

Model
One Size Fits All:
A Minimal R-parity Violating Supersymmetric Model for the Flavor
Anomalies, Muon $g - 2$ and ANITA

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07/29/20

RPV3
+ flavor
Anomalies

Based primarily on 1) arXiv:2002.12910 [Altmannshofer, Dev,Sui+A.S]
2) arXiv:1704.06659 [Altmannshofer, Dev+A.S]=>PRD (2017)

Outline

- Recapitulate : The anomalies

- The RPV3 framework

→ 3rd gen superpartners are lightest.

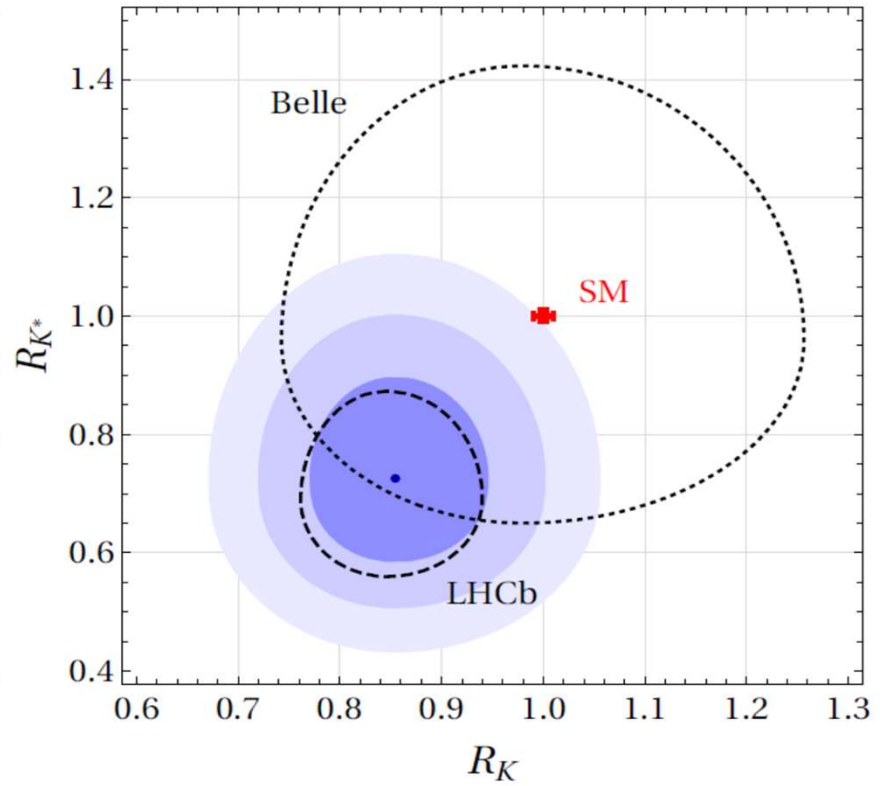
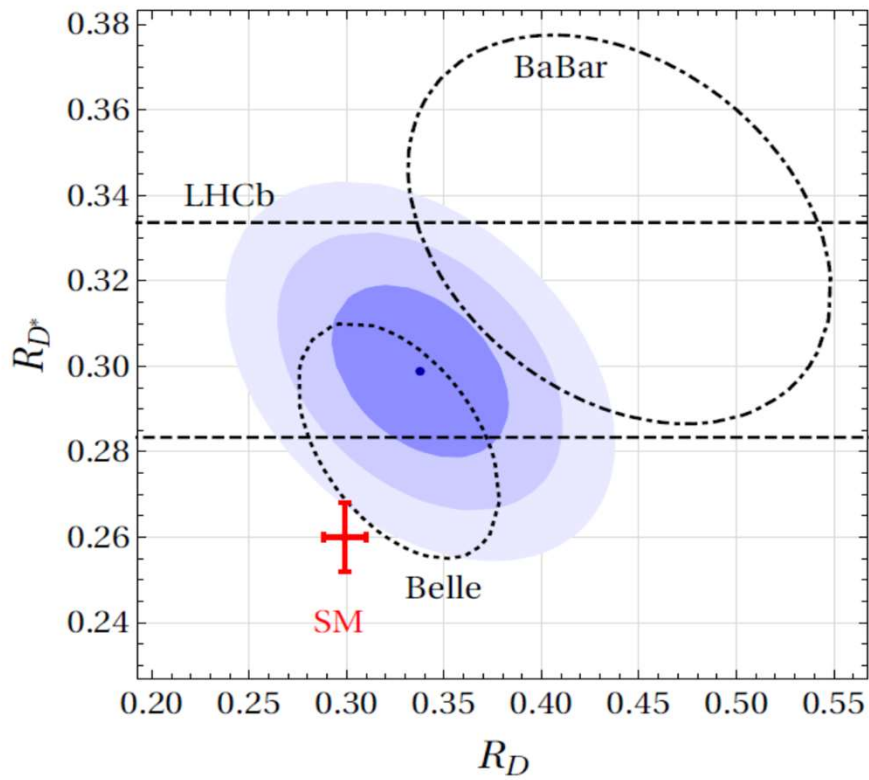
- The benchmark cases

For simplification three special cases

- Conclusion

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

$$R_{K^{(*)}} = \frac{\text{BR}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\text{BR}(B \rightarrow K^{(*)} e^+ e^-)}$$



FACT OR FARCE?

