Supersymmetric Solutions of the Flavor Anomalies

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Anomalies 2021
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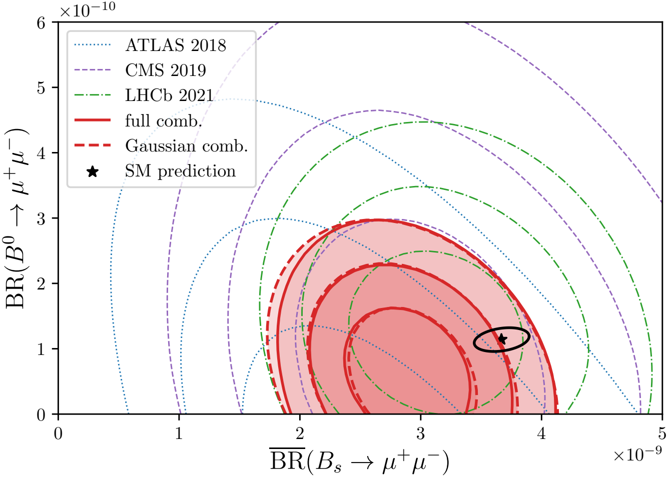
Overview of the Anomalies

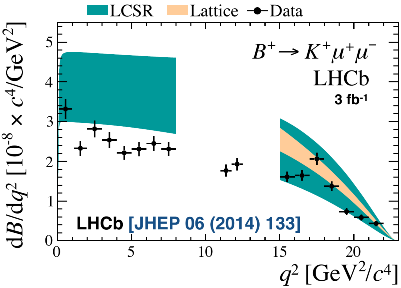
The $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ Decays

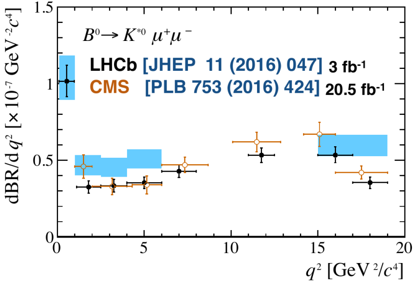
WA, Stangl 2103.13370; combination of LHCb 2108.09284, CMS 1910.12127, ATLAS 1812.03017

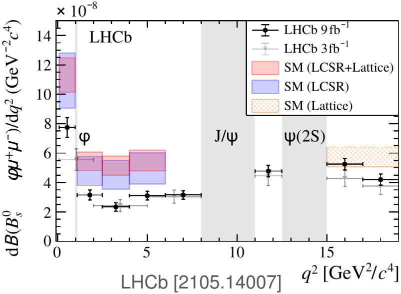


$\sim 2\sigma$ tension between SM and experiment

Semileptonic Branching Ratios







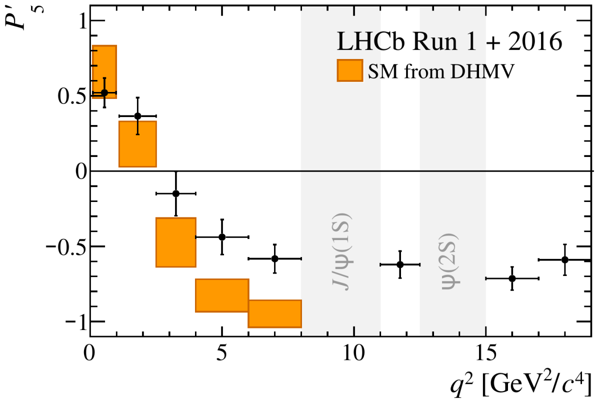
LHCb [2105.14007]

Experimental results for
$\text{BR}(B \to K\mu\mu)$
$\text{BR}(B \to K^*\mu\mu)$
$\text{BR}(B_s \to \phi\mu\mu)$
are consistently low
across many q^2 bins

The P_5' Anomaly

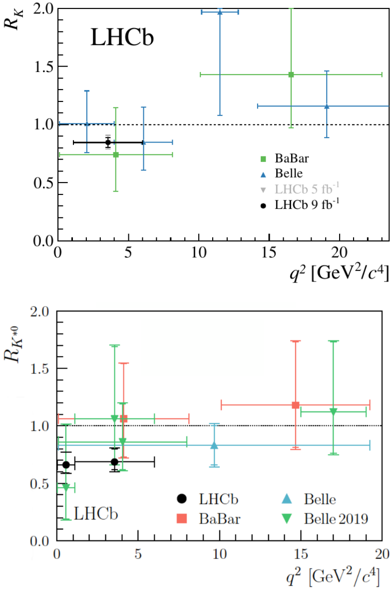
$P_5' \sim$ a moment of the $B \to K^* \mu^+ \mu^-$ angular distribution

