BSM Interpretations of the Flavor Anomalies

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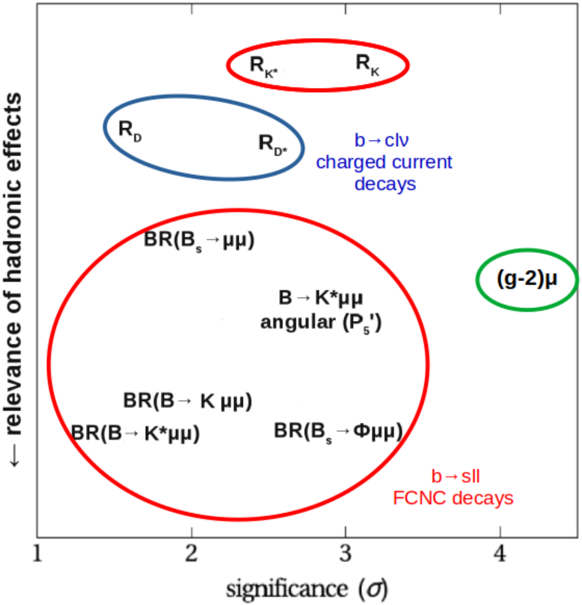
Washington University in St. Louis

SchwingerFest 2022: Muon $g - 2$

University of California, Los Angeles

June 16, 2022

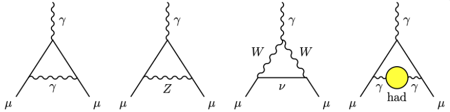
Flavor Anomalies

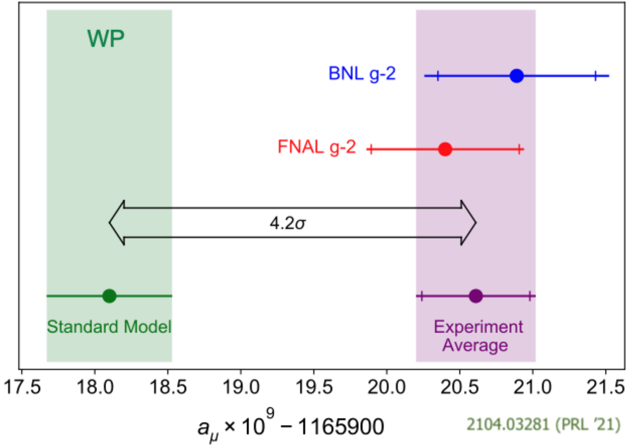


[from W. Altmannshofer's talk at *Anomalies 2021*]

Can a single BSM framework explain all the flavor anomalies?

Muon Anomalous Magnetic Moment





2104.03281 (PRL '21)

$$a_\mu^{(\mathrm{expt})} - a_\mu^{(\mathrm{SM})} = (251 \pm 59) \times 10^{-11}$$

[see talk from G. Venanzoni]

BSM Solutions to $(g-2)_\mu$ Anomaly

Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL #1

Muon g-2 Collaboration • G.W. Bennett (Brookhaven) et al. (Feb, 2006)

Published in: *Phys.Rev.D* 73 (2006) 072003 • e-Print: hep-ex/0602035 [hep-ex]

pdf DOI cite 2,882 citations

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm #1

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[see talks from S. Heinemeyer, P. Paradisi, E. Sessolo, P. Athron]

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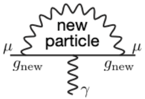
[see talks from S. Heinemeyer, P. Paradisi, E. Sessolo, P. Athron]

- Need $\Delta a_\mu = 251(59) \times 10^{-11}$ which is coincidentally at the same level as $a_\mu^{\rm EW} = 153.6(1.0) \times 10^{-11}$.

$$\Delta a_\mu \sim \frac{g_{\rm new}^2}{16\pi^2} \frac{(\text{muon mass} \sim 0.1\ \text{GeV})^2}{(\text{new particle mass})^2}$$

$$\sim a_\mu^{\rm EW} \quad \text{when} \quad \begin{cases} g_{\rm new} \sim W \text{ boson coupling} \\ m_{\rm new} \sim W \text{ boson mass} \end{cases}$$



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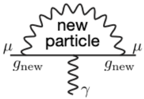
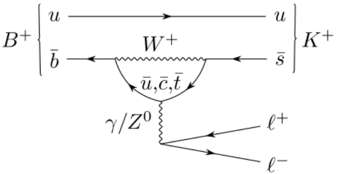


- Essentially two types of solutions:
  - Small interaction, small mass (e.g., ALP, dark photon, light Z') [see talks from J. Heeck, J. Fan]
  - $\mathcal{O}(1)$ interaction, $\mathcal{O}(\text{EW})$ mass (e.g. 2HDM, SUSY, leptoquark) [see talk from S. Heinemeyer]
- New particle(s) in the loop can be anything: neutral/charged spin 0, 1/2, 1.

  [Lindner, Platscher, Queiroz, 1610.06587 (Phys. Rep. '18)]
- Need to be careful about the sign of the BSM contribution.
- Also need flavor non-universal couplings to avoid other experimental constraints (mostly involving electron/quark sector).

$R_{K^{(*)}}$ Anomaly ($b \to s\ell^+\ell^-$)

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



- Flavor Changing Neutral Current $\longrightarrow$ loop-suppressed in the SM.
- New physics can be heavy (multi-TeV).

$$R_{K^+}^{[1,6]} = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$$

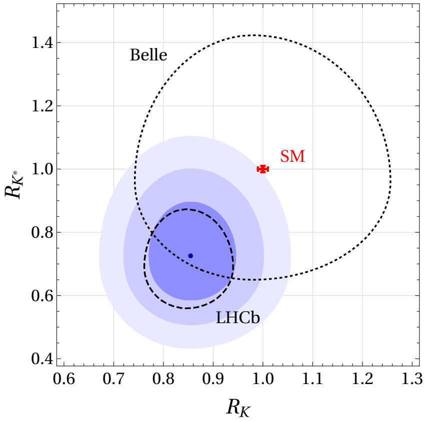
$$R_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

$$R_{K_S}^{[1.1,6]} = 0.66^{+0.20\,+0.02}_{-0.14\,-0.04}$$

$$R_{K^{*+}}^{[0.045,6]} = 0.70^{+0.18\,+0.03}_{-0.13\,-0.04}$$

$$R_{pK}^{[0.1,6]} = 0.86^{+0.14}_{-0.11} \pm 0.05$$



[Altmannshofer, BD, Soni, Sui, 2002.12910 (PRD '20)]

- 3.4σ net discrepancy.
- All measurements are consistently below the SM.
- LHCb update [2103.11769 (Nature Phy. '22)] didn't change the central value.

