Addressing $R_{D^{(*)}}$, $R_{K^{(*)}}$, muon $g-2$ and ANITA anomalies in a minimal RPV-SUSY framework

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W. Altmannshofer, BD, A. Soni, Y. Sui, PRD **102**, 015031 (2020) [2002.12910]

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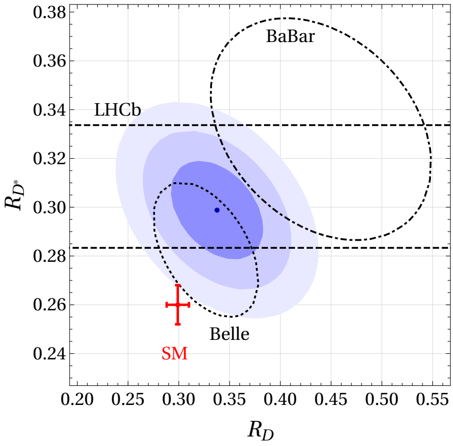
Outline

- The Anomalies
- The RPV3 Framework
- Three Benchmark Cases
- Conclusion

B-Anomalies

(see talks by D. Guadagnoli and F. Archilli)

$$R_{D^{(*)}} = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \quad (\text{with } \ell = e, \mu)$$



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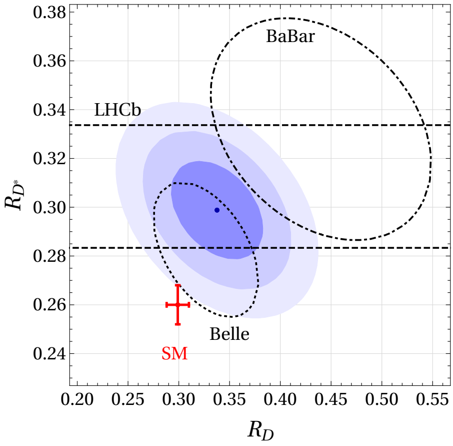
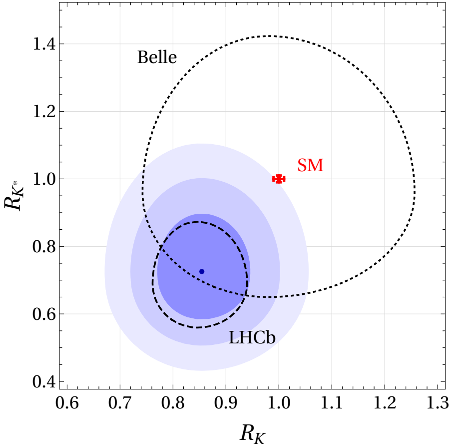
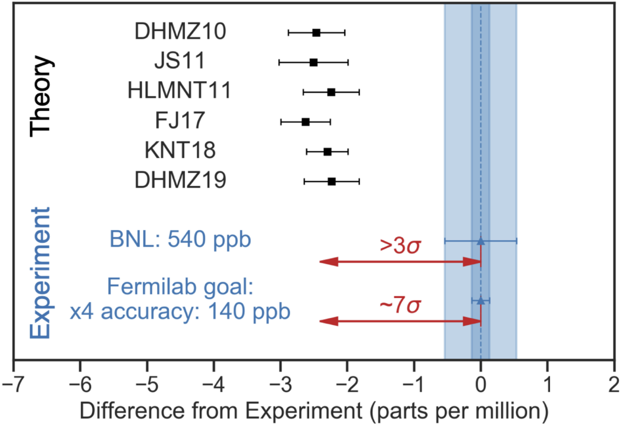




Muon $g-2$

[figure from J. Kasper (PHENO ’20)]



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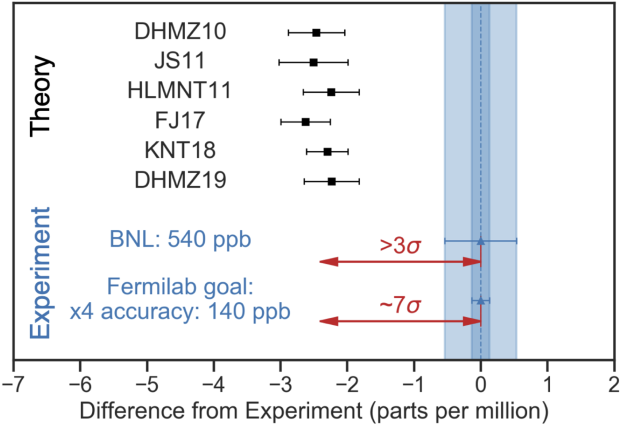


Observable	$R_{D^{(*)}}, R_{J/\psi}$	$R_{K^{(*)}}$	$(g-2)_\mu$	All but $(g-2)_\mu$	All
Pull	3.3σ (2.2σ)	3.4σ	3.3σ	4.5σ (3.7σ)	5.3σ (4.6σ)

ANITA

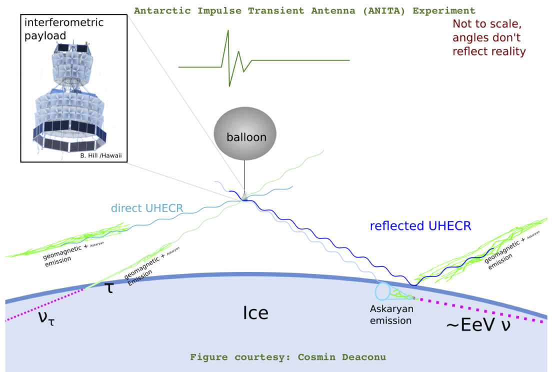


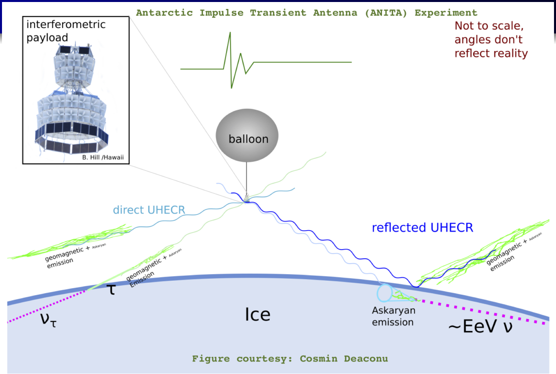
TABLE I: *ANITA-I,-III anomalous upward air showers.*

ANITA Collaboration, PRL'18

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[1]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°$, $159.62 \pm 0.7°$	$-35.0 \pm 0.3°$, $61.41 \pm 0.7°$
RA, Dec[2]	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

[1] Latitude, Longitude of the estimated ground position of the event.
[2] Sky coordinates projected from event arrival angles at ANITA.
[3] For upward shower initiation at or near ice surface.

