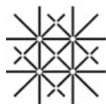


Neutrino mass and flavor anomalies

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June 30, 2022

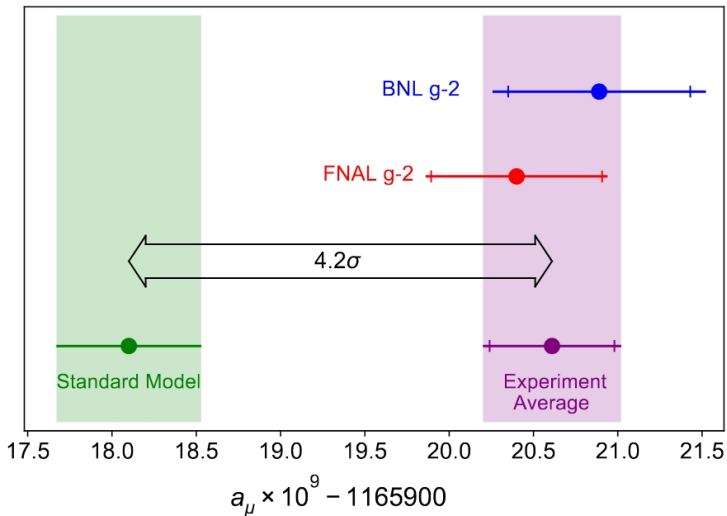
[arXiv:2202.10479](https://arxiv.org/abs/2202.10479) (J. Julio, S. Saad, A. Thapa)

[arXiv:2203.15499](https://arxiv.org/abs/2203.15499) (J. Julio, S. Saad, A. Thapa)

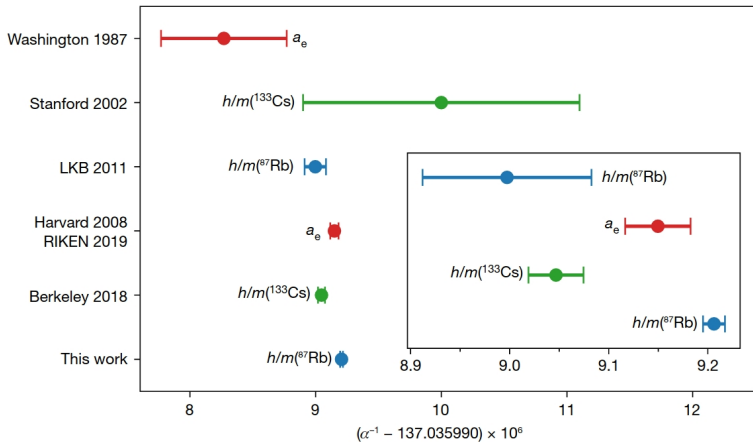
Outline

- Flavor anomalies
- Proposed model
- Solutions to flavor anomalies

Anomaly in a_μ



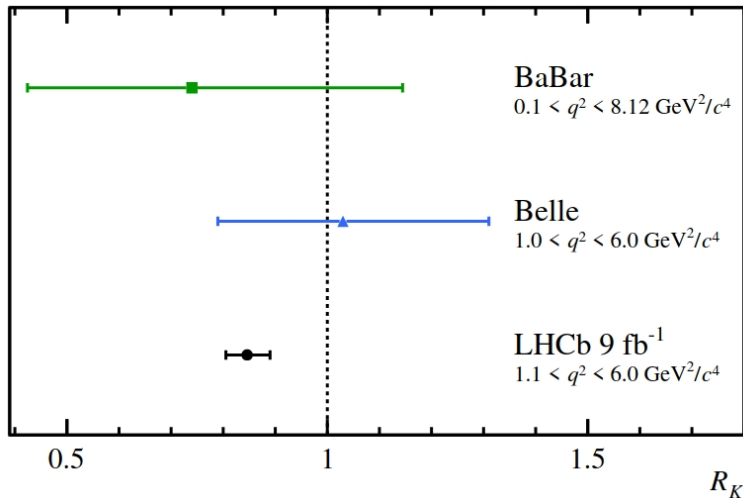
Anomaly in a_e



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

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

Anomaly in R_K



Anomalies in B -meson decays

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

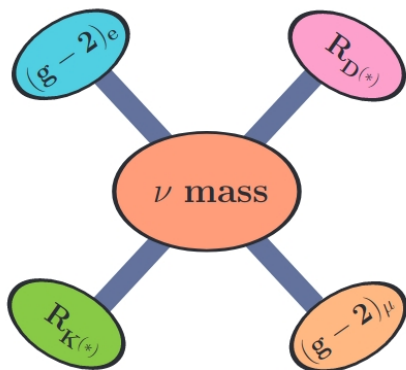
- LHCb (2017): $R_{K^*}^{[1.1,6]} = 0.71 \pm 0.10 \quad \sim -2.5\sigma$

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

- Belle (2019):

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

Model Building Motivation

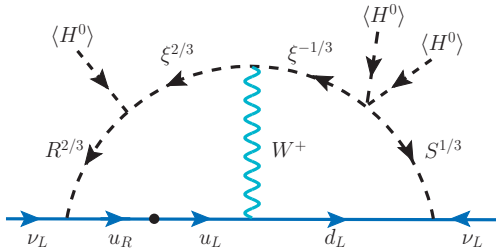


✓ Scalar Leptoquarks !