BSM Solutions to $R_{K^{(*)}}$ Anomaly

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i$$

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

Altmannshofer, Stangl, 2103.13370 (EPJC '21)

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
$C_9^{bs\mu\mu}$	$-0.75^{+0.22}_{-0.23}$	3.4σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.73^{+0.15}_{-0.15}$	5.2σ
$C_{10}^{bs\mu\mu}$	$+0.42^{+0.23}_{-0.24}$	1.7σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.54^{+0.12}_{-0.12}$	4.7σ
$C_9'^{bs\mu\mu}$	$+0.24^{+0.27}_{-0.26}$	0.9σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.18^{+0.13}_{-0.14}$	1.4σ
$C_{10}'^{bs\mu\mu}$	$-0.16^{+0.16}_{-0.16}$	1.0σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.02^{+0.10}_{-0.10}$	0.2σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.20^{+0.15}_{-0.15}$	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

BSM Solutions to $R_{K^{(*)}}$ Anomaly

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^\star \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i$$

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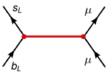
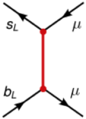
- **Possible BSM models**

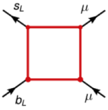


- Heavy Z′ model
- $SU(2)_L$ singlet or triplet
- arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...



- Leptoquark model
- Spin 0 or 1
- arXiv:01511.01900, 1503.01084, 1704.05835, 1512.01560, 1511.06024, 1408.1627, ...

arXiv:1706.07808



- Other new heavy scalars/vectors also leptoquark possible
- arXiv:01509.05020, 1608.07832, 1704.05438, 1607.01659, 1704.07845, hep-ph/0610037, ...

$R_{D^{(*)}}$ Anomaly ($b \to c\tau\nu$)

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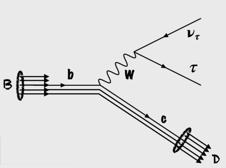
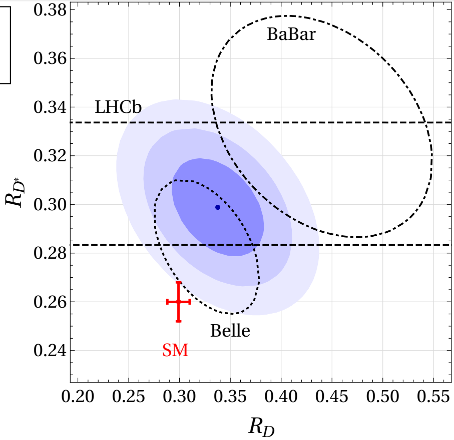


Experiment	Tag method	τ decay mode	R_D	R_{D^*}	$R_{J/\psi}$
Babar (2012) [1]	hadronic	$\ell\nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.0.018$	
Belle (2015) [2]	hadronic	$\ell\nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015) [5]	hadronic	$\ell\nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
Belle (2016) [2]	semileptonic	$\ell\nu\nu$	-	$0.302 \pm 0.030 \pm 0.011$	
Belle (2017) [3]	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) [4]	semileptonic	$\ell\nu\nu$	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	
LHCb (2016) [67]	hadronic	$\ell\nu\nu$	-	-	$0.71 \pm 0.17 \pm 0.18$
SM	-	-	0.299 ± 0.011 [63]	0.260 ± 0.008 [64]	0.26 ± 0.02 [68]



[Altmannshofer, BD, Soni, Sui, 2002.12910 (PRD '20)]

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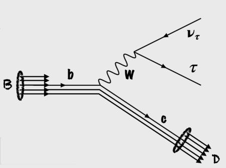

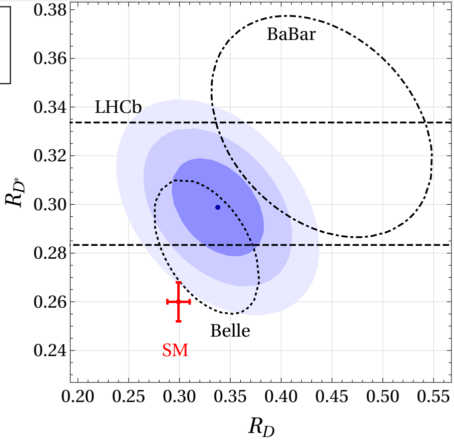

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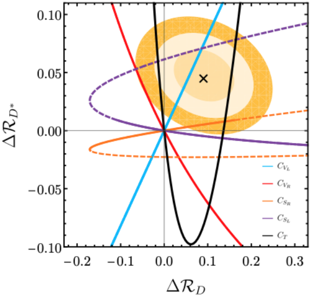
[Altmannshofer, BD, Soni, Sui, 2002.12910 (PRD '20)]

- Flavor Changing Charged Current – tree-level in the SM (only CKM-suppressed).
- BSM effect has to be large $\Longrightarrow \lesssim \mathcal{O}$(TeV)-scale new particle.
- *All* experimental measurements to date are consistently *above* the SM prediction.
- 3.3σ discrepancy (HFLAV gives 3.1σ) $\longrightarrow$ **Lattice can improve SM prediction.**

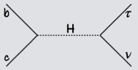
BSM Solutions to $R_{D^{(*)}}$ Anomaly

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\mathcal{O}_{V_L} + \frac{1}{\Lambda^2}\sum_i C_i^{(\prime,\prime\prime)}\mathcal{O}_i^{(\prime,\prime\prime)}$$



[Murgui, Peñuelas, Jung, Pich, 1904.09311 (JHEP '19)]

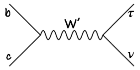
2HDM



$\mathcal{O}_{S_L} : (\bar{c}\, P_L b)(\bar{\tau} P_L \nu)$

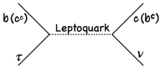
$\mathcal{O}_{S_R} : (\bar{c}\, P_R b)(\bar{\tau} P_L \nu)$

W'