ANITA



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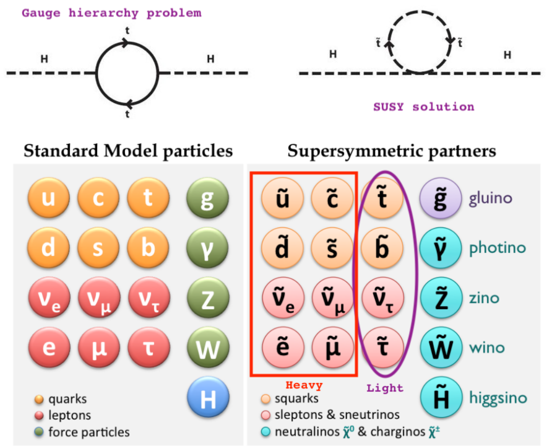
This talk: A SUSY solution to ANITA, muon $g-2$ and the B-anomalies!



Natural SUSY

[Papucci, Ruderman, Weiler (JHEP '12); Brust, Katz, Lawrence, Sundrum (JHEP '12)]

RPV3 SUSY

- More natural to include RPV couplings. [Brust, Katz, Lawrence, Sundrum (JHEP '12)]
- Preserves gauge coupling unification. [Altmannshofer, BD, Soni (PRD '17)]
- **RPV3**: RPV SUSY with light 3rd-generation sfermions.
- Can naturally accommodate $R_{D^{(*)}}$ $(b \to c\tau\nu)$ via *LQD* interactions. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); Trifinopoulos (EPJC '18); Hu, Li, Muramatsu, Yang (PRD '19)]

$$\boxed{\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\widetilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \widetilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \widetilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \widetilde{e}_{iL}\bar{d}_{kR}u_{jL} - \widetilde{u}_{jL}\bar{d}_{kR}e_{iL} - \widetilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \mathrm{H.c.}}$$

- Can *simultaneously* explain $R_{K^{(*)}}$ $(b \to s\ell\ell)$ by invoking *LLE* interactions, together with *LQD*. [Das, Hati, Kumar, Mahajan (PRD '17); Earl, Grégoire (JHEP '18); Trifinopoulos (EPJC '18); Hu, Huang (PRD '20); Altmannshofer, BD, Soni, Sui '20]

$$\boxed{\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}\left[\widetilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \widetilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \widetilde{e}^*_{kR}\bar{\nu}^c_{iL}e_{jL} - (i \leftrightarrow j)\right] + \mathrm{H.c.}}$$

- Restricting to RPV3 and using some ansatz, can limit the number of independent λ' and λ couplings.

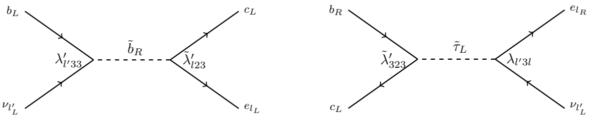
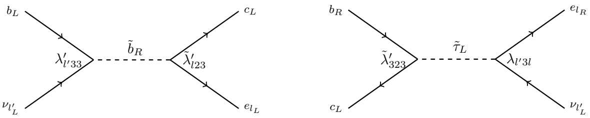


Figure: RPV3 contributions to $R_{D^{(*)}}$. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); $\cdots$]



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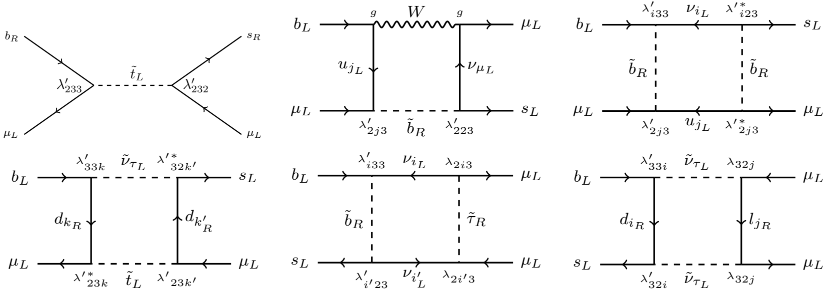

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Muon $g-2$ and ANITA

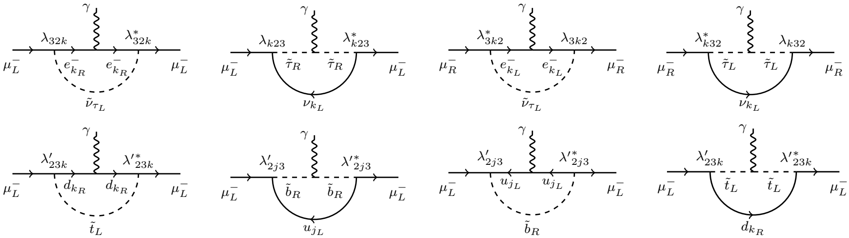

Figure: RPV3 contributions to $(g-2)_\mu$. [Kim, Kyae, Lee (PLB '01)]

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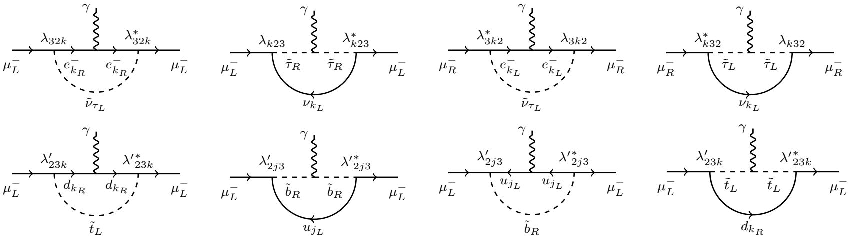

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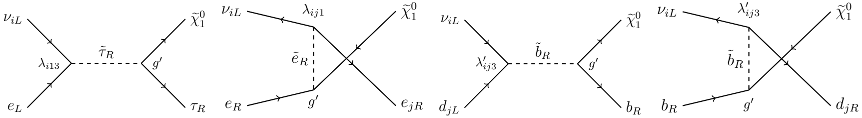

Figure: RPV3 contributions to ANITA anomalous events. [Collins, BD, Sui (PRD '19)]

Three Benchmark Cases

- **Case 1: CKM-like Structure**

$$\lambda'_{ijk} = \lambda'_{333}\,\epsilon^{(3-i)+(3-j)+(3-k)}\,, \qquad \lambda_{ijk} = \lambda_{233}\,\epsilon^{(2-i)+(3-j)+(3-k)}\,.$$

Only 3 independent coupling parameters: $\{\lambda'_{333}, \lambda_{233}, \epsilon\}$.