1) Exptal results (not all independent); AhL central values above Theory

4

experiment	tag method	τ decay mode	R_D	R_D^*	R_ψ
Babar (2012)[1]	hadronic	$1 \nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$	
Belle (2015)[2]	hadronic	$1 \nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015)[5]	hadronic	$1 \nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
Belle (2016)[2]	semileptonic	$1 \nu\nu$	-	$0.302 \pm 0.030 \pm 0.011$	
Belle (2017)[4]	hadronic	$\pi(\rho)\nu$	-	$0.270 \pm 0.035 \pm 0.027$	
LHCb (2017)[6]	hadronic	$3\pi\nu$	-	$0.291 \pm 0.019 \pm 0.029$	
Belle (2019)[7]	semileptonic	$1 \nu\nu$	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	
LHCb(2016) [9]	hadronic	$1 \nu\nu$	-	-	$0.71 \pm 0.17 \pm 0.18$
SM	-	-	0.299 ± 0.011	0.260 ± 0.008	0.26 ± 0.02

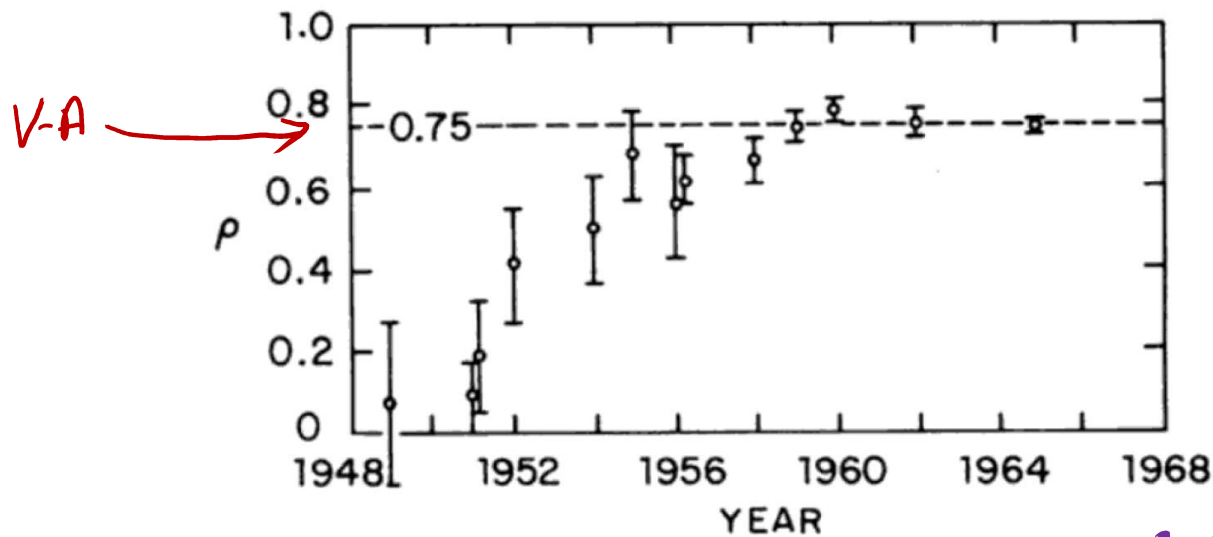
TABLE I: All experimental results announced to date on R_D , R_{D^*} and on R_ψ versus the predictions of those for the SM

ALTMANNSHOFER, DEUTSCH, YICONG SWITZERLAND, 2002.12.10

RECAP

- 3 different major B-experiments
 - 3 with $B \Rightarrow D$
 - 7 with $B \Rightarrow D^*$
 - 1 with $B_c \Rightarrow \psi$
 - 9 with $\tau \Rightarrow l$ ($l = \mu$ or e) $\nu \nu'$
 - 2 with $\tau \Rightarrow \text{hadron} + \nu$
-
- **Each and everyone of the 11 experimental results seem to imply tau is NOT just a heavy muon(electron) as dictated by SM.**

Symp. Historical ~~Aside~~ CAUTION



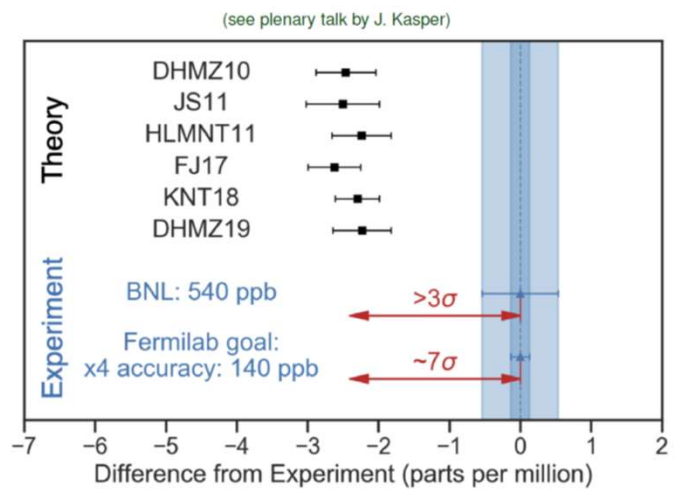
FROM M PUROHIT

Figure 16. The change of the Michel parameter ρ from year to year.

From T. D. Lee's text

Muon $g - 2$

$(g-2)$ from LQCD
 \sim NOT SHOWN



NO ANITA
 [CAUSE Systematics
 NOT Reliable]



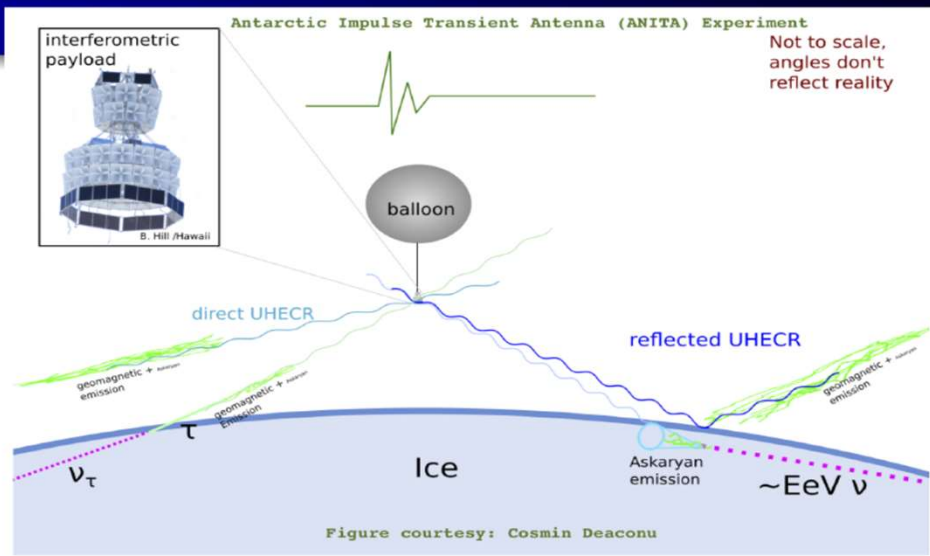
PULLS

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)