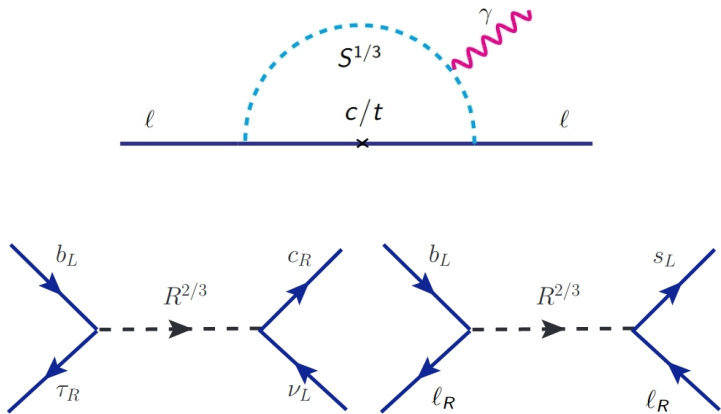
Julio, Saad, Thapa (2022)

New Proposal

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



Addressing flavor anomalies



(example diagrams)

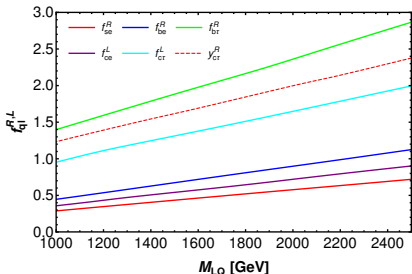
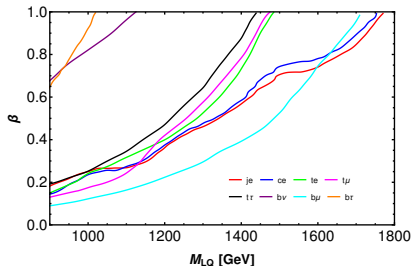
LFV constraints

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

Meson decays constraints

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

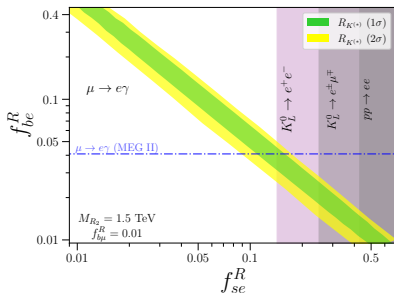
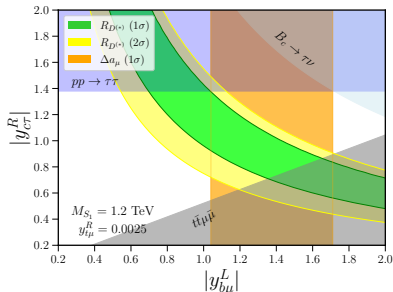
LHC constraints



Benchmark: TX-I-NH

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

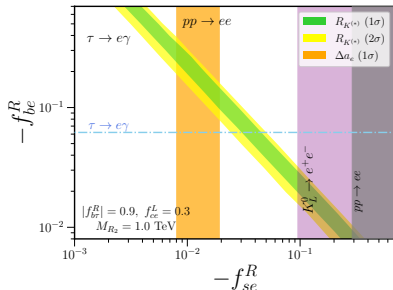
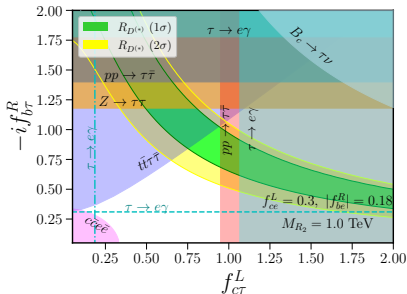
$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ -0.2 & 0 & 1.0 \\ 0 & 0.0025 & 0 \end{pmatrix}, \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0.02 & 0 & 0 \\ 0 & 1.2 & 0 \end{pmatrix}.$$



Benchmark: TX-II-IH

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

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



TX-I/TX-II Fit values

Oscillation parameters	3 σ range NuFit5.1	Model prediction	
		TX-I-NH	TX-II-IH
$\Delta m_{21}^2 (10^{-5} \text{ eV}^2)$	6.82 - 8.04	7.41	7.39
$\Delta m_{23}^2 (10^{-3} \text{ eV}^2)$ (IH)	2.410 - 2.574	-	2.53
$\Delta m_{31}^2 (10^{-3} \text{ eV}^2)$ (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 σ 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