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- **Case 2: $U(2)_q \times U(2)_\ell$ Flavor Symmetry**

$$\begin{aligned}
&\lambda'_{1jk} = \lambda'_{211} = \lambda'_{231} = \lambda'_{213} = \lambda'_{311} = \lambda'_{331} = \lambda'_{313} \simeq 0\,, \qquad \lambda'_{233} \simeq \lambda'\epsilon_\ell\,,\\
&\lambda'_{221} = \lambda'_{212} \simeq \lambda'\epsilon_\ell\epsilon'_q\,, \qquad \lambda'_{321} = \lambda'_{312} \simeq \lambda'\epsilon'_q\,,\\
&\lambda'_{222} = \lambda'_{223} = \lambda'_{232} \simeq \lambda'\epsilon_\ell\epsilon_q\,, \qquad \lambda'_{322} = \lambda'_{323} = \lambda'_{332} \simeq \lambda'\epsilon_q\,,
\end{aligned}$$

$$\begin{aligned}
&\lambda_{121} = \lambda_{131} = \lambda_{133} \simeq 0\,, \qquad \lambda_{123} = \lambda_{132} = \lambda_{231} \simeq \lambda\epsilon'_\ell\,,\\
&\lambda_{232} \simeq \lambda\epsilon_{\ell S}\,, \quad \lambda_{122} \simeq \lambda\epsilon_\ell\epsilon'_\ell\,, \qquad \lambda_{233} \simeq \lambda\epsilon_\ell\,,
\end{aligned}$$

where $\epsilon_q \approx m_s/m_b \simeq 0.025$, $\epsilon'_q \approx \epsilon_q\sqrt{m_d/m_s} \simeq 0.005$, $\epsilon_\ell \simeq 1$, $\epsilon'_\ell \simeq 0.004$ and $\epsilon_{\ell S} \simeq 0.06$ [Trifinopoulos (EPJC '18)]. Again, 3 independent couplings: $\{\lambda'_{333}, \lambda', \lambda\}$.

Three Benchmark Cases

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- **Case 3: No Symmetry** Also choose 3 independent couplings:

$$\{\lambda'_{223}\,, \quad \lambda' \equiv \lambda'_{123} = \lambda'_{233} = \lambda'_{323}\,, \quad \lambda \equiv \lambda_{132} = \lambda_{231} = \lambda_{232}\}.$$

- In each case, six free mass parameters: $\{m_{\tilde{b}_R}, m_{\tilde{t}_L}, m_{\tilde{\tau}_L}, m_{\tilde{\tau}_R}, m_{\tilde{\nu}_\tau}, m_{\tilde{\chi}_1^0}\}$.

Parameter Dependence of Observables

Observable	Parameter dependence	Relevant terms
$R_{D^{(*)}}$	$\lambda'_{i33}, \lambda'_{3j3}, \lambda'_{2j3}, m_{\tilde{b}_R}$, $\lambda_{i33},\ \lambda_{i32},\ m_{\tilde{\tau}_L}$	$\frac{\lambda'_{i33}\cdot\lambda'_{3j3}}{m^2_{\tilde{b}_R}},\ -\frac{\lambda'_{i33}\cdot\lambda'_{2j3}}{m^2_{\tilde{b}_R}}$, $\frac{\lambda_{i33}\cdot\lambda'_{3j3}}{m^2_{\tilde{\tau}_L}},\ \frac{\lambda_{i32}\cdot\lambda'_{3j3}}{m^2_{\tilde{\tau}_L}}$
$R_{K^{(*)}}$	$\lambda'_{331}, \lambda'_{332}, \lambda'_{321}, \lambda'_{322}, \lambda'_{231}, \lambda'_{232}$, $\lambda'_{i33}, \lambda'_{i23}, \lambda'_{213}, \lambda'_{312}, \lambda_{32k}, \lambda_{3j2}$, $m_{\tilde{b}_R}, m_{\tilde{t}_L}, m_{\tilde{\tau}_R}$	$\frac{\lvert\lambda'_{233}\rvert^2}{m^2_{\tilde{b}_R}}$, $\frac{(\lambda'_{i33}\cdot\lambda'_{i23})\lvert\lambda'_{2j3}\rvert^2}{m^2_{\tilde{b}_R}}$, $\frac{\log\left(m^2_{\tilde{t}_L}/m^2_{\tilde{\nu}_\tau}\right)}{(m^2_{\tilde{t}_L}-m^2_{\tilde{\nu}_\tau})}(\lambda'_{33i}\cdot\lambda'_{32i})\lvert\lambda'_{23i}\rvert^2$, $\frac{\log\left(m^2_{\tilde{b}_R}/m^2_{\tilde{\tau}_R}\right)}{(m^2_{\tilde{b}_R}-m^2_{\tilde{\tau}_R})}\lambda'_{i33}\lambda'_{i'23}\lambda_{2i3}\lambda_{2i'3}$, $\frac{1}{m^2_{\tilde{\nu}_\tau}}\lambda'_{33i}\lambda'_{3i2}\lambda_{32j}\lambda_{3j2}$
$(g-2)_\mu$	$\lambda_{32k}, \lambda_{3k2}, \lambda_{k23}$ $\lambda'_{233}, \lambda'_{223}, \lambda'_{213}$, $m_{\tilde{b}_R}, m_{\tilde{\tau}_R}, m_{\tilde{\tau}_L}, m_{\tilde{\nu}_\tau}$	$\lvert\lambda_{32k}\rvert^2\frac{2}{m^2_{\tilde{\nu}_\tau}}$, $\lvert\lambda_{3k2}\rvert^2\left(\frac{2}{m^2_{\tilde{\nu}_\tau}}-\frac{1}{m^2_{\tilde{\tau}_L}}\right)$, $-\lvert\lambda_{k23}\rvert^2\frac{1}{m^2_{\tilde{\tau}_R}}$, $\frac{\lvert\lambda'_{233}\rvert^2}{m^2_{\tilde{b}_R}-m^2_t}$, $\frac{1}{m^2_{\tilde{b}_R}}(\lvert\lambda'_{213}\rvert^2+\lvert\lambda'_{223}\rvert^2)$
ANITA	$\lambda'_{123}, \lambda'_{223}, \lambda'_{233}, \lambda'_{323}, \lambda'_{333}, m_{\tilde{b}_R}, m_{\tilde{\chi}^0_1}$	$\frac{\lvert\lambda'_{ij3}\rvert^2 m^5_{\tilde{\chi}^0_1}}{m^4_{\tilde{b}_R}}$

