*}_{\alpha\mu}\rvert\right) \mathcal{C} < 7.63 \times 10^{-5} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2 \left(\frac{1\ \text{GeV}}{m_q}\right)$
$\tau \to e\gamma$	$\lvert f^R_{\alpha e} f^{R*}_{\alpha\tau}\rvert + \lvert f^L_{\alpha e} f^{L*}_{\alpha\tau}\rvert < 0.32 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
	$\left(\lvert f^R_{\alpha e} f^{L*}_{\alpha\tau}\rvert + \lvert f^L_{\alpha e} f^{R*}_{\alpha\tau}\rvert\right) \mathcal{C} < 0.85 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2 \left(\frac{1\ \text{GeV}}{m_q}\right)$
$\tau \to \mu\gamma$	$\lvert f^R_{\alpha\mu} f^{R*}_{\alpha\tau}\rvert + \lvert f^L_{\alpha\mu} f^{L*}_{\alpha\tau}\rvert < 0.37 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
	$\left(\lvert f^R_{\alpha\mu} f^{L*}_{\alpha\tau}\rvert + \lvert f^L_{\alpha\mu} f^{R*}_{\alpha\tau}\rvert\right) \mathcal{C} < 0.98 \left(\frac{M_{R_2}}{\text{TeV}}\right)^2 \left(\frac{1\ \text{GeV}}{m_q}\right)$
$\mu - e$	$\lvert \hat{f}^R_{ue} \hat{f}^{R*}_{u\mu}\rvert \leq 8.58 \times 10^{-6} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$

Meson decays constraints

Process	Constraints
$K_L \to e^+ e^-$	$\|\hat{f}^R_{de} \hat{f}^{R*}_{se}\| \leq 2.0 \times 10^{-3} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K^0_L \to e^\pm \mu^\mp$	$\|\hat{f}^R_{d\mu} \hat{f}^{R*}_{se} + \hat{f}^R_{s\mu} \hat{f}^{R*}_{de}\| \leq 1.9 \times 10^{-5} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K^0_L \to \pi^0 e^\pm \mu^\mp$	$\|\hat{f}^R_{d\mu} \hat{f}^{R*}_{se} - f^R_{s\mu} f^{R*}_{de}\| \leq 2.9 \times 10^{-4} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K^+ \to \pi^+ e^+ e^-$	$\|\hat{f}^R_{de} \hat{f}^{R*}_{s\mu}\| \leq 2.3 \times 10^{-2} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K^+ \to \pi^+ e^- \mu^+$	$\|\hat{f}^R_{d\mu} \hat{f}^{R*}_{se}\|, \|\hat{f}^R_{de} \hat{f}^{R*}_{s\mu}\| \leq 1.9 \times 10^{-4} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
$K - \bar{K}$	$\|\hat{f}^{R*}_{d\alpha} \hat{f}^R_{s\alpha}\| \leq 0.0266 \left(\frac{M_{R_2}}{\text{TeV}}\right)$
$K^+ \to \pi^+ \nu\nu$	$\text{Re}[\hat{y}^L_{de} \hat{y}^L_{se}] = [-3.7, 8.3] \times 10^{-4} \left(\frac{M_{S_1}}{\text{TeV}}\right)^2$ $[\sum_{m \neq n} \|\hat{y}^L_{dm} \hat{y}^{L*}_{sn}\|^2]^{1/2} < 6.0 \times 10^{-4} \left(\frac{M_{S_1}}{\text{TeV}}\right)^2$
$B \to K^{(*)} \nu\nu$	$\hat{y}^L_{b\alpha} \hat{y}^L_{s\beta} = [-0.036, 0.076] \left(\frac{M_{S_1}}{\text{TeV}}\right)^2, [R^{\nu\bar{\nu}}_{K^*} < 2.7]$ $\hat{y}^L_{b\alpha} \hat{y}^L_{s\beta} = [-0.047, 0.087] \left(\frac{M_{S_1}}{\text{TeV}}\right)^2, [R^{\nu\bar{\nu}}_{K} < 3.9]$