$\leftarrow B \rightarrow (g-2)_\mu$

ANITA

PW Gorham et al
arXiv 1603.05218;
1803.05088



See Coll in Dev, Sui
1810.08479
Alanemshifter, Dev,
Sui + AS
2002.12910

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.	$-27.4 \pm 0.3^\circ$, $59.62 \pm 0.7^\circ$	$-35.0 \pm 0.3^\circ$, $1.41 \pm 0.7^\circ$
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.

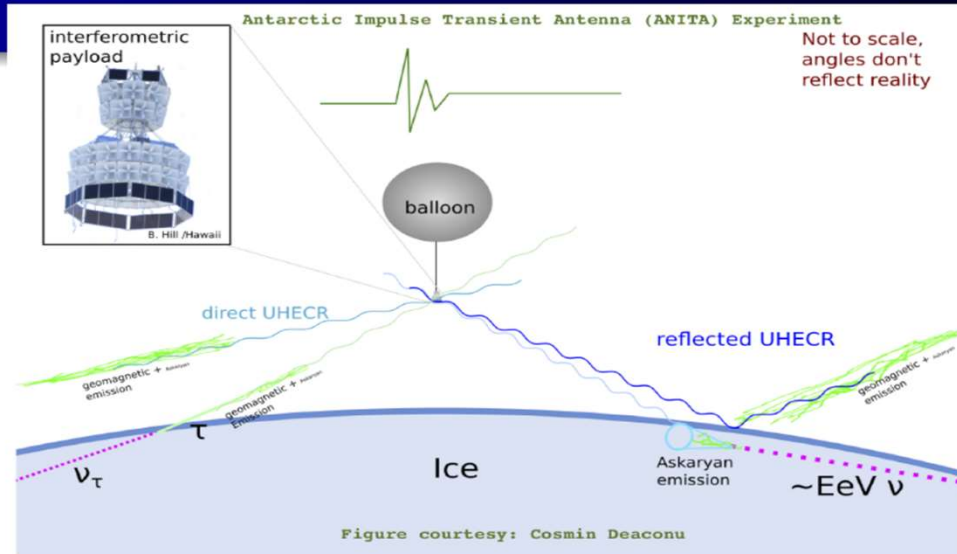


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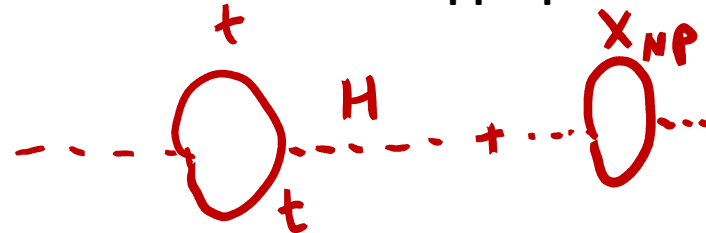
This talk: A SUSY solution to ANITA, muon $g - 2$ and the B -anomalies!



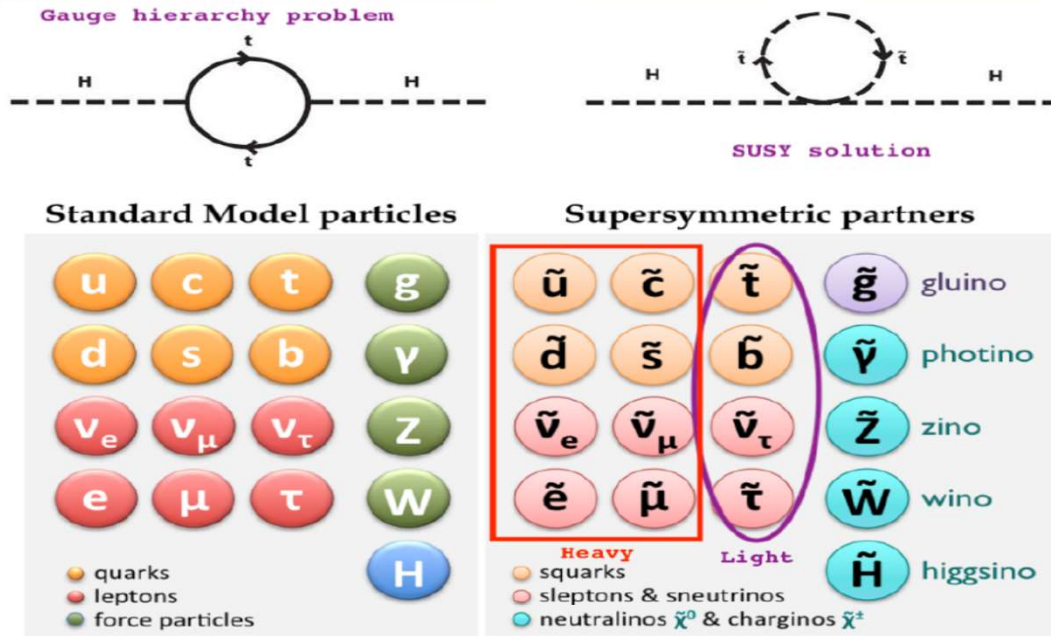
Motivation for RPV3; see ADS' 1704.06659