Constraint	Parameter dependence	Relevant terms
$B \to \tau\nu$	$\lambda'_{\ell' 33},\ \lambda'_{3j3}\ ,\ m_{\tilde{b}_R}$	$\frac{\lambda'_{\ell' 33}\cdot\lambda'_{3j3}}{m^2_{\tilde{b}_R}}$
$B \to K^{(*)}\nu\bar{\nu}$	$\lambda'_{\ell' 33},\ \lambda'_{\ell 23}\ ,\ m_{\tilde{b}_R}$	$\frac{\lambda'_{\ell' 33}\cdot\lambda'_{\ell 23}}{m^2_{\tilde{b}_R}},\ \frac{\lambda'_{\ell' 33}\cdot\lambda'_{\ell 32}}{m^2_{\tilde{b}_L}}$
$B \to \pi/\rho\,\nu\bar{\nu}$	$\lambda'_{\ell' 33},\ \lambda'_{\ell 13}\ ,\ m_{\tilde{b}_R}$	$\frac{\lambda'_{\ell' 33}\cdot\lambda'_{\ell 13}}{m^2_{\tilde{b}_R}}$
$B_s - \overline{B}_s$ mixing	$\lambda'_{i33},\ \lambda'_{i23},\ \lambda'_{i32}\ ,$ $m_{\tilde{b}_R},\ m_{\tilde{\nu}}$	$\frac{\lambda'_{i23}\lambda'_{i33}\lambda'_{j23}\lambda'_{j33}}{m^2_{\tilde{b}_R}},$ $\frac{\lambda'_{i23}\lambda'_{i32}\lambda'_{j33}\lambda'_{j33}}{m^2_{\tilde{b}_R}}\ ,$ $\frac{\lambda'_{332}\lambda'_{323}}{m^2_{\tilde{\nu}}}$
$D - \overline{D}$ mixing	$\lambda'_{323},\ m_{\tilde{b}_R},\ m_{\tilde{\tau}_R}$	$\frac{\lambda'^4_{323}}{m^2_{\tilde{b}_R}},\ \frac{\lambda'^4_{323}}{m^2_{\tilde{\tau}_R}}$
$D^0 \to \mu^+\mu^-$	$\lambda'_{2j3},\ m_{\tilde{b}_R}$	$\frac{\lambda'_{2j3}\lambda'_{2j'3}}{m^2_{\tilde{b}_R}}$
$\tau \to \ell\nu\bar{\nu}$	$\lambda_{323},\ \lambda'_{333},\ m_{\tilde{\tau}_R},\ m_{\tilde{b}_R}$	$\frac{\lambda^2_{323}}{m^2_{\tilde{\tau}_R}},\ \frac{\lambda'^2_{333}}{m^2_{\tilde{b}_R}}$
$Z \to \ell\bar{\ell}'$	$\lambda'_{333},\ m_{\tilde{b}_R}$	$\frac{\lambda'^2_{333}}{m^2_{\tilde{b}_R}}$

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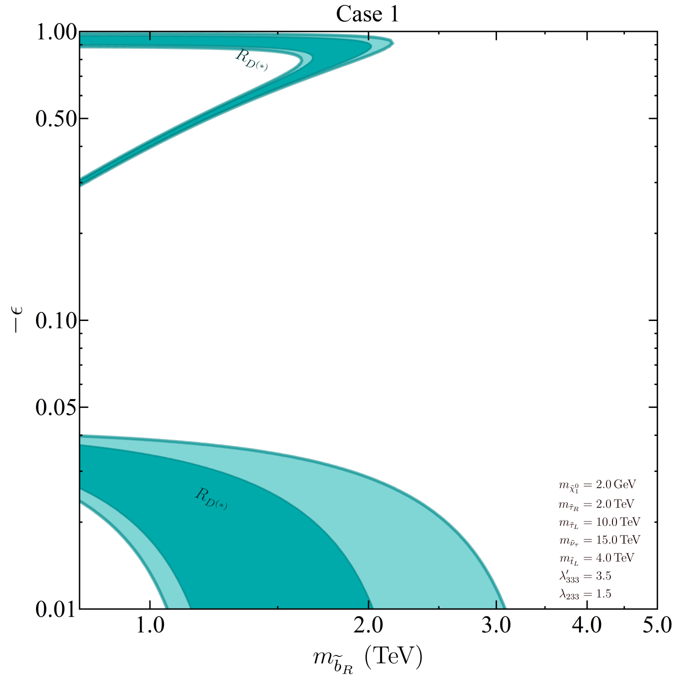

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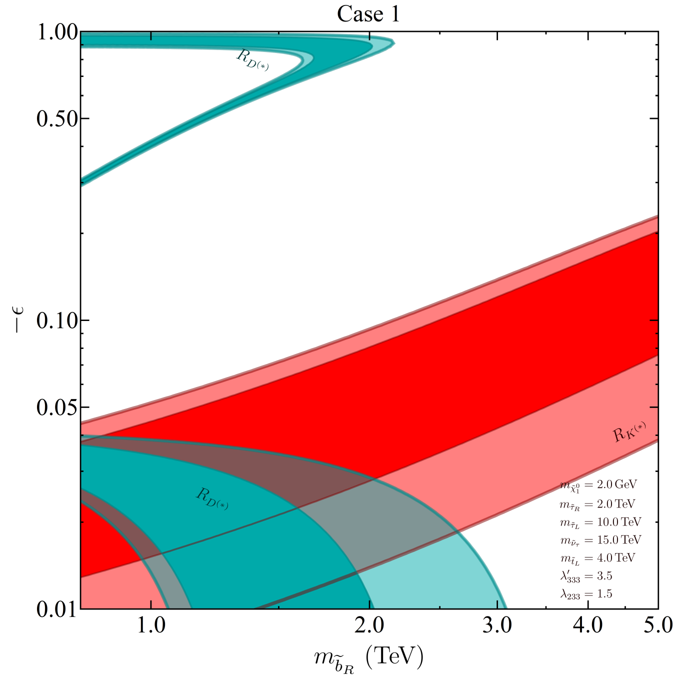

