Resolving R_K and R_{K*} anomalies via R-parity violating interactions

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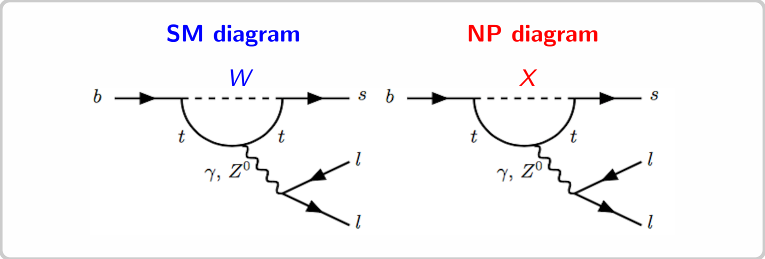
Talk based on **Phys. Rev. D 96, 095033 (2017)**
with Diganta Das, Chandan Hati, Namit Mahajan

December 12, 2017

Rare decays as indirect probe of NP

- Rare B decays mediated by the flavor-changing neutral (e.g. $b \to s$) transitions are sensitive probes of parameters of the Standard Model.



- SM amplitude is suppressed,
- New heavy particles in extensions of the SM can appear in competing diagrams and affect the amplitude,

$\to$ excellent probes for indirect search of NP.

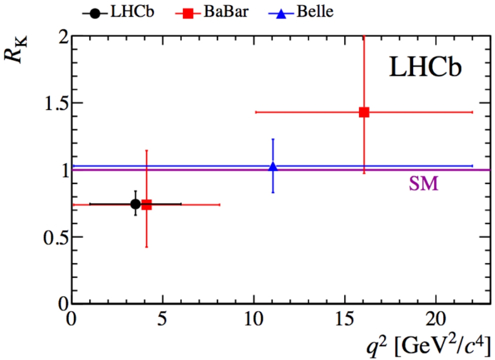
LFU violation in B decays ?

- In the SM, couplings of the gauge bosons to leptons are independent of lepton flavor

- A 2.6 σ tension in lepton flavor universality ratio in $B^+ \to K^+ \ell^+ \ell^-$

LHCb, PRL 113 (2014) 151601

$$R_K = \frac{\mathrm{BR}(\bar{B} \to \bar{K}\mu^+\mu^-)}{\mathrm{BR}(\bar{B} \to \bar{K}e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036, \qquad R_K^{\mathrm{SM}} = 1.00 \pm \mathcal{O}(10^{-2})$$



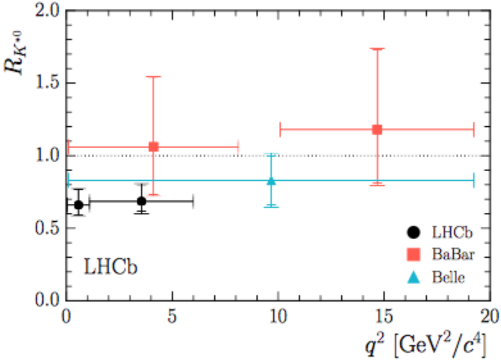
LFU violation in B decays ?

- Very recently, the LHCb Collaboration presented their first results for R_{K*}

LHCb, JHEP **1708**, 055 (2017)

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

$$R_{K*[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05, \quad R^{\text{SM}}_{K*[1.1,6]} = 1.00 \pm \mathcal{O}(10^{-2})$$
$$R_{K*[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03, \quad R^{\text{SM}}_{K*[0.045,1.1]} = 0.98 \pm \mathcal{O}(10^{-2})$$



Hints of New Physics ?