- ASSUMING the anomaly is REAL & HERE TO STAY [BIG ASSUMPTION due to caveats mentioned]
- Anomaly involves simple tree-level semi-leptonic decays
- Also $b \Rightarrow \tau$ (3rd family)
- **Speculate: May be related to Higgs naturalness**
- Seek minimal solution: perhaps 3rd family super-partners (a lot) lighter than other 2 gens > proton decay concerns may not be relevant \Rightarrow RPV ["natural" SUSY]
- **RPV natural setting for LUV ...can accommodate g-2 and eps' if needs be**
- Collider signals tend to get a lot harder than (usual-RPC) SUSY
- RPV makes leptoquarks natural [and respectable]
- Moreover, RPV should be viewed as an umbrella i.e. under appropriate limits other models are incorporated

$$m_H \approx 126 \text{ GeV}$$



Natural SUSY



RPV₃

3rd gen
 sp are
 taken to be
 lightest

Natural SUSY

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

RPV₃ preserves gauge coupling unification irrespective of # of effective gens. 1, 2 or 3.

See ADS'
1704.06659

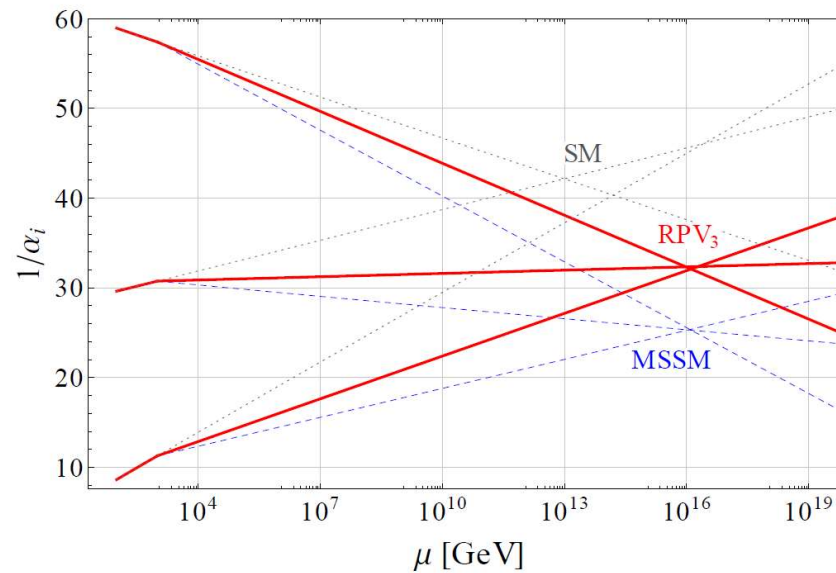


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale stays same.; only value of couplings shifts

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 $R_{D^{(*)}}$ ($b \rightarrow c\tau\nu$) via LQD interactions. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); Trifinopoulos (EPJC '18); Hu, Li, Muramatsu, Yang (PRD '19)]

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

- Can *simultaneously* explain $R_{K^{(*)}}$ ($b \rightarrow s\ell\ell$) 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]

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

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

B-anomalies in RPV3

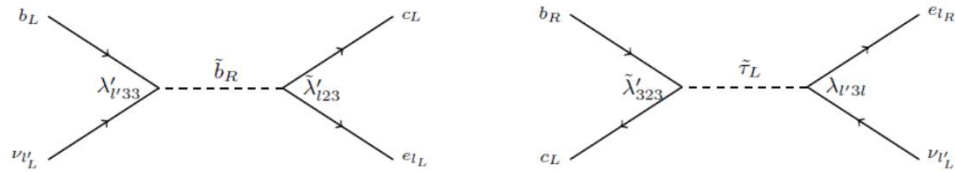


Figure: RPV3 contributions to $R_{D^{(*)}}$. [Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); . . .]

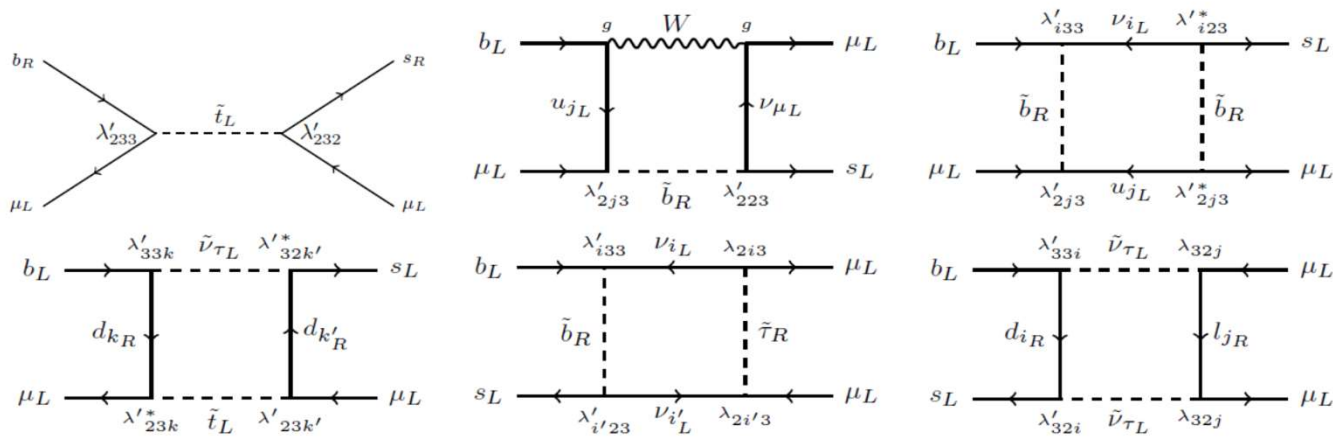


Figure: RPV3 contributions to $R_{K^{(*)}}$. [Das, Hati, Kumar, Mahajan (PRD '17); Trifinopoulos (EPJC '18)]