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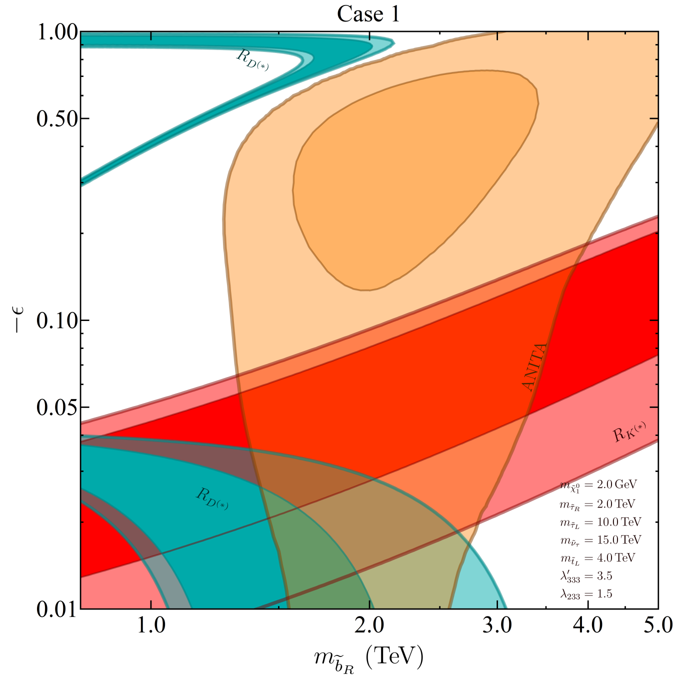

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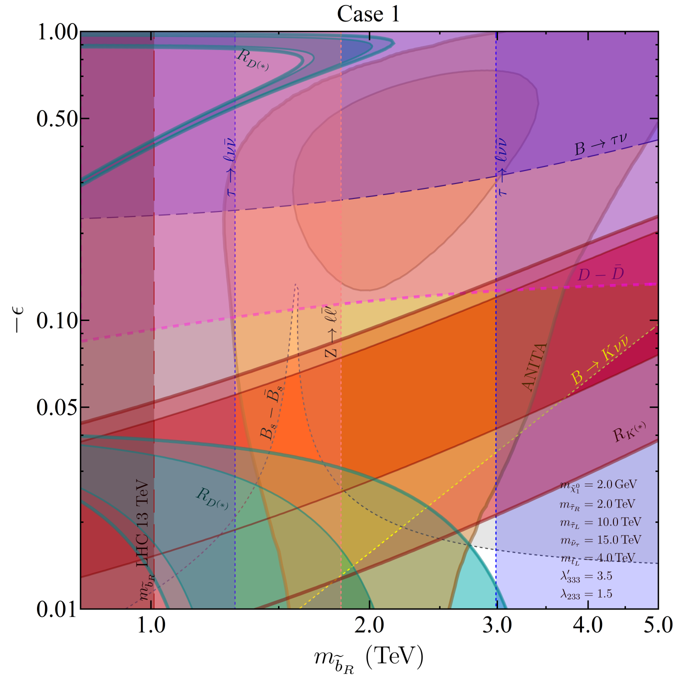

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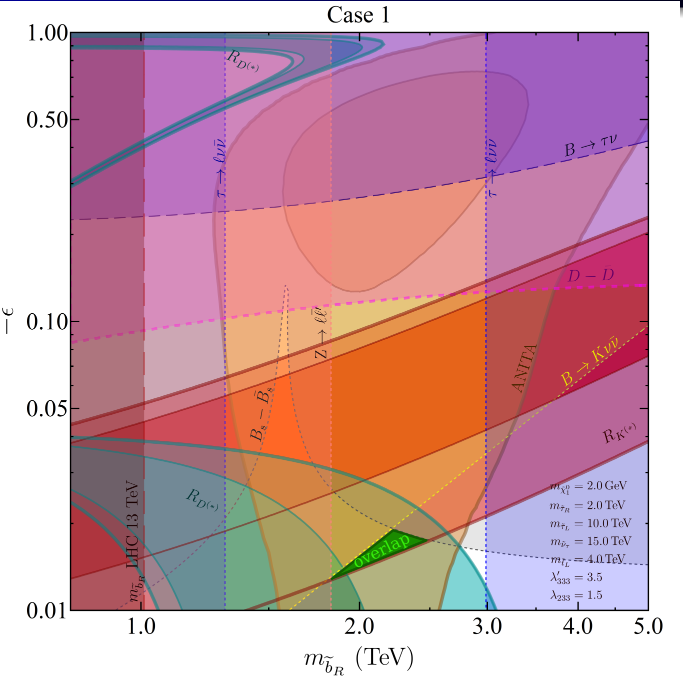
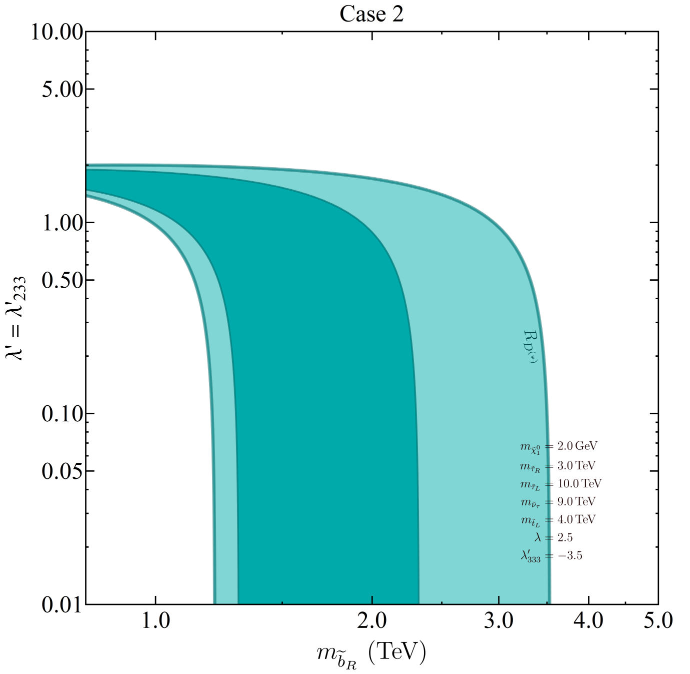


Case 2 (Flavor Symmetry)