LHC constraints

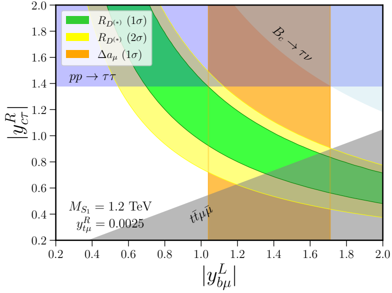


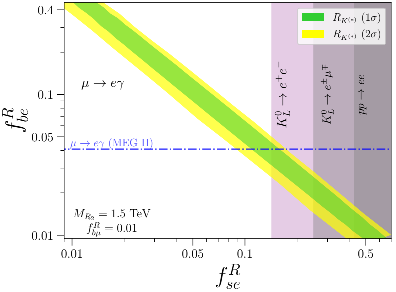


Benchmark: TX-I-NH

$$f^R = \begin{pmatrix} 0 & 0 & 0 \\ 0.13 & 0 & -0.027 \\ 0.036 & 0.01 & 0 \end{pmatrix}, \quad f^L = \begin{pmatrix} 0 & 0 & 1.0 \\ 0 & 0 & 6.36 \times 10^{-4} \\ 0 & 0 & -5.32 \times 10^{-6} \end{pmatrix},$$

$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ -0.2 & 0 & 1.0 \\ 0 & 0.0025 & 0 \end{pmatrix}, \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0.02 & 0 & 0 \\ 0 & \boxed{1.2} & 0 \end{pmatrix}.$$

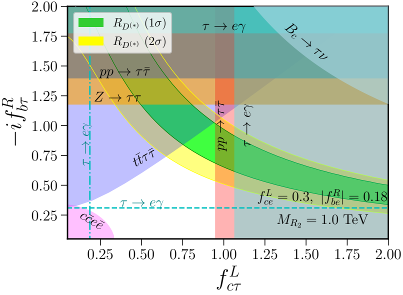


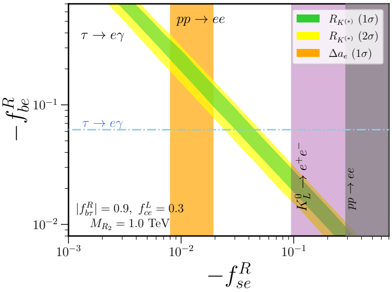


Benchmark: TX-II-IH

$$f^R = \begin{pmatrix} 0 & 0 & 0 \\ \boxed{-0.013} & 0 & 0 \\ -0.180 & 0 & -0.9\,i \end{pmatrix}, \quad f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0.3 & 0 & 0.9 \\ 0 & 0 & 0 \end{pmatrix},$$

$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1.85\times 10^{-4} \\ 0 & 1.0 & 0 \end{pmatrix}, \quad y^L = 10^{-3}\begin{pmatrix} 0 & 0 & 0 \\ -1.82 & 5.78\,i & 0 \\ 0 & 4.40 & 0 \end{pmatrix}.$$





TX-I/TX-II Fit values

Oscillation parameters	3σ range NuFit5.1	Model prediction	
		TX-I-NH	TX-II-IH
$\Delta m^2_{21}(10^{-5}\ \mathrm{eV}^2)$	6.82 - 8.04	7.41	7.39
$\Delta m^2_{23}(10^{-3}\ \mathrm{eV}^2)$(IH)	2.410 - 2.574	-	2.53
$\Delta m^2_{31}(10^{-3}\ \mathrm{eV}^2)$(NH)	2.43 - 2.593	2.53	-
$\sin^2\theta_{12}$	0.269 - 0.343	0.316	0.2986
$\sin^2\theta_{23}$ (IH)	0.410 - 0.613	-	0.534
$\sin^2\theta_{23}$ (NH)	0.408 - 0.603	0.506	-
$\sin^2\theta_{13}$ (IH)	0.02055 - 0.02457	-	0.0227
$\sin^2\theta_{13}$(NH)	0.02060 - 0.02435	0.0218	-
Observable	$1\,\sigma$ **range**		
$C_9^{ee} = C_{10}^{ee}$	$[-1.65, -1.13]$	-1.39	-1.57
$(g-2)_e\ (10^{-14})$	-88 ± 36	-86	-84
$(g-2)_\mu\ (10^{-10})$	25.1 ± 6.0	22.4	24.2

Summary

- Strong evidence of new physics
- A new two-loop Neutrino Mass Model

✓ Neutrino oscillation data

✓ $(g-2)_\mu$

✓ $(g-2)_e$

✓ $R_{K^{(*)}}$

✓ $R_{D^{(*)}}$

THANK YOU!