- Claims of NP are further strengthened by other data on $b \to s\mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$: Measurements of form factor free observables (eg. P_5')

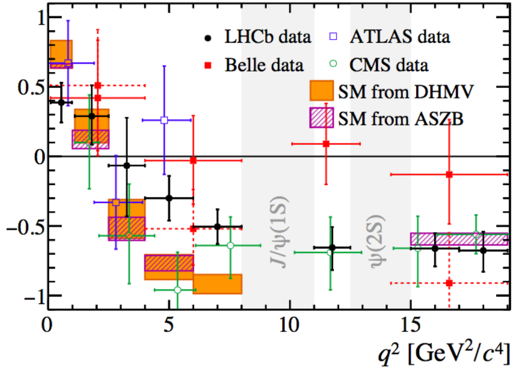


Fig. from T. Gershan's talk, Moriond 2017

- In $\mathcal{BR}(B_s \to \phi\mu^+\mu^-)$, a deviation of 3.5σ significance with respect to the SM
LHCb, JHEP 09 (2015) 179

Model-independent description in effective theory

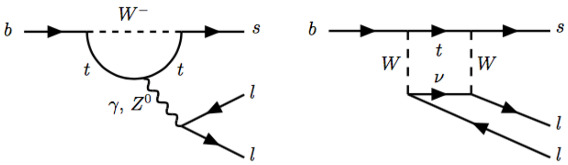
- Effective Hamiltonian for $b \to s\ell\ell$:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t \sum_i C_i^\ell O_i^\ell + \sum \frac{\mathcal{C}^{\rm NP}}{\Lambda^2_{\rm NP}}\mathcal{O}^{\rm NP}$$

- In the SM, the significant operators are:

$$O_9^\ell \propto (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell), \qquad O_{10}^\ell \propto (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

- The SM Wilson coeffs. $C_9 \simeq -C_{10} \simeq -4.1$



SM contributions to $b \to s\ell\ell$

Global analysis to $b \to s\ell\ell$ data

- Current fits to LFNU observables prefers NP over SM $\sim 3.5\sigma$

Hiller *et al*, arXiv:1704.05444

$$
\begin{aligned}
C_9^{\mathrm{NP}\mu} - C_{10}^{\mathrm{NP}\mu} - (\mu \to e) &\sim -1.1 \pm 0.3, \\
C_9'^{\mu} - C_{10}'^{\mu} - (\mu \to e) &\sim 0.1 \pm 0.4
\end{aligned}
$$

- Interestingly, the global fits to current $b \to s\ell\ell$ data also prefers a destructive NP contribution to C_9^{NP}. Matias *et al*, arXiv:1704.05340

$$
\begin{aligned}
\text{1D fit} &: \quad C_9^{\mathrm{NP}} = -1.10; \qquad C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}} = -0.61 \\
\text{2D fit} &: \quad (C_9^{\mathrm{NP}}, C_{10}^{\mathrm{NP}}) = (-1.17, 0.15)
\end{aligned}
$$

R-Parity Violating interactions

- The R-parity violating interactions with trilinear couplings are described by the following superpotential R. Barbier et al. Phys.Rept. 420 (2005)

$$W_{\not{R}} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k \,.$$

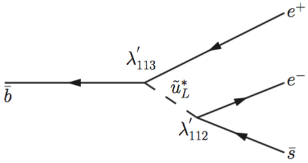
- $(\lambda,\ \lambda') : \not{L}, \quad \lambda'' : \not{B}$
- We set $\lambda''=0$
- fermion-fermion-sfermion interaction terms:

$$\mathcal{L}^{\not{R}}_{\rm int} = \lambda'_{ijk} \left(\tilde{\nu}^i_L \bar{d}^k_R d^j_L + \tilde{d}^j_L \bar{d}^k_R \nu^i_L + \tilde{d}^{k*}_R \bar{\nu}^{ci}_L d^j_L - \tilde{\ell}^i_L \bar{d}^k_R u^j_L - \tilde{u}^j_L \bar{d}^k_R \ell^i_L - \tilde{d}^{k*}_R \bar{\ell}^{ci}_L u^j_L \right) \,,$$

Earlier works in RPV

- $\mathcal{L}^{\not R}_{\rm int}$ contains a term $\sim -\tilde{u}^j_L \bar{d}^k_R \ell^i_L$ which allows for tree level contribution to $b \to s\ell\ell$