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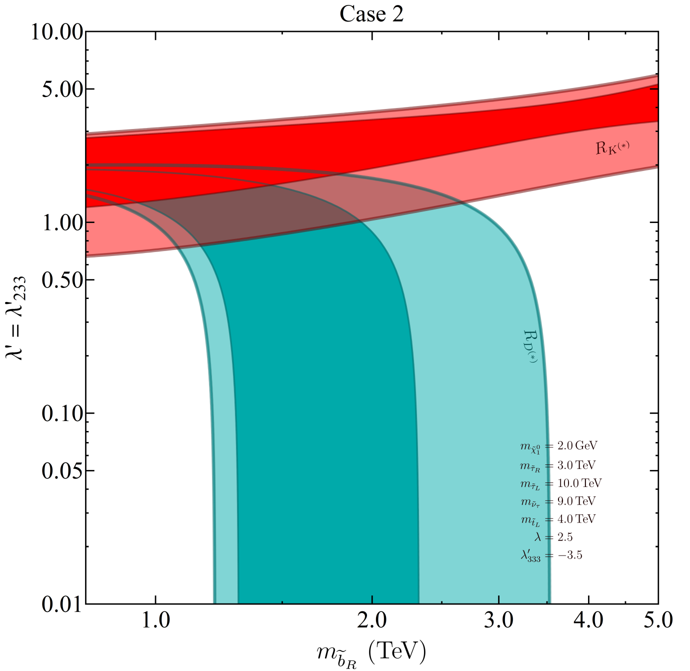

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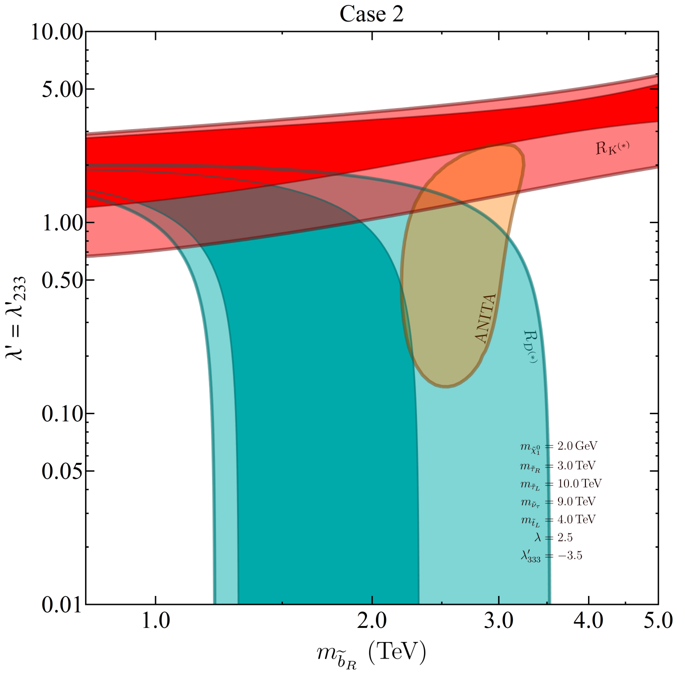

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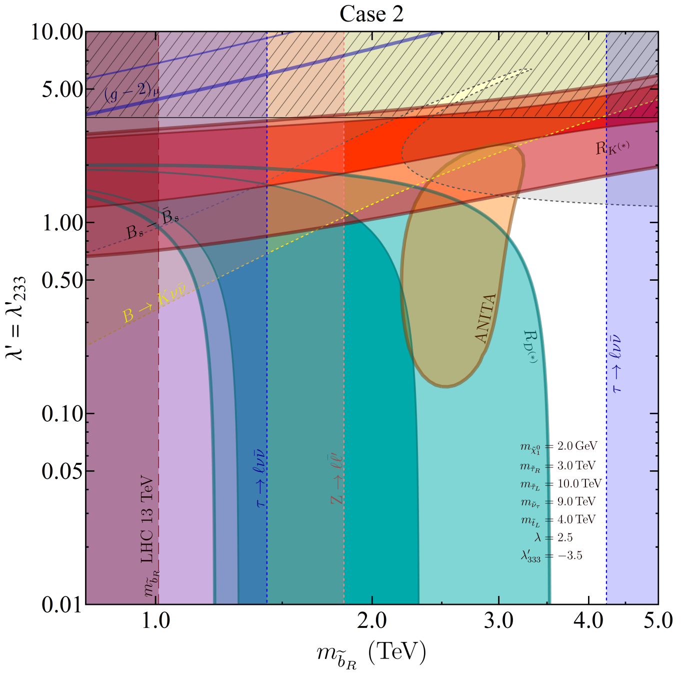

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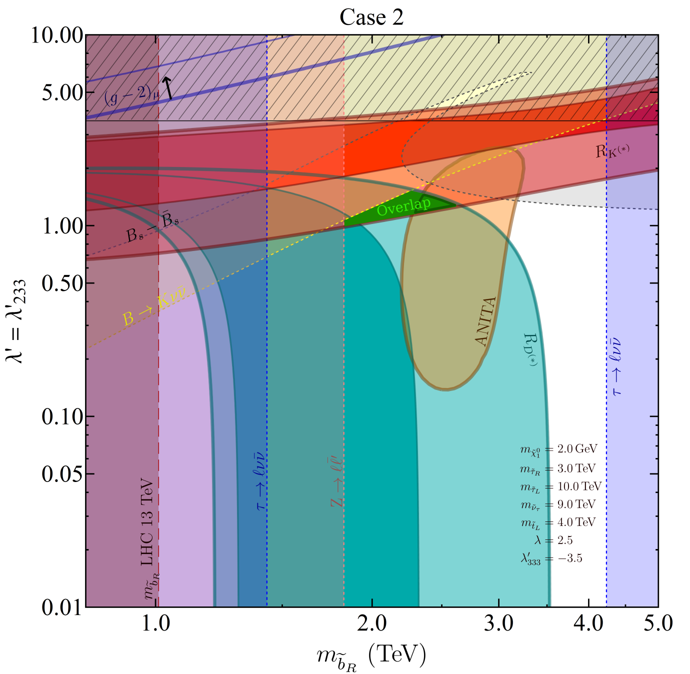
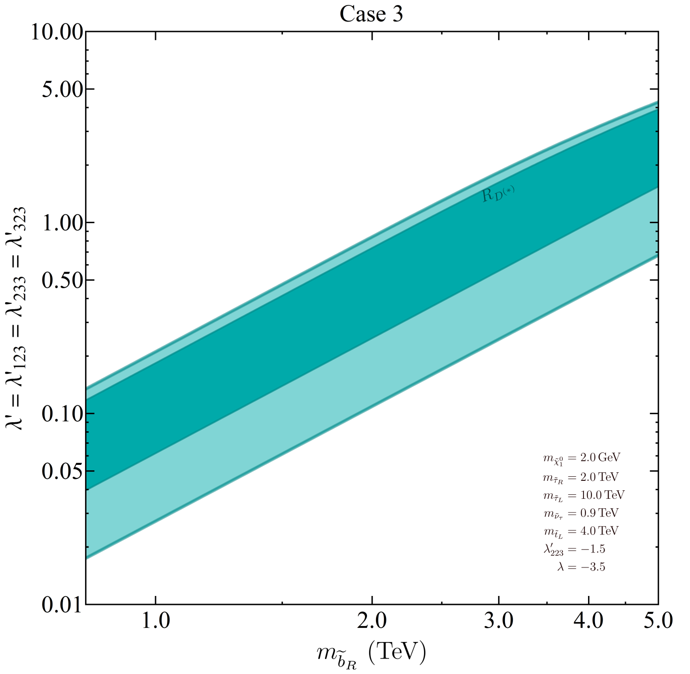