LHCb 2003.04831



Anomaly persists in the latest update of $B^0 \to K^{*0} \mu^+ \mu^-$ with 2016 data.
(Anomaly also seen in $B^\pm \to K^{*\pm} \mu^+ \mu^-$ LHCb 2012.13241)

Evidence for Lepton Flavor Universality Violation



$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

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

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

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

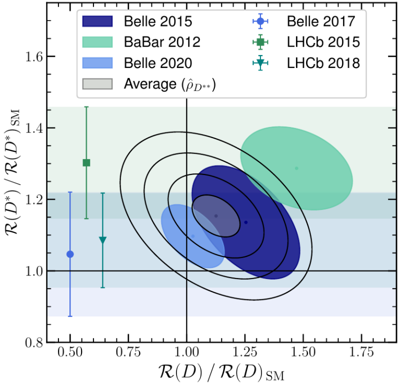
$$R_{K_S}^{[1.1,6]} = 0.66^{+0.20}_{-0.14}{}^{+0.02}_{-0.04}$$

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

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

LHCb 2103.11769

Bernlochner, Franco Sevilla, Robinson, 2101.08326



$$R_D = \frac{BR(B \to D\tau\nu)}{BR(B \to D\ell\nu)}$$

$$R_{D^*} = \frac{BR(B \to D^*\tau\nu)}{BR(B \to D^*\ell\nu)}$$

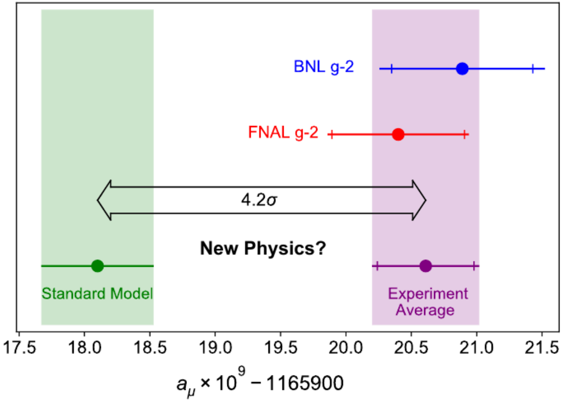
$\ell = \mu, e$ (BaBar/Belle)
$\ell = \mu$ (LHCb)

$$R_D^{\rm exp}/R_D^{\rm SM} = 1.13 \pm 0.10\,, \quad R_{D^*}^{\rm exp}/R_{D^*}^{\rm SM} = 1.15 \pm 0.06$$

combined discrepancy with the SM: 3.6σ

(the heavy flavor averaging group quotes 3.1σ)

Anomalous Magnetic Moment of the Muon

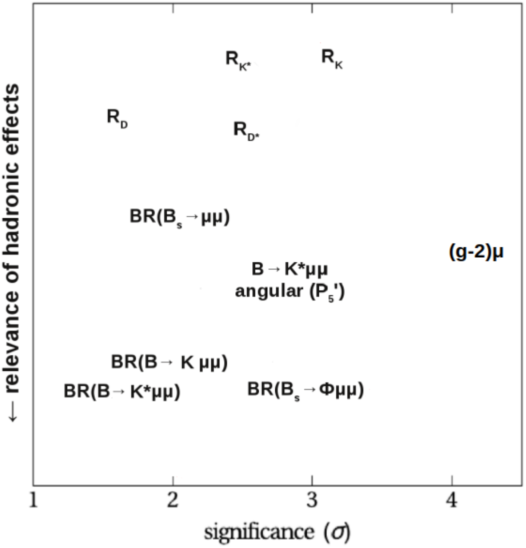


4.2 σ discrepancy between the experimental average (Fermilab g-2, 2104.03281) and the SM consensus (Aoyama et al. 2006.04822)

(see, however, the lattice results from BMW 2002.12347)

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

(Selection of) Anomalies in 2021



(inspired by Zoltan Ligeti)