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

Scalar Leptoquark

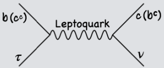


$\mathcal{O}'_{S_L} : (\bar{\tau} P_L b)(\bar{c} P_L \nu)$

$\mathcal{O}''_{S_L} : (\bar{\tau} P_L c^c)(\bar{b}^c P_L \nu)$

$\mathcal{O}''_{S_R} : (\bar{\tau} P_R c^c)(\bar{b}^c P_L \nu)$

Vector Leptoquark



$\mathcal{O}'_{V_L} : (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu)$

$\mathcal{O}'_{V_R} : (\bar{\tau}\gamma_\mu P_R b)(\bar{c}\gamma^\mu P_L \nu)$

$\mathcal{O}''_{V_R} : (\bar{\tau}\gamma_\mu P_R c^c)(\bar{b}^c\gamma^\mu P_L \nu)$

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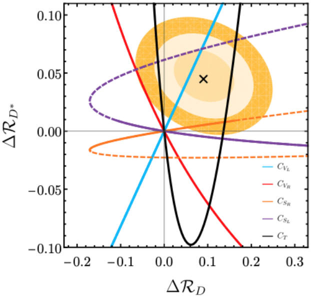
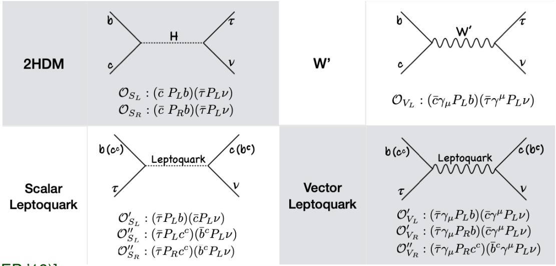


[Murgui, Peñuelas, Jung, Pich, 1904.09311 (JHEP ’19)]



- Charged Higgs solution in type-II 2HDM (MSSM-type) goes in the wrong direction [BaBar, 1303.0571 (PRD ’13); Belle, 1906.06871].
- In general, tension with LHC mono-τ data [Greljo, Camalich, Ruiz-Alvarez, 1811.07920 (PRL ’19)] and induces a large $\mathrm{BR}(B_c \to \tau\nu) > 50\%$ which is problematic [Alonso, Grinstein, Camalich, 1611.06676 (PRL ’17); Akeroyd, Chen, 1708.04072 (PRD ’17); Aebischer, Grinstein, 2105.02988]
- W' solution is challenged by LHC di-tau data [Faroughy, Greljo, Kamenik, 1609.07138 (PLB ’17)] and by precision Z-pole observables [Feruglio, Paradisi, Pattori, 1606.00524 (PRL ’17)].

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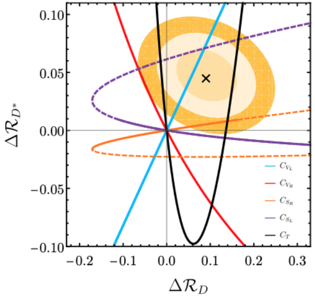
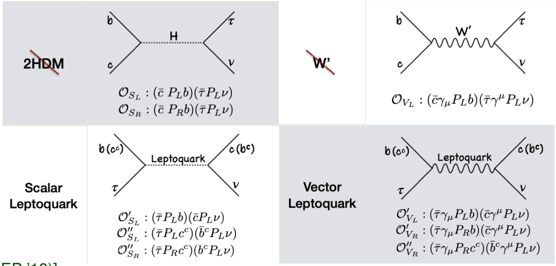
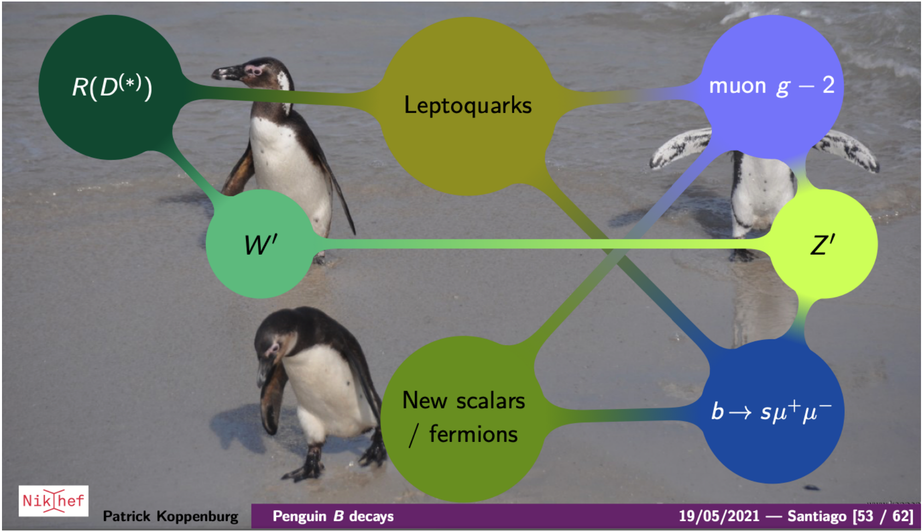




[Murgui, Peñuelas, Jung, Pich, 1904.09311 (JHEP '19)]

- Charged Higgs solution in type-II 2HDM (MSSM-type) goes in the wrong direction [BaBar, 1303.0571 (PRD '13); Belle, 1906.06871].
- In general, tension with LHC mono-τ data [Greljo, Camalich, Ruiz-Alvarez, 1811.07920 (PRL '19)] and induces a large $\mathrm{BR}(B_c \to \tau\nu) > 50\%$ which is problematic [Alonso, Grinstein, Camalich, 1611.06676 (PRL '17); Akeroyd, Chen, 1708.04072 (PRD '17); Aebischer, Grinstein, 2105.02988]
- W' solution is challenged by LHC di-tau data [Faroughy, Greljo, Kamenik, 1609.07138 (PLB '17)] and by precision Z-pole observables [Feruglio, Paradisi, Pattori, 1606.00524 (PRL '17)].

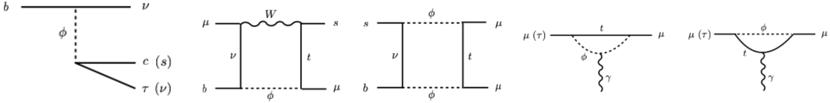
BSM Solutions to All Flavor Anomalies



Leptoquarks emerge as the winner! (or not too soon?)