Case 3 (No Symmetry)



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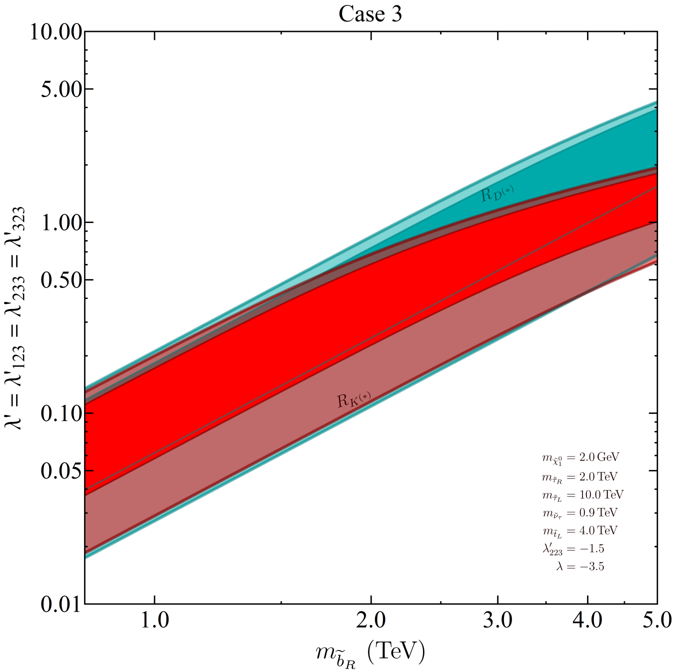

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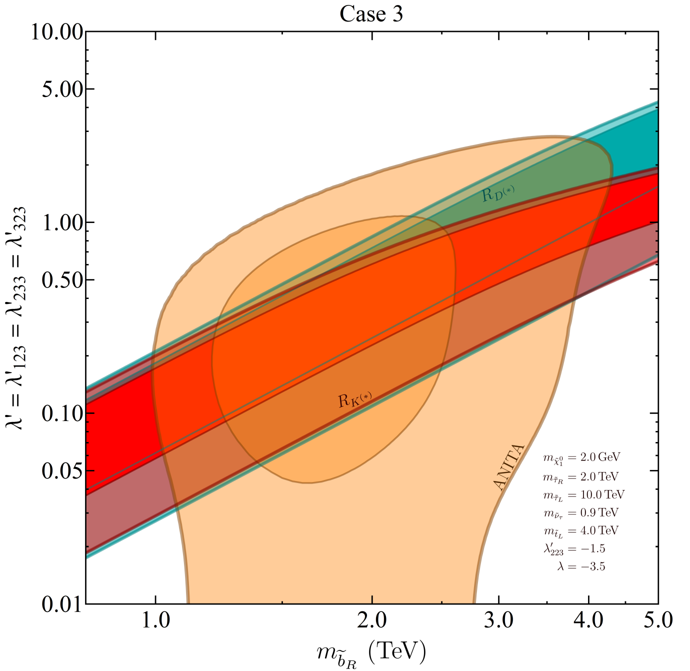

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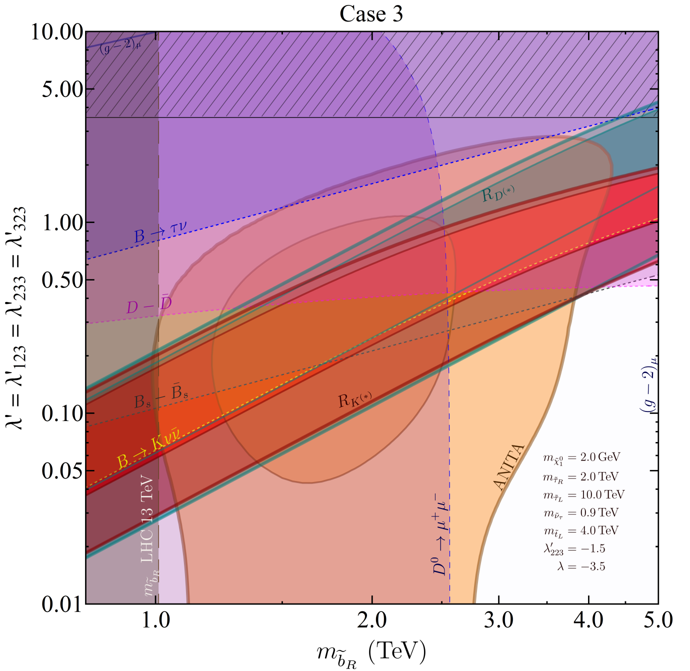