  Biswas et al. JHEP 1502, 142 (2015)



$$\mathcal{L}_{eff} = -\frac{\lambda'_{ijk}\lambda'^{*}_{i'jk'}}{2m^2_{\tilde{u}^j_L}} \bar{\ell}^{i'}_L \gamma^\mu \ell^i_L \; \bar{d}^k_R \gamma_\mu d^{k'}_R ,$$

$$C'^{\ell}_{10} = -C'^{\ell}_{9} = \frac{\lambda'_{\ell j2}\lambda'^{*}_{\ell j3}}{V_{tb}V^*_{ts}} \frac{\pi}{\alpha_e} \frac{\sqrt{2}}{4m^2_{\tilde{u}^j_L} G_F}$$

Note that quark current is right-handed!

A suppressed R_K is correlated with enhanced R^*_K and vice versa

Cannot explain R_K and R^*_K simultaneously.

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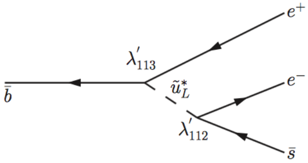

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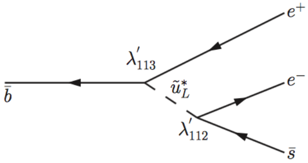

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- In this scenario tree-level contributions to $b \to s\ell\ell$ are absent.

- The exchange of down type right-handed sbottom coupled to quarks and leptons produces the right chirality for operators O_9.

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- The exchange of down type right-handed sbottom coupled to quarks and leptons produces the right chirality for operators O_9.
- But constraints from $b \to s\nu\nu$ data are too severe to accommodate R_K in their scenario.

There are additional contributions to $b \to s$ processes present in this framework that could help in explaining R_K and R_K^* without being in conflict with other flavor bounds.

One-loop contributions to $b \to s\ell\ell$

Going to lepton chirality basis:

$$\begin{aligned} O_{\mathrm{LL}} &= (\bar{s}_L \gamma^\alpha b_L)\,(\bar{\mu}_{\mathrm{L}} \gamma_\alpha \mu_{\mathrm{L}}) \\ O_{\mathrm{LR}} &= (\bar{s}_L \gamma^\alpha b_L)\,(\bar{\mu}_{\mathrm{R}} \gamma_\alpha \mu_{\mathrm{R}}) \end{aligned}$$

$$\text{with} \quad C_{\mathrm{LL}}^{\mu\mathrm{NP}} = C_9^{\mu\mathrm{NP}} - C_{10}^{\mu\mathrm{NP}}, \quad C_{\mathrm{LR}}^{\mu\mathrm{NP}} = C_9^{\mu\mathrm{NP}} + C_{10}^{\mu\mathrm{NP}}$$

In this set-up, we have $C_9^{\mathrm{NP}} = -C_{10}^{NP} \Longrightarrow$ New Contributions to $C_{\mathrm{LL}}^{\mu\mathrm{NP}}$ are:

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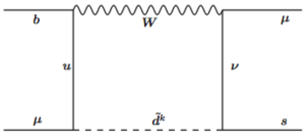
$W - \tilde{d}_R^k$ exchange gives



$$= \frac{\lambda'_{23k}\lambda'^{*}_{23k}}{8\pi\alpha_e}\left(\frac{m_t}{m_{\tilde{d}_R^k}}\right)^2$$

This is a positive quantity.

One-loop contributions to $b \to s\ell\ell$

$\tilde{d}_R^k - \tilde{d}_R^k$ exchange gives

$$= -\frac{\lambda'_{i3k}\lambda'^{*}_{i2k}\lambda'_{2jk}\lambda'^{*}_{2jk}}{32\sqrt{2}\,G_F\,V_{tb}V_{ts}^{*}\pi\alpha_e m^2_{\tilde{d}_R^k}}$$

These two diagrams combined can yield a negative contribution for a TeV scale sbottom

But low-energy constraints spoils the viability of accommodating data.