Leptoquarks

- Single scalar leptoquark solution [Bauer, Neubert, 1511.01900 (PRL '16)]



- Now disfavored by global fits (including $b \to s\mu^+\mu^-$ observables, as well as LHC constraints). [Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504]

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 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

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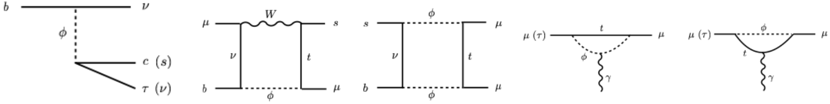

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U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

- Vector LQ must be embedded into some UV-completion [e.g. Heeck, Teresi, 1808.07492]
- Solutions with more than one scalar LQ also possible. [Chen, Nomura, Okada, 1703.03251; Bigaran, Gargalionis, Volkas, 1906.01870); Saad, 2005.04352; Babu, BD, Jana, Thapa, 2009.01771; Heeck, Thapa, 2202.08854; Crivellin, Fuks, Schnell, 2203.10111; ...]

An alternative route: R-parity violating Supersymmetry!

(not just another LQ model)

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By Davide Castelvecchi | April 25, 2012 | 29

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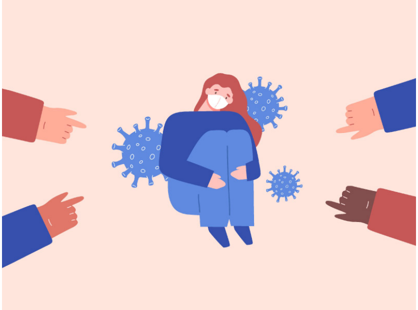
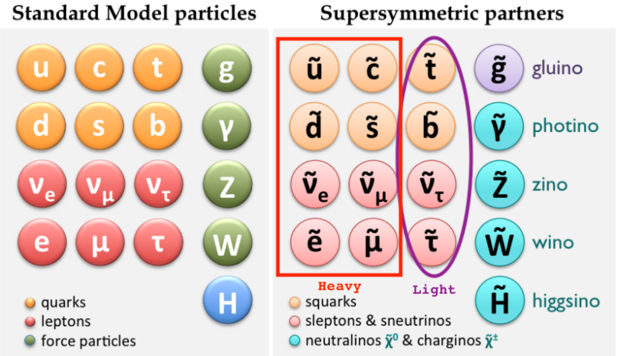


SUSY is alive and doing just fine.

Why SUSY?

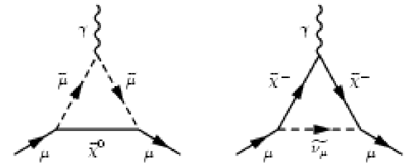
Why SUSY?



Natural SUSY

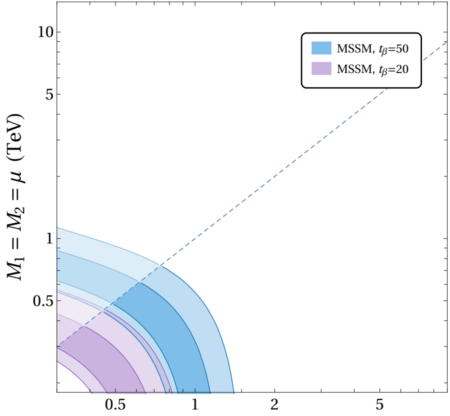
[Brust, Katz, Lawrence, Sundrum, 1110.6670 (JHEP '12); Papucci, Ruderman, Weiler, 1110.6926 (JHEP '12)]

Muon $g-2$ in MSSM



$$a_\mu^{\tilde{\chi}^\pm - \tilde{\nu}_\mu} \simeq \frac{\alpha m_\mu^2 \mu M_2 \tan\beta}{4\pi \sin^2\theta_W m_{\tilde{\nu}_\mu}^2} \left[\frac{f_{\chi^\pm}\left(M_2^2/m_{\tilde{\nu}_\mu}^2\right) - f_{\chi^\pm}\left(\mu^2/m_{\tilde{\nu}_\mu}^2\right)}{M_2^2 - \mu^2} \right],$$

$$a_\mu^{\tilde{\chi}^0 - \tilde{\mu}} \simeq \frac{\alpha m_\mu^2 M_1 (\mu \tan\beta - A_\mu)}{4\pi \cos^2\theta_W \left(m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2\right)} \left[\frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_R}^2\right)}{m_{\tilde{\mu}_R}^2} - \frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_L}^2\right)}{m_{\tilde{\mu}_L}^2} \right]$$



$m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$ (TeV)

[Barbieri, Maiani (PLB '82); Moroi (PRD '96); Chakraborti, Heinemeyer, Saha (2104.03287); Altmannshofer, Gadam, Gori, Hamer (2104.08293)]

$R_{D^{(*)}}$ in MSSM

- There are tree level contributions to $B \to D^{(*)}\tau\nu$ from charged Higgs exchange

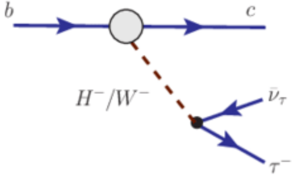
$$\frac{R_D}{R_D^{SM}} \sim 1 - 1.5\frac{m_\tau m_b}{m_{H^\pm}^2}\tan^2\beta$$

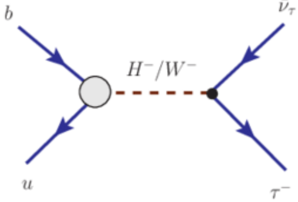
$$\frac{R_{D^*}}{R_{D^*}^{SM}} \sim 1 - 0.12\frac{m_\tau m_b}{m_{H^\pm}^2}\tan^2\beta$$

- Effect goes in the wrong direction and is much smaller for R_{D^*}
- Correlated with effect in $B \to \tau\nu$

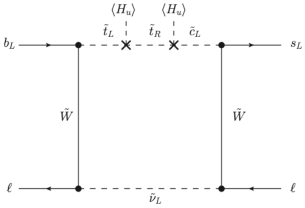
$$\frac{\text{BR}(B\to\tau\nu)}{\text{BR}(B\to\tau\nu)_{\text{SM}}} \simeq \left(1 - \frac{m_B^2}{m_{H^\pm}^2}\tan^2\beta\right)^2$$

$\Rightarrow$ Can't explain $R_{D^{(*)}}$ with charged Higgs exchange in the MSSM





$R_{K^{(*)}}$ in MSSM



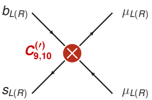
- only way to get lepton flavor non universal contribution to rare $b \to s\ell\ell$ decays is through box diagrams with light winos (or Binos) and large non-universality in slepton masses.