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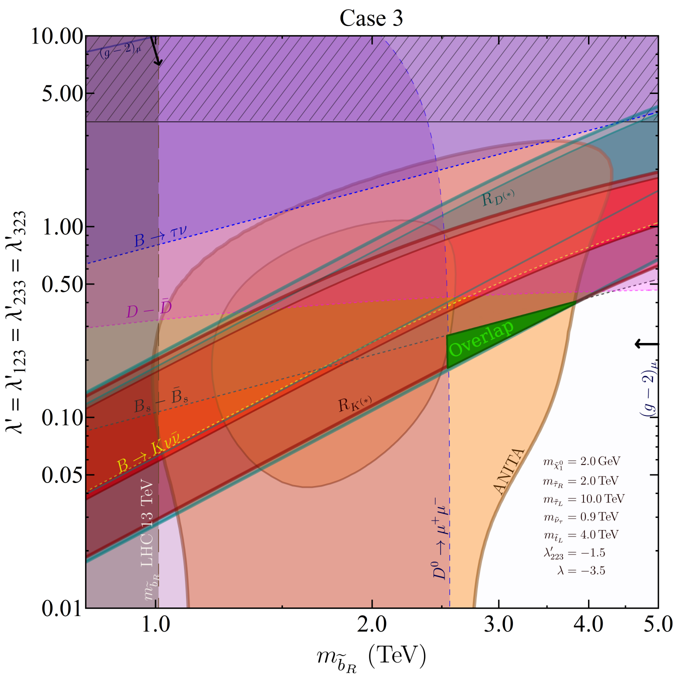
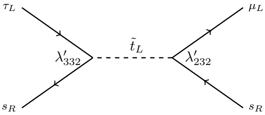
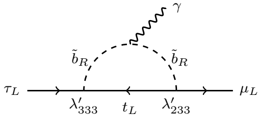
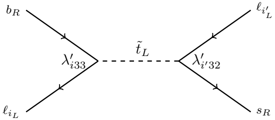


Flavor-violating decay mode	λ,λ' dependence	RPV3 Prediction Case 1	RPV3 Prediction Case 2	RPV3 Prediction Case 3	Current experimental bound/measurement
$\tau \to \mu\phi$	$\lambda'_{332}\lambda'_{232}$, $\lambda_{323}\lambda'_{322}$	1.9×10^{-15}	3.8×10^{-10}	2.6×10^{-12}	$< 8.4\times10^{-8}$
$\tau \to \mu KK$	$\lambda'_{332}\lambda'_{232}$, $\lambda_{323}\lambda'_{322}$	1.2×10^{-17}	2.4×10^{-12}	2.9×10^{-13}	$< 4.4\times10^{-8}$
$\tau \to \mu K^0_S$	$\lambda'_{332}\lambda'_{231}$, $\lambda'_{312}\lambda_{323}$	4.5×10^{-19}	8.7×10^{-12}	3.1×10^{-13}	$< 2.3\times10^{-8}$
$\tau \to \mu\gamma$	$\lambda'_{333}\lambda'_{233}$, $\lambda_{133}\lambda_{123}$	1.3×10^{-10}	1.3×10^{-8}	2.4×10^{-10}	$< 4.4\times10^{-8}$
$\tau \to \mu\mu\mu$	$\lambda_{323}\lambda_{322}$	1.7×10^{-11}	1.2×10^{-9}	1.2×10^{-11}	$< 2.1\times10^{-8}$
$B_{(s)} \to K^{(*)}(\phi)\mu\tau$	$\lambda'_{333}\lambda'_{232}$, $\lambda'_{233}\lambda'_{332}$, $\lambda'_{332}\lambda_{323}$	4.1×10^{-9}	1.2×10^{-7}	2.2×10^{-10}	$< 2.8\times10^{-5}$
$B_s \to \tau\mu$	$\lambda'_{333}\lambda'_{232}$, $\lambda'_{233}\lambda'_{332}$, $\lambda'_{332}\lambda_{323}$	4.4×10^{-10}	1.3×10^{-8}	2.3×10^{-11}	$< 3.4\times10^{-5}$
$b \to s\tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.4×10^{-7}	2.8×10^{-8}	1.3×10^{-13}	N/A
$B \to K^{(*)}\tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.7×10^{-6}	4.2×10^{-8}	9.6×10^{-12}	$< 2.2\times10^{-3}$
$B_s \to \tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.7×10^{-8}	3.0×10^{-9}	1.4×10^{-14}	$< 6.8\times10^{-3}$
$b \to s\mu\mu$	$\lambda'_{233}\lambda'_{232}$, $\lambda'_{332}\lambda_{232}$	5.9×10^{-9}	3.2×10^{-8}	8.8×10^{-9}	4.4×10^{-6}
$B_s \to \mu\mu$	$\lambda'_{233}\lambda'_{232}$, $\lambda'_{332}\lambda_{232}$	4.1×10^{-11}	6.5×10^{-11}	1.8×10^{-11}	3.0×10^{-9}







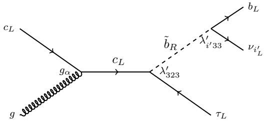
LHC Signals

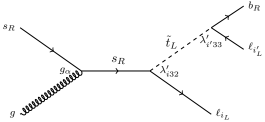
- Effective operators:

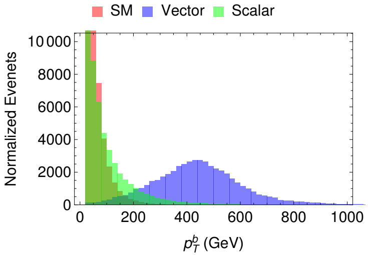
$$R_{D^{(*)}} \;:\; \mathcal{O}_{V_L} = (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu)$$

$$R_{K^{(*)}} \;:\; Q^{\ell}_{9(10)} = (\bar{s}\gamma^{\mu} P_L b)(\bar{\ell}\gamma_{\mu}(\gamma_5)\ell)$$

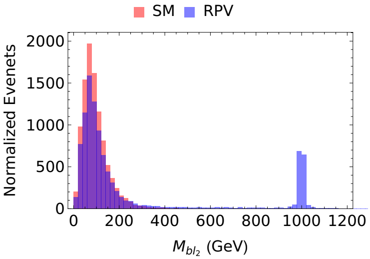
- Crossing symmetry: $b \to c\tau\nu$ leads to $gc \to b\tau\nu$, and $b \to s\ell\ell$ leads to $gs \to b\ell\ell$.







[Altmannshofer, BD, Soni (PRD '17)]



[Altmannshofer, BD, Soni, Sui (PRD '20)]

Conclusion

- A common origin of the B-anomalies, muon $g-2$, and ANITA anomaly in a single testable framework.
- Third-generation-centric RPV SUSY framework (RPV3), motivated by Higgs naturalness.
- Three benchmark cases, each with 9 parameters only.
- Remarkably, allowed overlap regions for all the anomalies still exist.
- Predictions for flavor-violating B-meson and tau decays could be tested at Belle II and LHCb.
- Complementary tests in the high-p_T LHC experiments.

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Thank You.