Muon $g - 2$ and ANITA

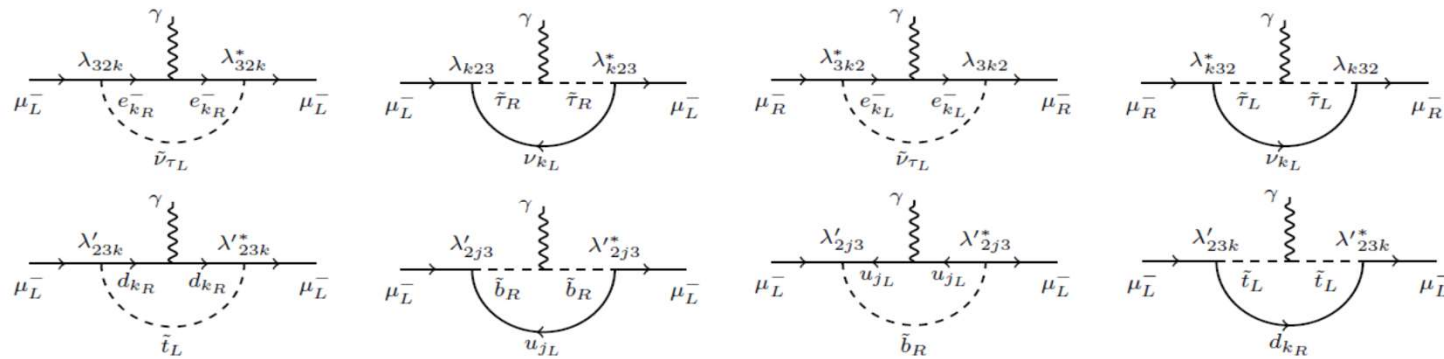


Figure: RPV3 contributions to $(g - 2)_\mu$. [Kim, Kyaee, Lee (PLB '01)]

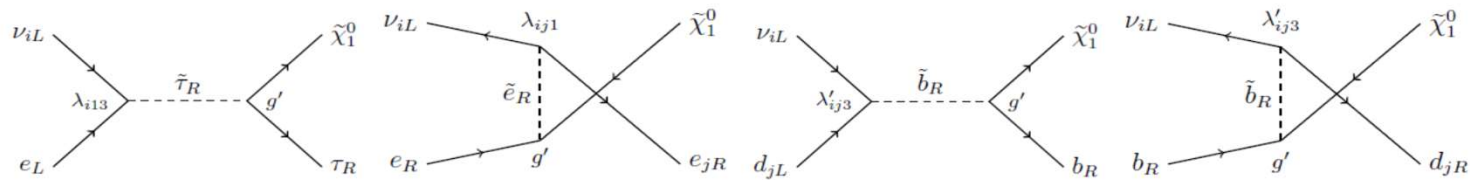


Figure: RPV3 contributions to ANITA anomalous events. [Collins, BD, Sui (PRD '19)]

Three Benchmark Cases

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

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

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

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

$$\begin{aligned} \lambda'_{1jk} &= \lambda'_{211} = \lambda'_{231} = \lambda'_{213} = \lambda'_{311} = \lambda'_{331} = \lambda'_{313} \simeq 0, & \lambda'_{233} &\simeq \lambda' \epsilon_\ell, \\ \lambda'_{221} &= \lambda'_{212} \simeq \lambda' \epsilon_\ell \epsilon'_q, & \lambda'_{321} &= \lambda'_{312} \simeq \lambda' \epsilon'_q, \\ \lambda'_{222} &= \lambda'_{223} = \lambda'_{232} \simeq \lambda' \epsilon_\ell \epsilon_q, & \lambda'_{322} &= \lambda'_{323} = \lambda'_{332} \simeq \lambda' \epsilon_q, \\ \lambda_{121} &= \lambda_{131} = \lambda_{133} \simeq 0, & \lambda_{123} &= \lambda_{132} = \lambda_{231} \simeq \lambda \epsilon'_\ell, \\ \lambda_{232} &\simeq \lambda \epsilon_{\ell S}, & \lambda_{122} &\simeq \lambda \epsilon_\ell \epsilon'_\ell, & \lambda_{233} &\simeq \lambda \epsilon_\ell, \end{aligned}$$