Backup slides

B-meson decays

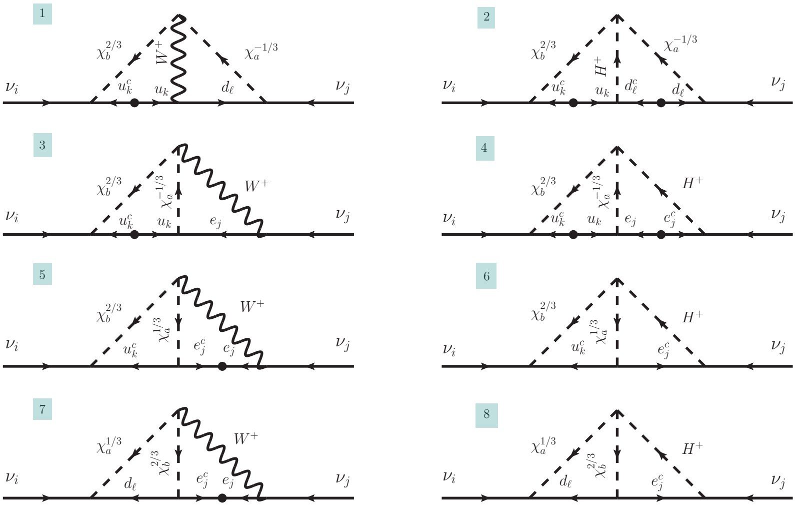
- neutral-current transitions: $b \to s\ell^+\ell^-$

$$R_K = \frac{Br\left(B \to K\mu^+\mu^-\right)}{Br\left(B \to Ke^+e^-\right)}, \quad R_{K^*} = \frac{Br\left(B \to K^*\mu^+\mu^-\right)}{Br\left(B \to K^*e^+e^-\right)}.$$

- charged-current transitions: $b \to c\tau\overline{\nu}$

$$R_D = \frac{Br\left(B \to D\tau\overline{\nu}_\tau\right)}{Br\left(B \to D\ell\overline{\nu}\right)}, \quad R_{D^*} = \frac{Br\left(B \to D^*\tau\overline{\nu}_\tau\right)}{Br\left(B \to D^*\ell\overline{\nu}\right)}.$$

New Proposal



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Global Fit

Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.20^{+0.15}_{-0.15}$	1.3σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$+0.05^{+0.12}_{-0.12}$	0.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.53^{+0.13}_{-0.13}$	3.7σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.39^{+0.07}_{-0.07}$	5.6σ
$C_9^{bsee} = C_{10}^{bsee}$			$-1.39^{+0.26}_{-0.26}$	4.0σ	$-1.28^{+0.24}_{-0.23}$	4.1σ
$C_9^{bsee} = -C_{10}^{bsee}$			$+0.37^{+0.10}_{-0.10}$	4.2σ	$+0.37^{+0.10}_{-0.10}$	4.3σ

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Neutrino Mass Formula

$$\begin{aligned}\mathcal{L} = {} & \overline{u}_{Ri}\left(f^L\right)_{ij}\ell_{Lj}R^{5/3} + \overline{u}_{Ri}\left(-f^L\right)_{ij}\nu_{Lj}R^{2/3} \\ & + \overline{u}_{Li}\left(f^R\right)_{ij}\ell_{Rj}R^{5/3} + \overline{d}_{Li}\left(V^\dagger f^R\right)_{ij}\ell_{Rj}R^{2/3} \\ & + \overline{u^c}_{Li}\left(y^L\right)_{ij}\ell_{Lj}S^{1/3} + \overline{d^c}_{Li}\left(-V^T y^L\right)_{ij}\nu_{Lj}S^{1/3} \\ & + \overline{u^c}_{Ri}\left(y^R\right)_{ij}\ell_{Rj}S^{1/3}\end{aligned}$$

$$\begin{aligned}(\mathcal{M}_\nu)_{ji} = \frac{3g^2 m_t}{\sqrt{2}(16\pi^2)^2}\Big\{ & \left[y^L_{mj}V_{ml}V^*_{kl}(D_u)_k f^L_{ki} + f^L_{kj}(D_u)_k V^*_{kl}V_{ml}y^L_{mi}\right]\hat{I}_{jkl} \\ & + \frac{m_\tau}{m_t}(D_\ell)_j\left[y^{R*}_{kj}f^L_{ki} + f^L_{kj}y^{R*}_{ki}\right]\tilde{I}_{jk} \\ & + \frac{m_\tau}{m_t}(D_\ell)_j\left[f^{R*}_{kj}V^*_{kl}V_{ml}y^L_{mi} + y^L_{mj}V_{ml}V^*_{kl}f^{R*}_{ki}\right]\bar{I}_{jl}\Big\}\end{aligned}$$

Julio, Saad, Thapa (2022)