- requires an extremely light spectrum to get $C_9^{bs\mu\mu} \sim -0.5$:

  winos and smuons around 100 GeV;
  sbottoms around 500 GeV;

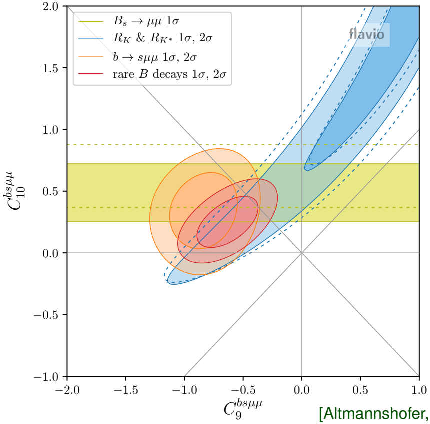
  very challenging to hide this at the LHC...

semileptonic operators



$C_9^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$

$C_{10}^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$



[Altmannshofer, Stangl (2103.13370)]

MSSM with R-Parity Violation

- More natural to include RPV couplings, rather than imposing *R*-parity by hand.
  [Brust, Katz, Lawrence, Sundrum, 1110.6670 (JHEP '12)]
- LFUV arises naturally – á la Yang-Mills. [BD, Soni, Xu, 2106.15647]
- Third generation may be special. (LFUV in *B*-sector, but not in *D* nor in Λ)
- **RPV3**: RPV SUSY with light 3rd-generation sfermions.
  [Altmannshofer, BD, Soni, 1704.06659 (PRD '17)]

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- **RPV3**: RPV SUSY with light 3rd-generation sfermions. [Altmannshofer, BD, Soni, 1704.06659 (PRD '17)]
- 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)]

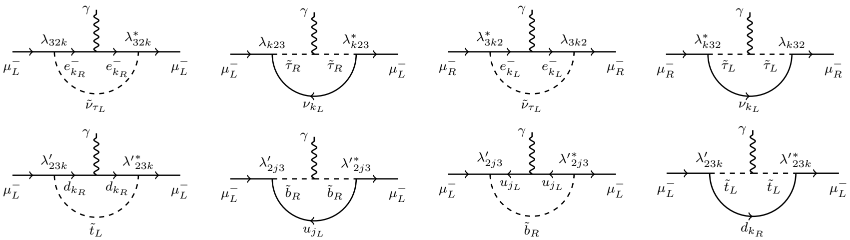
$$\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\widetilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \widetilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \widetilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \widetilde{e}_{iL}\bar{d}_{kR}u_{jL} - \widetilde{u}_{jL}\bar{d}_{kR}e_{iL} - \widetilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \mathrm{H.c.}$$

- Can *simultaneously* explain $R_{K^{(*)}}$ ($b \to s\ell\ell$) via *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 (PRD '20)]

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

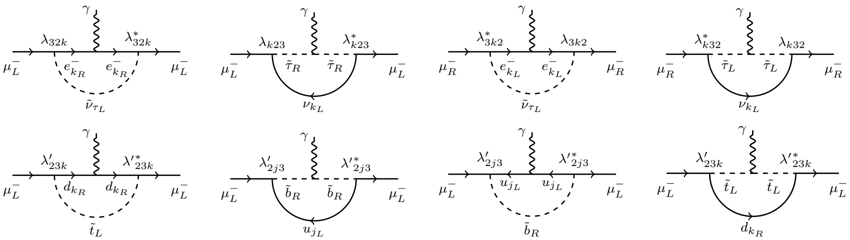
- Muon $g-2$ from both *LQD* and *LLE* terms, but *LLE* more relevant.

Muon $g-2$ in RPV3



[Kim, Kyae, Lee (PLB '01)]

Muon $g-2$ in RPV3



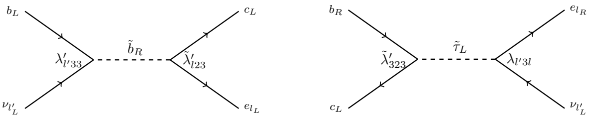
[Kim, Kyae, Lee (PLB '01)]

- 1-loop contributions from λ' and λ couplings
  (in addition to the standard MSSM contributions)

$$\Delta a_\mu = \frac{m_\mu^2}{96\pi^2}\sum_{k=1}^{3}\left(\frac{2(|\lambda_{32k}|^2+|\lambda_{3k2}|^2)}{m^2_{\tilde{\nu}_\tau}} - \frac{|\lambda_{3k2}|^2}{m^2_{\tilde{\tau}_L}} - \frac{|\lambda_{k23}|^2}{m^2_{\tilde{\tau}_R}} + \frac{3|\lambda'_{2k3}|^2}{m^2_{\tilde{b}_R}}\right)$$

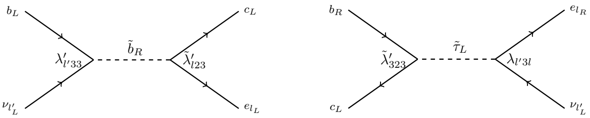
- Need light sbottoms and/or sneutrinos with large couplings to get a relevant contribution in the right direction

$R_{D^{(*)}}$ in RPV3



[Deshpande, He (EPJC ’17); Altmannshofer, BD, Soni (PRD ’17); · · ·]

$R_{D^{(*)}}$ in RPV3

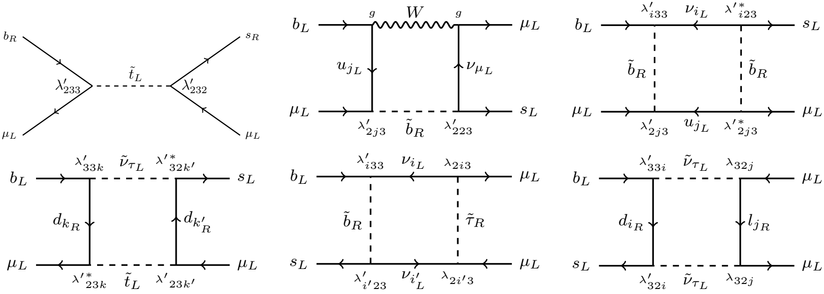


[Deshpande, He (EPJC '17); Altmannshofer, BD, Soni (PRD '17); · · ·]

- Tree level contributions from sbottom or stau exchange
- Stau behaves like a charged Higgs (but its couplings are less constrained). Stau contribution disfavored by $B_c \to \tau\nu$ branching ratio and kinematic distributions in $B \to D^{(*)}\tau\nu$.
- Sbottom behaves like a leptoquark. Chirality structure as prefered by model independent fits (Shi et al. 1905.08498; Murgui et al. 1904.09311; Asadi, Shih 1905.03311; Cheung et al. 2002.07272; ...)
- Can address the $R_{D^{(*)}}$ anomalies for sbottom masses $O(1\text{ TeV})$ and couplings $\lambda' \sim O(1)$
- need to be careful to keep $\mu - e$ universality in $b \to c\ell\nu$