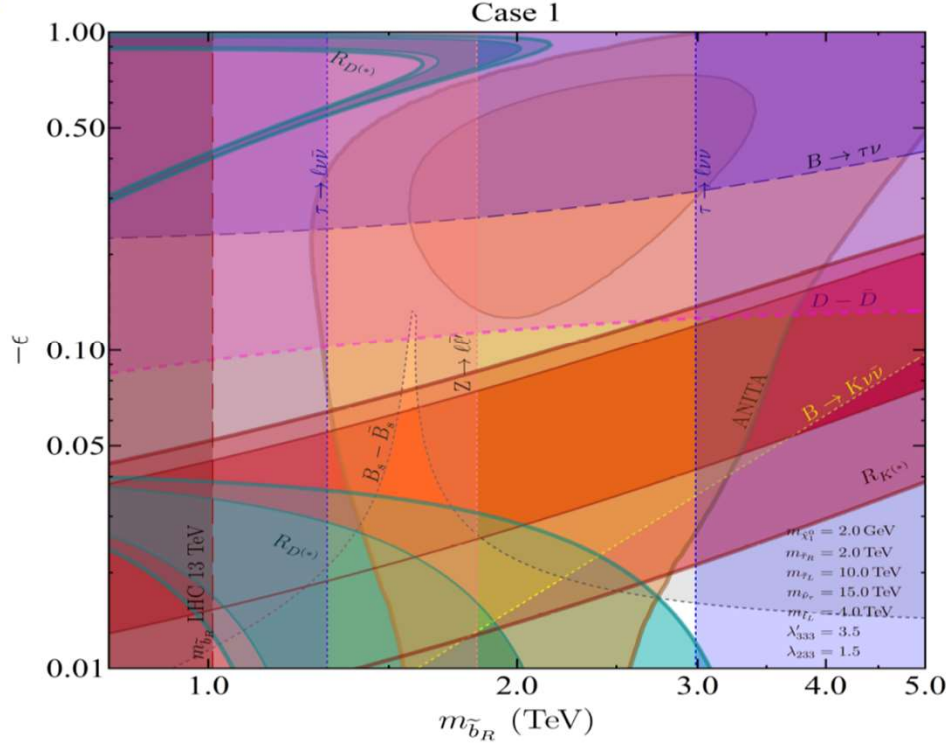
where $\epsilon_q \approx m_s/m_b \simeq 0.025$, $\epsilon'_q \approx \epsilon_q \sqrt{m_d/m_s} \simeq 0.005$, $\epsilon_\ell \simeq 1$, $\epsilon'_\ell \simeq 0.004$ and $\epsilon_{\ell S} \simeq 0.06$ [Trifinopoulos (EPJC '18)]. Again, 3 independent couplings: $\{\lambda'_{333}, \lambda', \lambda\}$.

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

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

- In each case, six free mass parameters: $\{m_{bR}^{\sim}, m_{tL}^{\sim}, m_{\tau L}^{\sim}, m_{\tau R}^{\sim}, m_{\nu\tau}^{\sim}, m_{\chi_1^0}^{\sim}\}$.

Case 1 (CKM-Like)

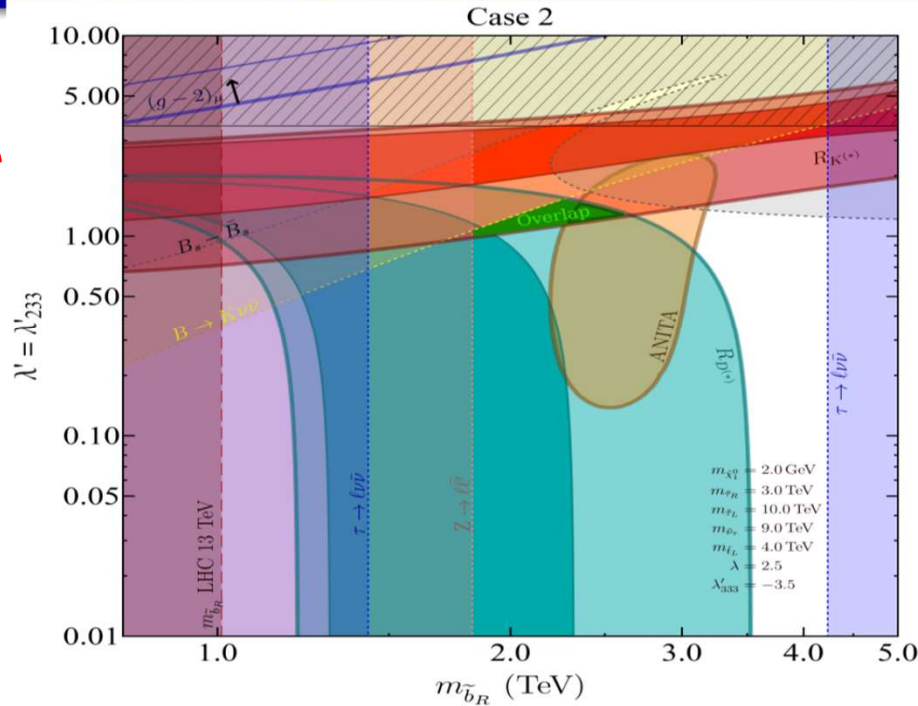


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FIG. 6. Benchmark scenario for Case 1 (with CKM-like symmetry) in the two-dimensional parameter plane $(m_{\tilde{b}_R}, -\epsilon)$, while keeping other free parameters fixed as shown in the figure. The shaded regions with solid boundaries are the 2σ (thin) and 3σ (thick) favored regions to explain the $R_{D^{(*)}}$ (cyan), $R_{K^{(*)}}$ (red) and ANITA (orange) anomalies. The $(g-2)_\mu$ anomaly requires $-\epsilon \sim \mathcal{O}(10)$, and therefore, not shown here. The shaded regions with dashed/dotted boundaries are the current experimental bounds on the parameter space from $B \rightarrow K\nu\bar{\nu}$ (yellow), $B_s - \bar{B}_s$ mixing (grey), $D - \bar{D}$ mixing (magenta), $B \rightarrow \tau\nu$ (dark blue), $Z \rightarrow \ell\ell'$ (pink), and $\tau \rightarrow \ell\nu\bar{\nu}$ (blue). The overlap region simultaneously explaining the $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomaly is shown by the green shaded region, and the region also explaining the ANITA anomaly along with $R_{D^{(*)}}$ and $R_{K^{(*)}}$ is shown by the green shaded region with thick boundaries.