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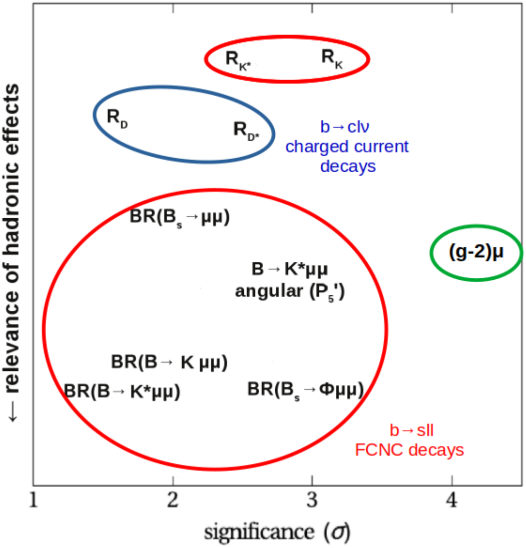

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What Could It Be?

	$B_s \to \mu\mu$ rate	semileptonic rates	angular observables	LFU ratios	$(g-2)_\mu$

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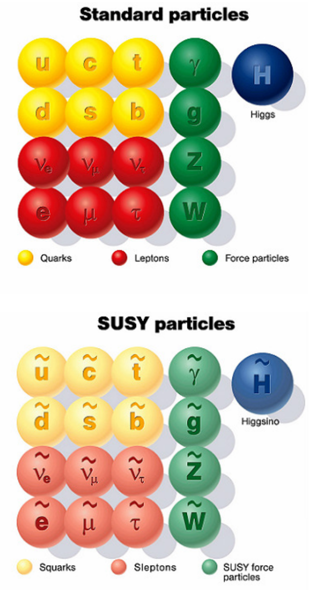
New Physics?	✓	✓	✓	✓	✓

The Flavor Anomalies in the MSSM

The Minimal Supersymmetric Standard Model

- Arguably still the best motivated extension of the Standard Model
- For a natural weak scale, need light Higgsinos, light stops, and relatively light gluinos
- First and second generation of sfermions can be heavy without spoiling the successes of the MSSM (naturalness, gauge coupling unification, dark matter, ...)



The Anomalous Magnetic Moment in the MSSM

- It is very well known that the MSSM can give sizeable contributions to $(g-2)_\mu$ via $\tan\beta$ enhanced smuon chargino/neutralino loops

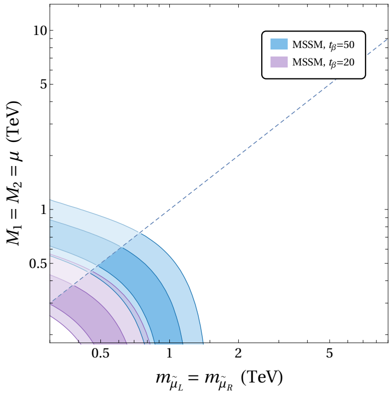
  many many recent references

  (apologies for the omission)

- Smuons, charginos, neutralinos need to be pretty light

- Compressed spectra to avoid exising LHC constraints

- Good discovery prospects at the high luminosity LHC and e^+e^- colliders (ILC, CLIC)



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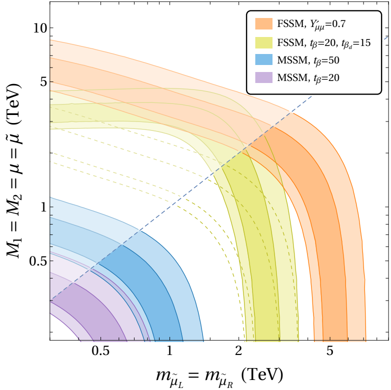


- With extended SUSY Higgs sectors, smuons, charginos, neutralinos can be significantly heavier

  WA, Gadam, Gori, Hamer 2104.08293

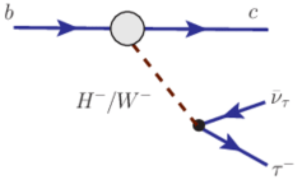
R_D and R_{D^*} in the MSSM

- 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^*}



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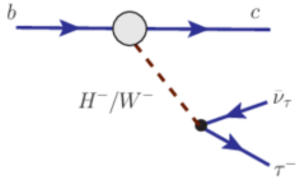
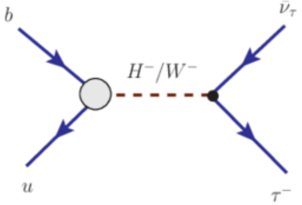
- Effect goes in the wrong direction and is much smaller for R_{D^*}
- Correlated with effect in $B \to \tau\nu$