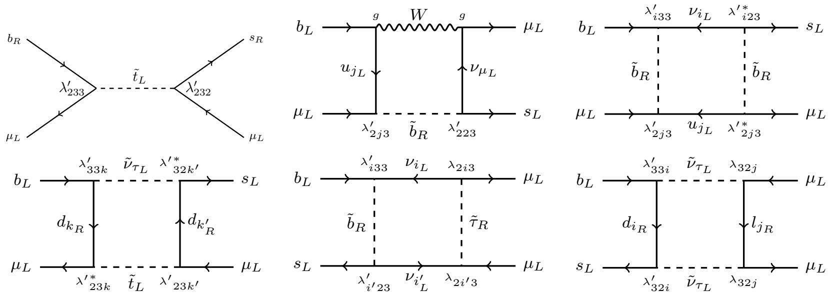
$$\frac{R_D}{R_D^{\rm SM}} = \frac{R_{D^*}}{R_{D^*}^{\rm SM}} = \frac{|\Delta^c_{31}|^2 + |\Delta^c_{32}|^2 + |1+\Delta^c_{33}|^2}{|\Delta^c_{21}|^2 + |1+\Delta^c_{22}|^2 + |\Delta^c_{23}|^2}\,,$$

$$\text{with } \Delta^c_{ll'} = \frac{v^2}{4m^2_{\tilde{b}_R}}\lambda'_{l'33}\left(\lambda'_{l33} + \lambda'_{l23}\frac{V_{cs}}{V_{cb}} + \lambda'_{l13}\frac{V_{cd}}{V_{cb}}\right).$$



[Das, Hati, Kumar, Mahajan (PRD ’17); Trifinopoulos (EPJC ’18); · · ·]

$R_{K^{(*)}}$ in RPV3



[Das, Hati, Kumar, Mahajan (PRD ’17); Trifinopoulos (EPJC ’18); · · ·]

- Tree level contribution from stop exchange have the wrong chirality
- Several loop contributions with the right chirality and $C_9 = -C_{10}$
- Both λ and λ' couplings can be involved

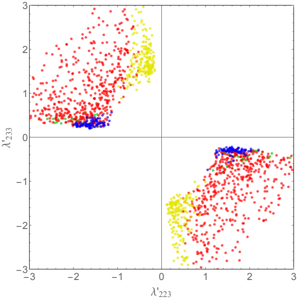
$$C_9^\mu = -C_{10}^\mu = \frac{m_t^2}{m_{\tilde{b}_R}^2}\frac{|\lambda'_{233}|^2}{16\pi\alpha_{\rm em}} - \frac{v^2}{m_{\tilde{b}_R}^2}\frac{X_{bs}X_{\mu\mu}}{64\pi\alpha_{\rm em}V_{tb}V_{ts}^*},$$

where $X_{bs} = \sum_{i=1}^3 \lambda'_{i33}\lambda'_{i23}$ and $X_{\mu\mu} = \sum_{j=1}^3 |\lambda'_{2j3}|^2$.

Low-energy Constraints

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	$\lambda'_{323},\ m_{\tilde{b}_R},\ m_{\tilde{\tau}_R}$	$\frac{\lambda'^4_{323}}{m^2_{\tilde{b}_R}},\ \frac{\lambda'^4_{323}}{m^2_{\tilde{\tau}_R}}$
$D^0 \to \mu^+\mu^-$	$\lambda'_{2j3},\ m_{\tilde{b}_R}$	$\frac{\lambda'_{2j3}\lambda'_{2j'3}}{m^2_{\tilde{b}_R}}$
$\tau \to \ell\nu\bar{\nu}$	$\lambda_{323},\ \lambda'_{333},\ m_{\tilde{\tau}_R},\ m_{\tilde{b}_R}$	$\frac{\lambda^2_{323}}{m^2_{\tilde{\tau}_R}},\ \frac{\lambda'^2_{333}}{m^2_{\tilde{b}_R}}$
$Z \to \ell\bar{\ell}'$	$\lambda'_{333},\ m_{\tilde{b}_R}$	$\frac{\lambda'^2_{333}}{m^2_{\tilde{b}_R}}$

Numerical Scan



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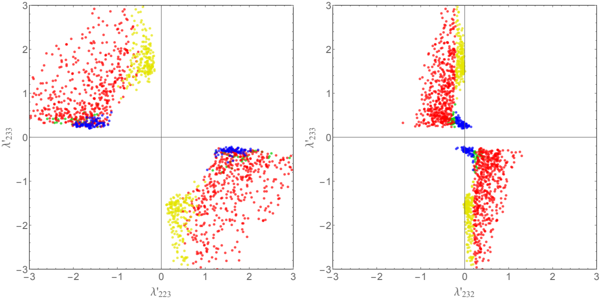

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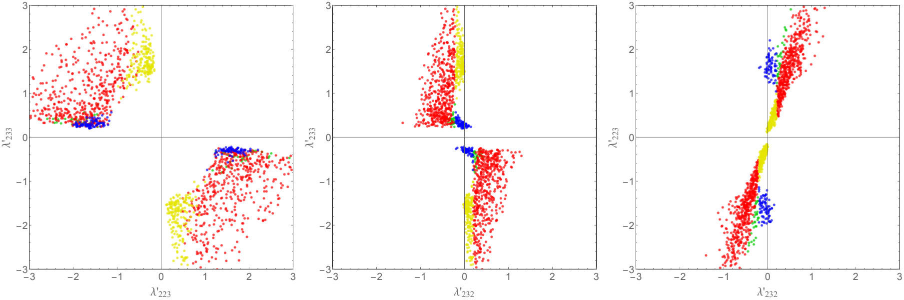