Case 2 (Flavor Symmetry)

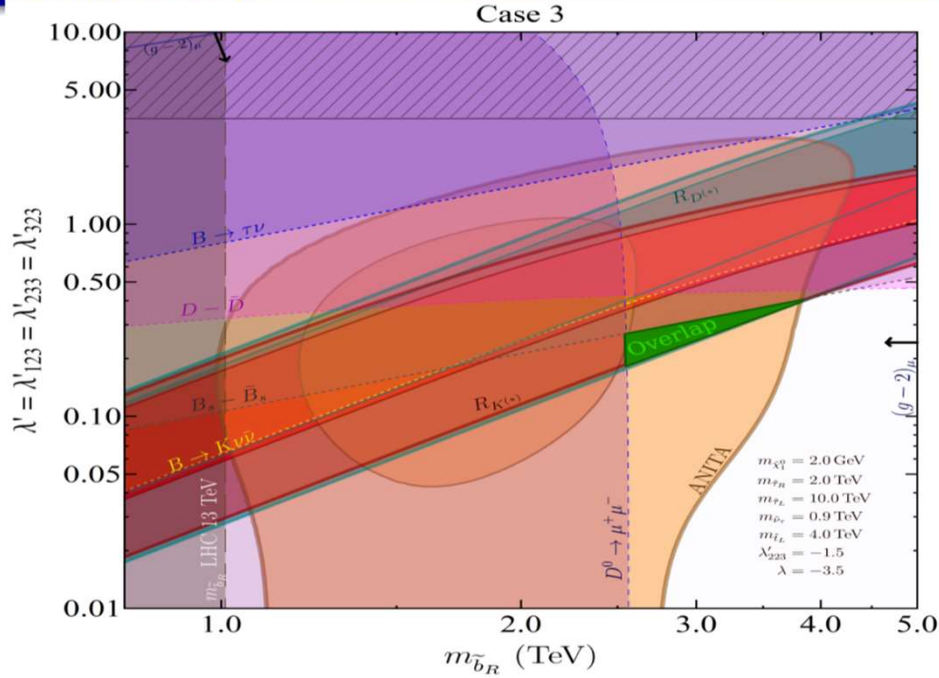
3rd right
 U2xU2 Sym
 See 1807.01638



201

FIG. 7. Benchmark scenario for Case 2 (with flavor symmetry) in the two-dimensional parameter plane $(m_{\tilde{b}}, \lambda')$, while keeping other free parameters fixed as shown in the figure. The labels for the shaded regions are the same as in Fig. 6. The horizontal hatched region is theoretically disfavored from perturbativity constraint on $\lambda' \leq \sqrt{4\pi}$. The thin (thick) blue line at the upper left corner shows the 2σ (3σ) region favored by the $(g-2)_\mu$ anomaly.

Case 3 (No Symmetry)

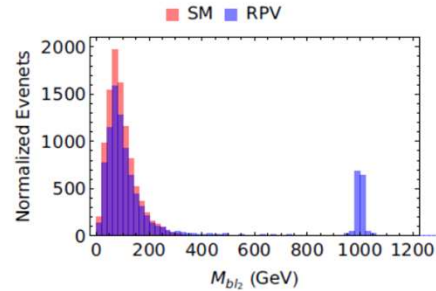
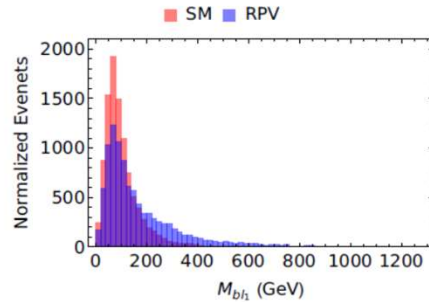
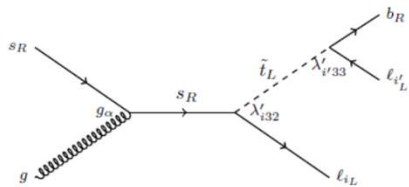


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FIG. 8. Benchmark scenario for Case 3 (with no symmetry) in the two-dimensional parameter plane $(m_{\tilde{b}}, \lambda')$, while keeping other free parameters fixed as shown in the figure. The labels for the shaded regions are the same as in Fig. 7. In addition, the $D^0 \rightarrow \mu^+ \mu^-$ constraint is shown by the blue shaded region (marked by the dashed blue boundary). The $2\sigma (g-2)_\mu$ region covers almost the entire shown parameter space, so the 3σ region is not shown. Also, as in Fig. 7, the horizontal hatched region is theoretically disfavored from perturbativity constraint on $\lambda' \leq \sqrt{4\pi}$.

Other Predictions

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



$R_K(x)$ via XS
 $\Rightarrow s + g \Rightarrow b \ell$
 anomalous

A more dedicated LHC analysis underway.

Summary /Outlook/Conclusion 1 of 2

- Hints of LUV are extremely interesting, intriguing and important. *There is nothing we know of that tells us that these hints cannot be true.*
- While these indications are rather serious, **they are not yet compelling. They ask for too radical a departure from conventional understanding so we must exercise extreme caution and care before accepting them. Moreover, in each of the 3 cases there are features that cause concern.**
- **Syst error in quad is NOT rigorous in $RD(*)$, $RK(*)$, $(g-2)\mu$**
- Fortunately significant experimental/theoretical progress should occur in $< \sim 2$ years and is eagerly awaited.
- Meantime, are there interesting theoretical frameworks that can accommodate such deviations from SM if they survive? =>>>>>

Conclusion

- Analyzed the possibility of 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. IS a very good candidate
- 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. → Intensity Frontier
- Complementary tests in the high- p_T LHC experiments. → Energy Frontier

RECAP

- 3 different major B-experiments
 - 3 with $B \Rightarrow D$
 - 7 with $B \Rightarrow D^*$
 - 1 with $B_c \Rightarrow \psi$
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- **Each and everyone of the 11 experimental results seem to imply tau is NOT just a heavy muon(electron) as dictated by SM.**

constraints

ADS'RPV19

- Direct searches via $pp \rightarrow \tilde{b}\tilde{b} \rightarrow \tau^+ \tau^- t\bar{t}$

Indirect constraints considered due $B \Rightarrow \tau \nu; \pi \tau \nu;$
 $\pi(K) \nu \nu \dots$
Also $B_c \Rightarrow \tau \nu \dots$