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

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

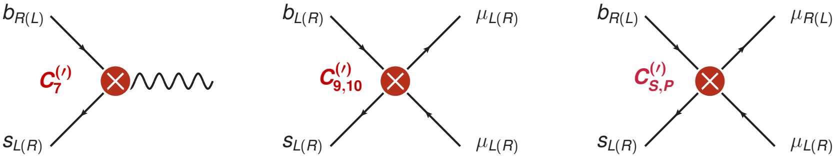




Interlude: R_K and R_{K^*} Model Independently

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \Big(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \Big)$$

magnetic dipole operators — semileptonic operators — scalar operators



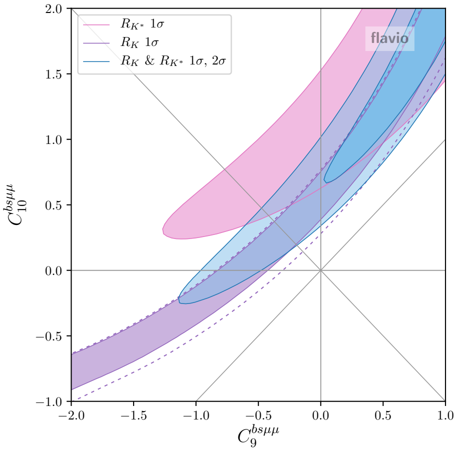
$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) \quad , \quad C_S^{(\prime)} (\bar{s} P_{R(L)} b)(\bar{\mu} P_{L(R)} \mu)$$

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

neglecting tensor operators and additional scalar operators

(they are dimension 8 in SMEFT: Alonso, Grinstein, Martin Camalich 1407.7044)

Interlude: Global Rare B Decay Fits

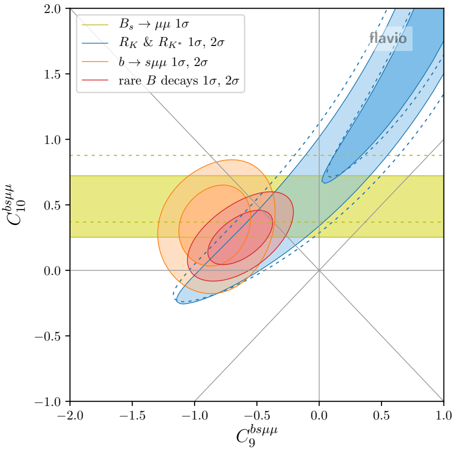


WA, Stangl 2103.13370 (other recent fits: Geng et al. 2103.12738; Cornella et al. 2103.16558; Alguero et al. 2104.08921; Hurth et al. 2104.10058; Ciuchini et al. 2110.10126)

$$C_9^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

$$C_{10}^{bs\mu\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios prefer non-standard C_{10}, but large degeneracy



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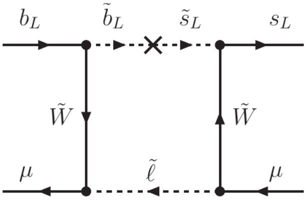
- LFU ratios prefer non-standard C_{10}, but large degeneracy
- $B_s \to \mu^+\mu^-$ branching ratio shows slight preference for non-standard C_{10}
- $b \to s\mu\mu$ observables prefer non-standard C_9
- best fit point

$$C_9^{bs\mu\mu} \simeq -0.63$$

$$C_{10}^{bs\mu\mu} \simeq +0.25$$



WA, Straub

1308.1501, 1411.3161

- 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...