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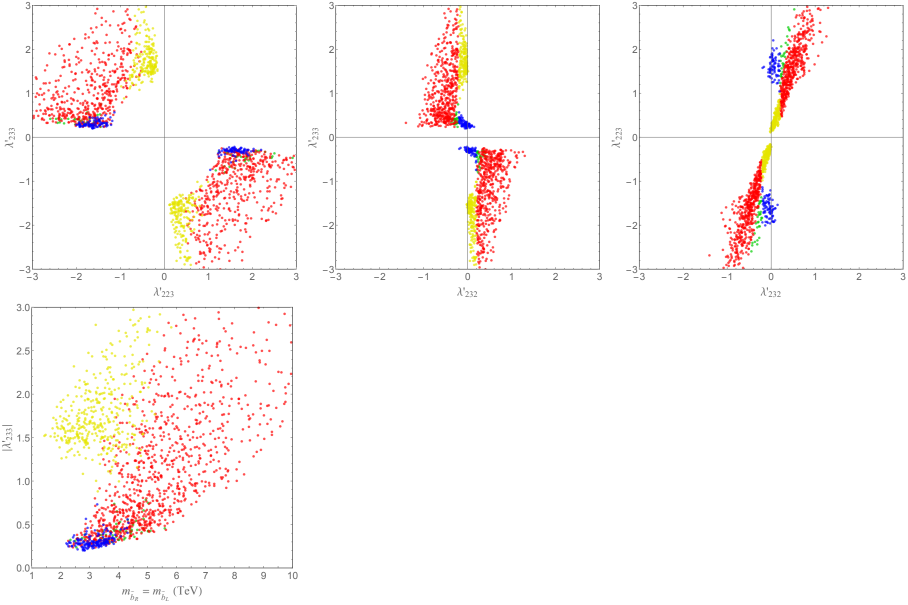

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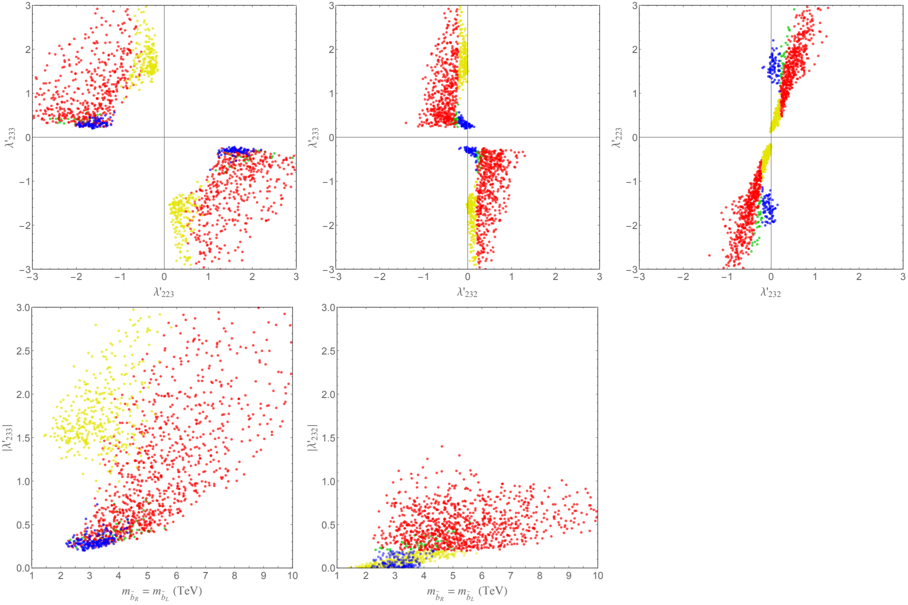

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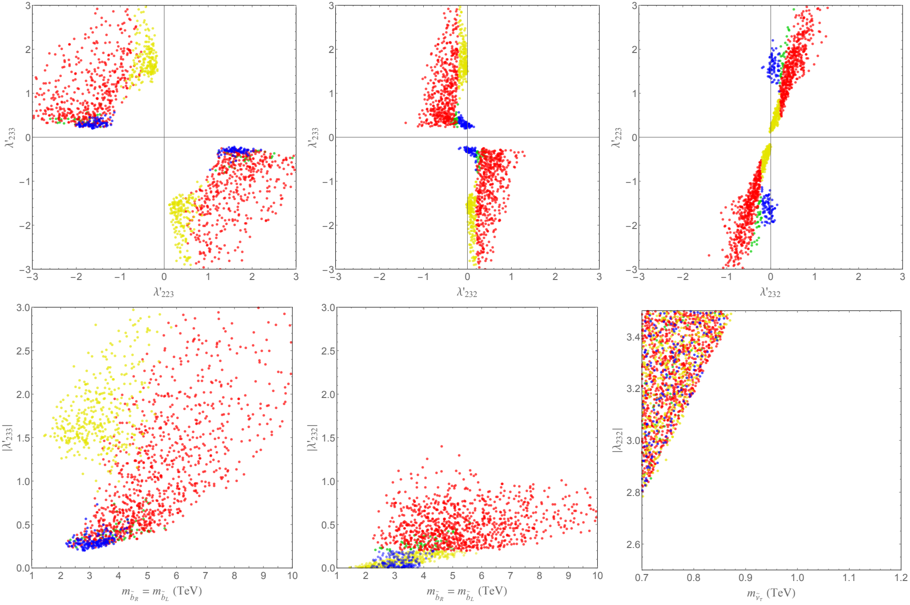
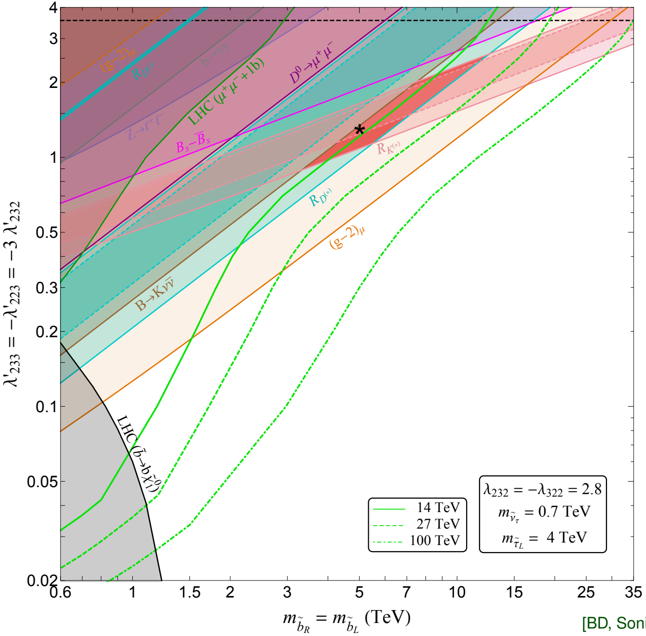


A Combined RPV3 Fit to All Flavor Anomalies



[BD, Soni, Xu (2106.15647)]