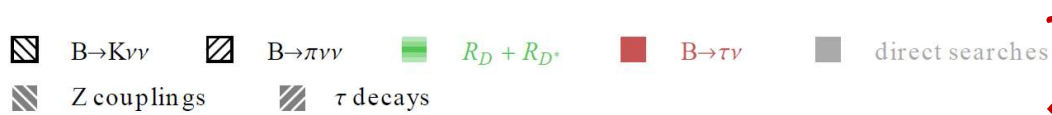
To a/c (within 1σ) of expt for $RD(*)$ needs largish $\lambda'_{333} \sim 1 - 2$ range with quite heavy sbottoms but such large couplings develop Landau pole below GUT scale. We require couplings stay perturbative below GUT so with $\lambda'_{333} < \sim 1$,

\Rightarrow TAKE HOME: This version of RPV is actually (surprisingly) well constrained

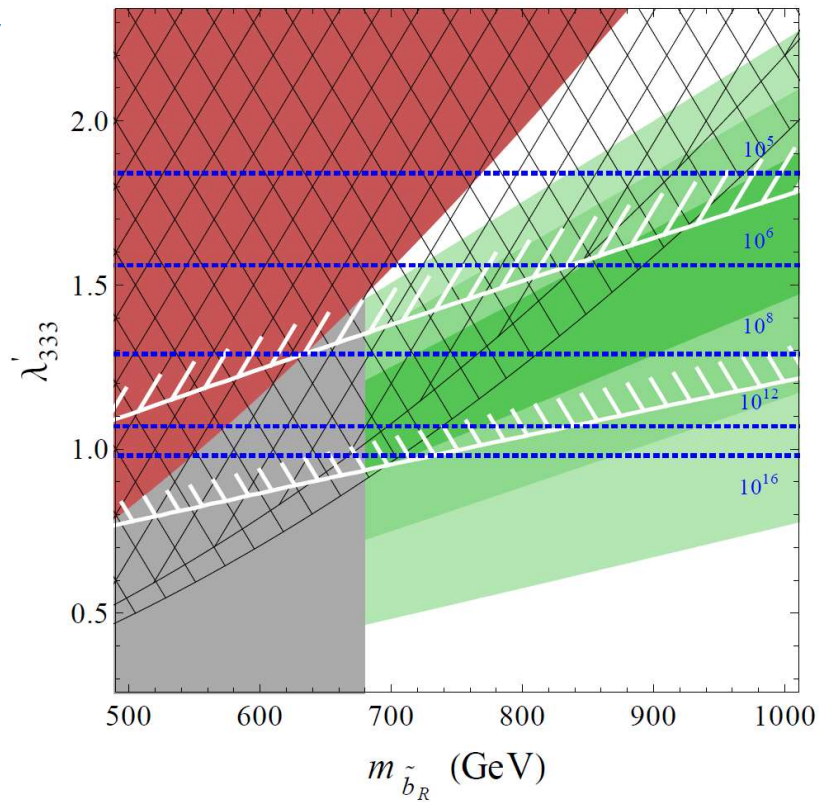
\Rightarrow With improved measurements $RD(*)$ in RPV3 may be difficult

As a specific illustration

ADS' PRD'17



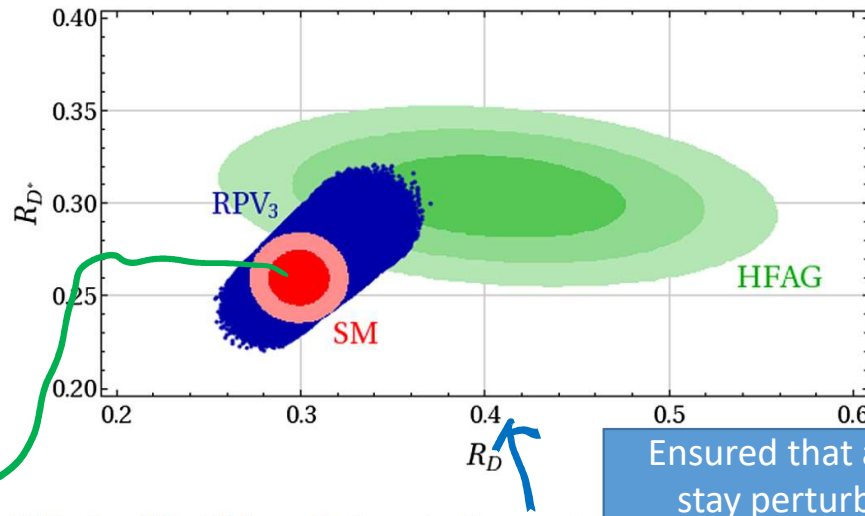
$$\lambda'_{313} = -0.05, \lambda'_{323} = 0.01$$



Constraints imposed

FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

RPV3 allows
 $R_D = (.254-.371)$
 $R_{D^*} = (.220-.320)$
 Contrast Fuentes-
 Martin:
 $\frac{\Delta R_{D^*}}{\Delta R_D} = 0.45$



HFAG dec2016
 $R_D = .403 \pm .040 \pm .024$
 $R_{D^*} = .310 \pm .015 \pm .008$
 LHCb 06/06/17
 $R_{D^*} = 0.305$

Ensured that all RPV3 couplings stay perturbative up to GUT

More Realistic SM Blob

FIG. 4. The SM predictions (red), experimental world average (green), and accessible values in our RPV-SUSY scenario (blue) in the R_D vs. R_{D^*} plane. For the SM, bearing in mind recent works [17,20,22] we are taking $(R_D^{SM}, R_{D^*}^{SM}) = (0.299 \pm 0.011, 0.260 \pm 0.010)$.

all constraints.....RPV(blue) region obtained by scanning with sbottom mass 680-1000Gev, $0 < \lambda_{333} < 2; |\lambda_{323}| < 0.1; |\lambda_{313}| < 0.3$

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