The Flavor Anomalies and R-Parity Violation

The MSSM with R-Parity Violation

- give up on a dark matter candidate, but open up possibilities to address the flavor anomalies

- consider the lepton number violating *LQD* and *LLE* interactions (no baryon number violating *UDD* interactions to avoid constraints from proton decay)

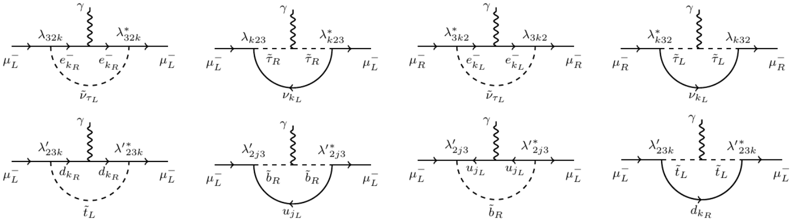
$$\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\widetilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \widetilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \widetilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \widetilde{e}_{iL}\bar{d}_{kR}u_{jL} - \widetilde{u}_{jL}\bar{d}_{kR}e_{iL} - \widetilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \mathrm{H.c.}$$

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

- assume that only the 3rd generation sfermions are light
$\Rightarrow$ 7 λ couplings and 19 λ' couplings are relevant

$\rightarrow$ RPV3 (WA, Dev, Soni 1704.06659; WA, Dev, Soni, Sui 2002.12910; Dev, Soni, Xu 2106.15647)

The Anomalous Magnetic Moment with RPV3



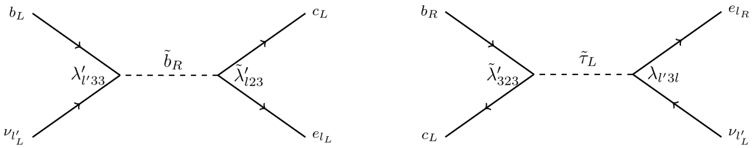
Kim, Kyae, Lee hep-ph/0103054

- 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

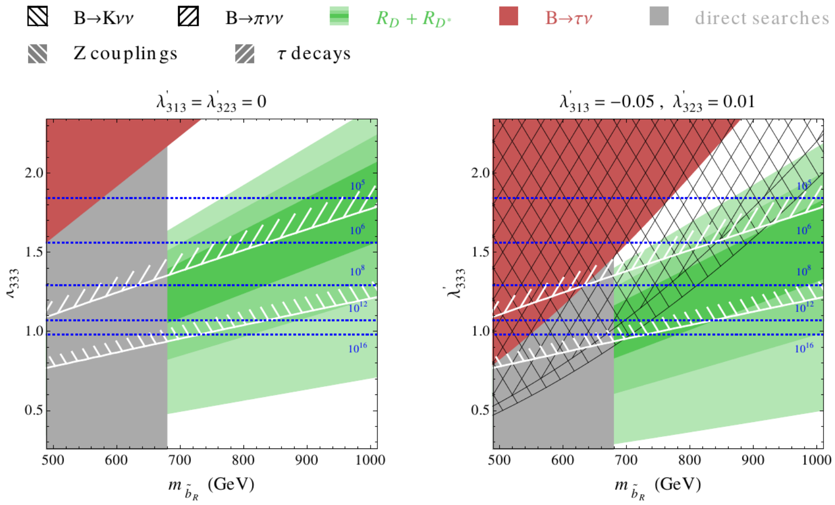
R_D and R_{D^*} with RPV3



Deshpande, He 1608.04817; WA, Dev, Soni 1704.06659; ...

- 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 $b \to c\ell\nu$

Viable Parameter Space

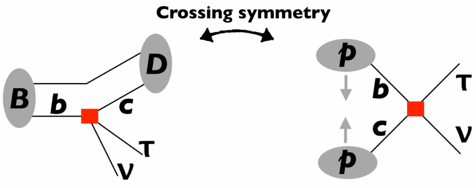


WA, Dev, Soni 1704.06659

Collider Signatures of $R_{D^{(*)}}$ Explanation

Expect non-standard
mono-tau production
at the LHC

(possibly in association
with b-jets)



WA, Dev, Soni 1704.06659; Greljo et al. 1811.07920;
Marzocca et al. 2008.07541; ...