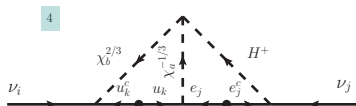
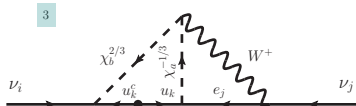
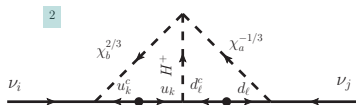
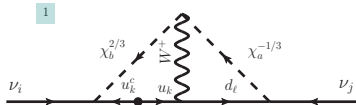
- neutral-current transitions: $b \rightarrow sl^+l^-$

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

- charged-current transitions: $b \rightarrow c\tau\bar{\nu}$

$$R_D = \frac{Br(B \rightarrow D\tau\bar{\nu}_\tau)}{Br(B \rightarrow D\ell\bar{\nu})}, \quad R_{D^*} = \frac{Br(B \rightarrow D^*\tau\bar{\nu}_\tau)}{Br(B \rightarrow D^*\ell\bar{\nu})}.$$

New Proposal



Global Fit

Wilson coefficient	$b \rightarrow s\mu\mu$		LFU, $B_s \rightarrow \mu\mu$		all rare B decays	
	best fit	pull	best fit	pull	best fit	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

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

$$(\mathcal{M}_\nu)_{ji} = \frac{3g^2 m_t}{\sqrt{2}(16\pi^2)^2} \left\{ [y_{mj}^L V_{ml} V_{kl}^* (D_u)_k f_{ki}^L + f_{kj}^L (D_u)_k V_{kl}^* V_{ml} y_{mi}^L] \hat{I}_{jkl} \right. \\
 \left. + \frac{m_\tau}{m_t} (D_\ell)_j [y_{kj}^{R*} f_{ki}^L + f_{kj}^L y_{ki}^{R*}] \tilde{I}_{jk} \right. \\
 \left. + \frac{m_\tau}{m_t} (D_\ell)_j [f_{kj}^{R*} V_{kl}^* V_{ml} y_{mi}^L + y_{mj}^L V_{ml} V_{kl}^* f_{ki}^{R*}] \bar{I}_{jl} \right\}$$

Minimal Textures

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

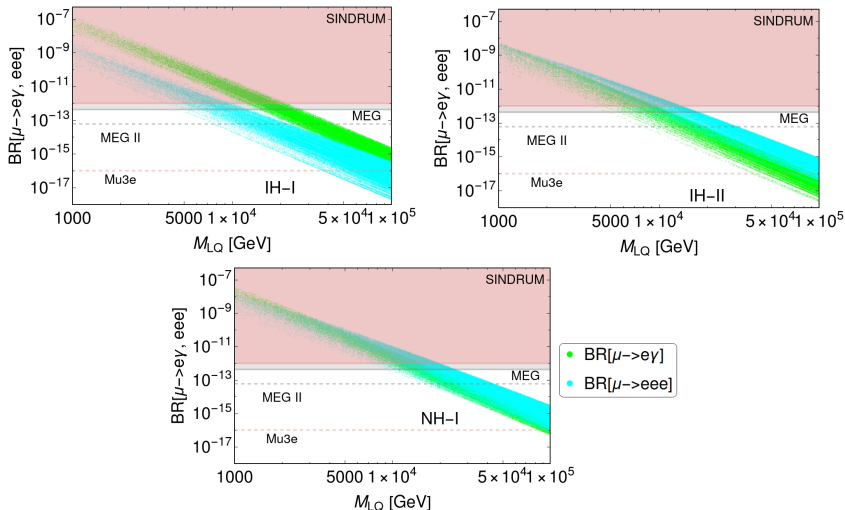
$$\text{IH-II: } f^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & 0 & * \end{pmatrix}, \quad y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}.$$

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

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

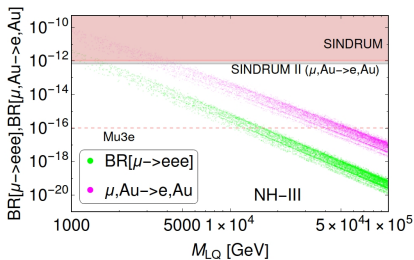
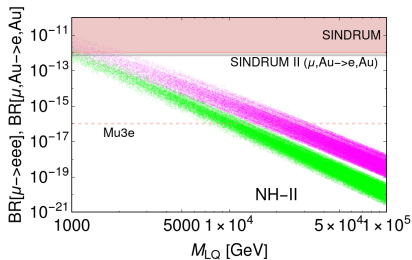
Lepton Flavor Violation

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



(minimal textures)

Lepton Flavor Violation



(modified minimally extended textures)