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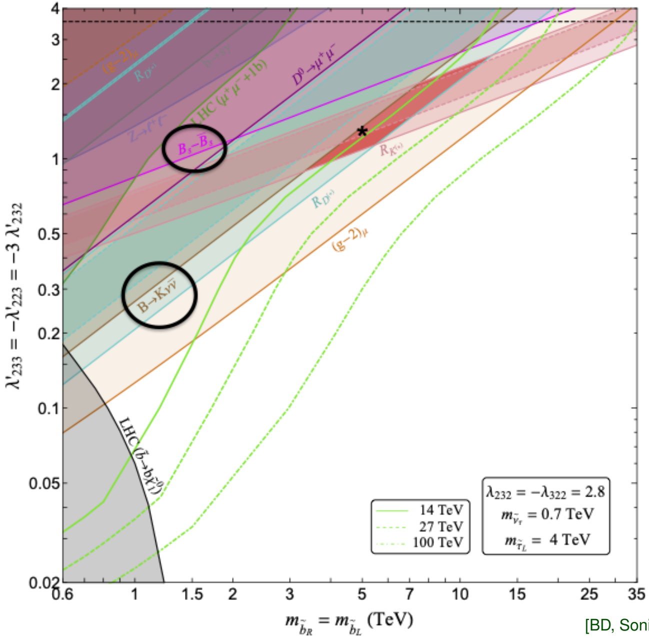

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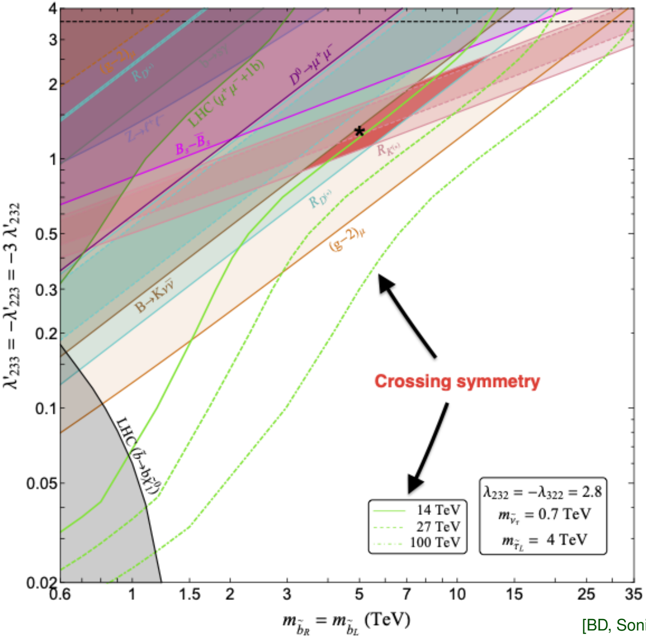


[BD, Soni, Xu (2106.15647)]

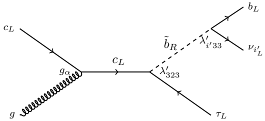
Distinct LHC Signals in RPV3

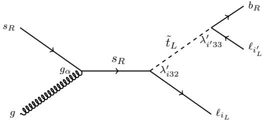
- Effective operators:

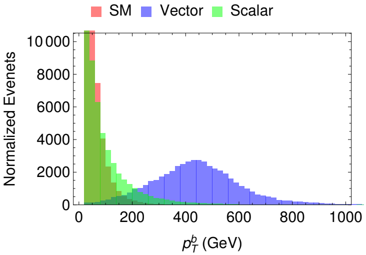
$$R_{D^{(*)}} \;:\; \mathcal{O}_{V_L} = (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu)$$

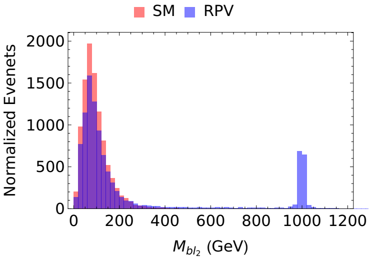
$$R_{K^{(*)}} \;:\; Q^{\ell}_{9(10)} = (\bar{s}\gamma^{\mu} P_L b)(\bar{\ell}\gamma_{\mu}(\gamma_5)\ell)$$

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





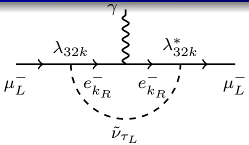


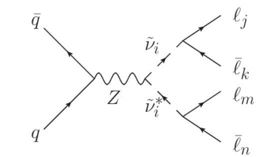


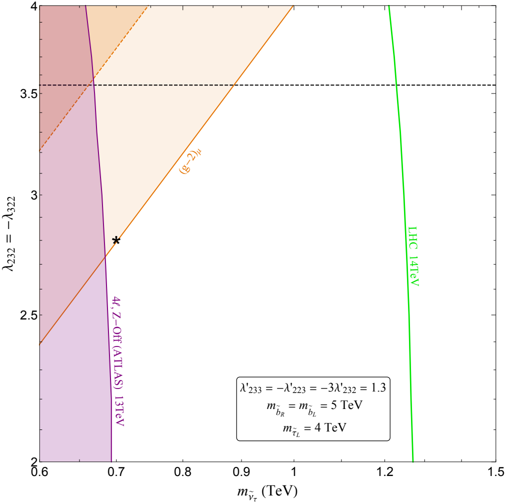
[Altmannshofer, BD, Soni (PRD '17)]

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

An LHC Test of Muon $g-2$







[BD, Soni, Xu (2106.15647)]

Conclusion

- Mounting evidence for the violation of lepton flavor universality.
  [Crivellin, Hoferichter, 2111.1273 (Science '21)]
- Can be explained by invoking BSM physics (true for any anomaly).
- Leptoquarks and RPV-SUSY remain as the most attractive scenarios for a simultaneous explanation of B-anomalies and muon $g-2$.
- Personal choice: **RPV3** – motivated by Higgs naturalness and other beautiful features of SUSY, while being consistent with null searches at the LHC.
  - Removes the accidental flavor symmetry of the SM.
  - Same chiral structure as the SM $\Longrightarrow$ correct D^* and τ polarizations, as well as $R_K - R_{K^{(*)}}$ correlation come automatically.
  - Highly predictive and testable at Belle II, LHCb and high-p_T LHC experiments.
  - Improved lattice input for $B \to K\nu\bar{\nu}$ and $B_s - \overline{B}_s$ will be crucial.
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Thank You.