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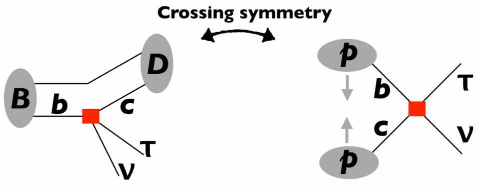

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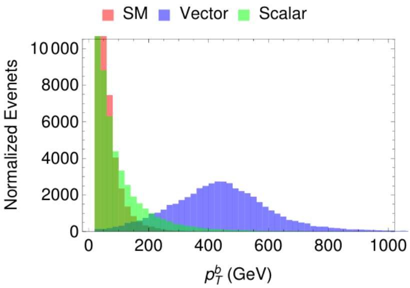
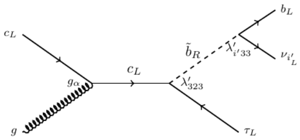
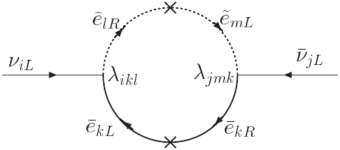
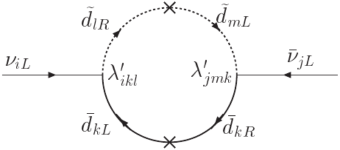




- In RPV3, look for sbottom production $gc \to \tilde{b}\tau \to b\nu\tau$

Implications for Neutrino Masses



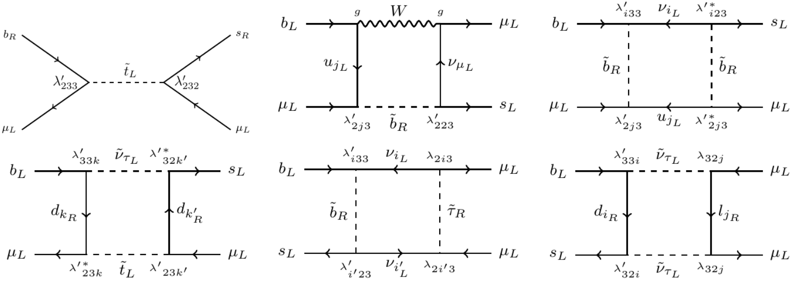


Barbier et al. hep-ph/0406039; WA, Dev, Soni 1704.06659

- The RPV couplings give also 1-loop contributions to Majorana neutrino masses

$$(\hat{M}_\nu)_{ij} = (\hat{M}_\nu)^{\text{tree}}_{ij} + \frac{3}{8\pi^2}\frac{m_b^2(A_b - \mu\tan\beta)}{m^2_{\tilde{b}}}\lambda'_{i33}\lambda'_{j33} + \frac{1}{8\pi^2}\frac{m_\tau^2(A_\tau - \mu\tan\beta)}{m^2_{\tilde{\tau}}}\lambda_{i33}\lambda_{j33} + \dots$$

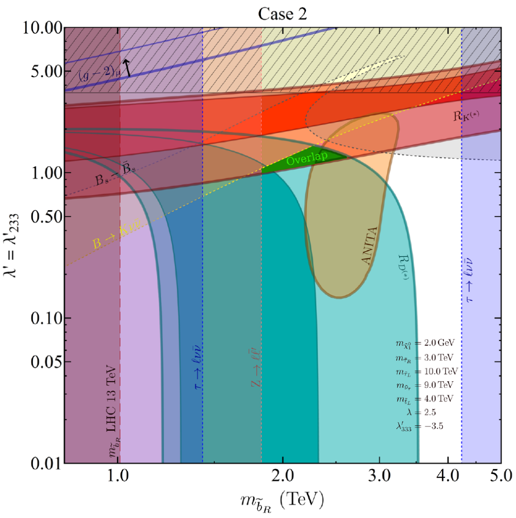
- Generic size of neutrino masses for sbottoms/staus masses of $O(1\text{ TeV})$ and couplings of $O(1)$ is ~ 0.1 MeV
- Need cancellation to obtain sub-eV neutrino masses



Das et al. 1705.09188; Earl Gregoire 1806.01343; Trifinopoulos 1807.01638; Hu, Huang 1912.03676;
WA, Dev, Soni, Sui 2002.12910; Bardhan et al. 2107.10163

- 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

Combined Explanations of the Anomalies



WA, Dev, Soni, Sui 2002.12910

- We consider a few benchmark scenarios
- We include a very long list of constraints:

  meson mixing;

  rare decays;

  Z decays;

  lepton flavor violation;

  direct LHC searches;

  ...

- Bonus: can also explain ANITA events

  Collins, Dev, Sui 1810.08479

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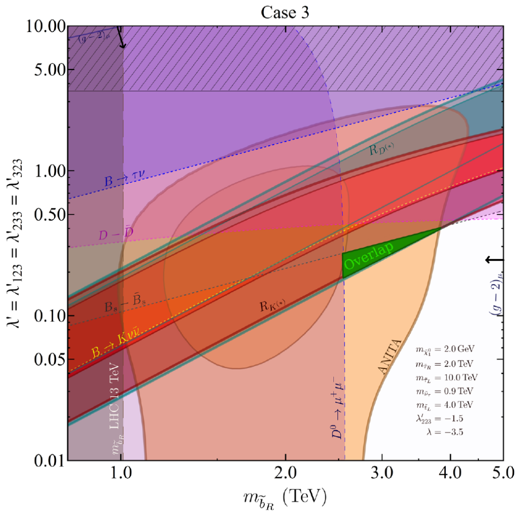

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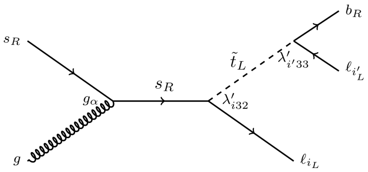
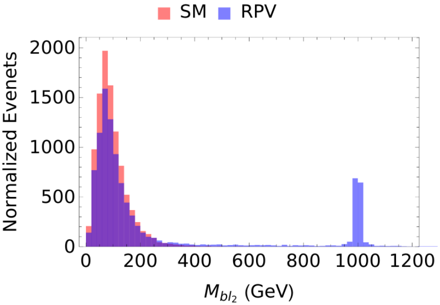
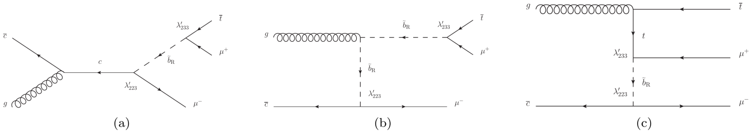
  Collins, Dev, Sui 1810.08479

- Based on crossing symmetry expect the processes $bs \to \ell\ell$, $gb \to s\ell\ell$, and $gs \to b\ell\ell$.
- In RPV3: for example single stop production, giving a $b\mu$ resonance.



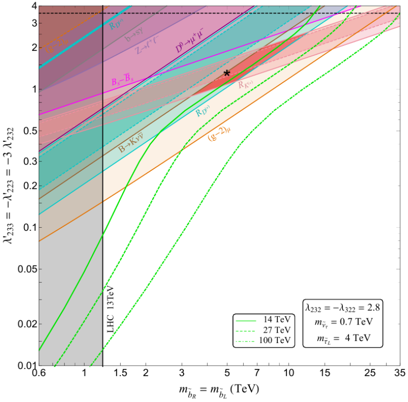


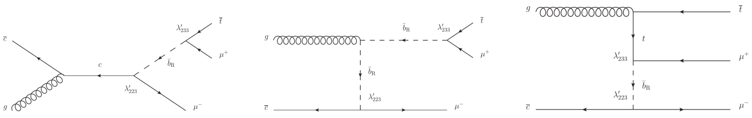
WA, Dev, Soni, Sui 2002.12910



- $t\mu\mu$ production mediated by sbottoms

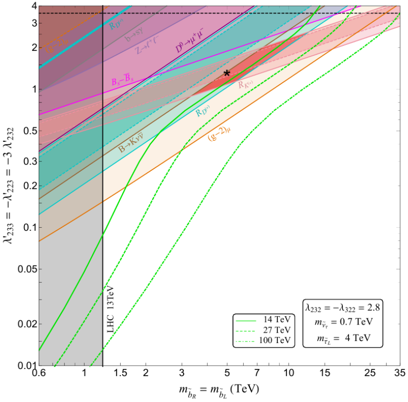
Dev, Soni, Xu 2106.15647





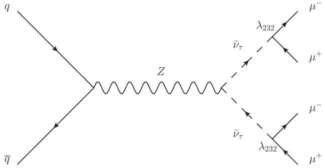
(a) (b) (c)

- $t\mu\mu$ production mediated by sbottoms



Dev, Soni, Xu 2106.15647

- pair of di-muon resonances



Summary

- Rare B decays and muon g-2 show persistent discrepancies with SM predictions.
- It's not possible to explain $R_{D^{(*)}}$ and $R_{K^{(*)}}$ in the MSSM.
- In the context of SUSY, need RPV interactions to explain hints for lepton flavor universality violation.
- In RPV3, combined explanations of the anomalies are strongly constrained but possible.
- RPV3 explanations lead to interesting collider signatures.