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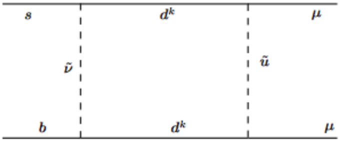
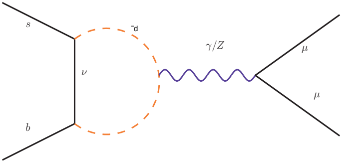


$$= -\frac{\lambda'_{i3k}\lambda'^*_{i2k}\lambda'_{2jk}\lambda'^*_{2jk}}{32\sqrt{2}\,G_F\,V_{tb}V^*_{ts}\pi\alpha_e}\,\frac{\log\left(m^2_{\tilde{u}^j_L}/m^2_{\tilde{\nu}^i_L}\right)}{m^2_{\tilde{u}^j_L}-m^2_{\tilde{\nu}^i_L}}$$

This contribution helps in relaxing the flavor constraints!



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Das et al, Phys.Rev. D94 (2016) 055034

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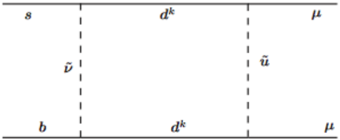

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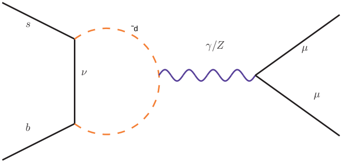

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Flavor constraints: $B - \bar{B}$ mixing

- $C_{LL}^{\mathrm{NP}\mu}$ depends on the product of couplings $\lambda'_{i3k}\lambda'^{*}_{i2k}$ which also contributes to $B_s - \bar{B}_s$ at one-loop mixing

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- Defining $C_{B_s} e^{2i\phi_{B_s}} = \langle B_s | H_{\mathrm{eff}}^{\mathrm{full}} | \bar{B}_s \rangle / \langle B_s | H_{\mathrm{eff}}^{\mathrm{SM}} | \bar{B}_s \rangle$:

$$C_{B_s} e^{2i\phi_{B_s}} = 1 + \frac{m_W^2}{g^4 S_0(x_t)} \left(\frac{1}{m^2_{\tilde{d}_R^k}} + \frac{1}{m^2_{\tilde{\nu}_L^i}} \right) \frac{\lambda'_{i3k}\lambda'^{*}_{i2k}\lambda'_{i'3k}\lambda'^{*}_{i'2k}}{(V_{tb}V_{ts}^{*})^2},$$

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- The latest UT*fit* values $C_{B_s} = 1.070 \pm 0.088$ and $\phi_{B_s} = (0.054 \pm 0.951)^\circ$

$$\left|\lambda'_{i3k}\lambda'^{*}_{i2k}\right| \lesssim \frac{0.13}{\left(1/m^2_{\tilde{d}^k_R} + 1/m^2_{\tilde{\nu}^i_L}\right)^{1/2}}, \quad \text{(masses are in TeV)}$$

Flavor constraints: $b \to s\nu\nu$

- The same set of couplings also induces $b \to s\nu\nu$ at tree-level via right-handed down-type squarks.
- The latest experimental data from Belle give $R_{B\to K(K*)\nu\bar{\nu}} < 3.9(2.7)$ at 90% confidence level where Belle Collab. 1702.03224

$$R_{\bar{B}\to K(K*)\nu\bar{\nu}} = \Gamma_{\rm RPV}(\bar{B} \to K(K^*)\nu\bar{\nu})/\Gamma_{\rm SM}(\bar{B} \to K(K^*)\nu\bar{\nu})$$

- Assuming one set of the product of couplings to be non-zero, the bounds on these couplings turn out to be

$$0.038 \left(\frac{m_{\tilde{d}_R}}{1\ \text{TeV}}\right)^2 \gtrsim (\lambda'_{23k}\lambda'^*_{22k} + \lambda'_{33k}\lambda'^*_{32k}) \gtrsim -0.079 \left(\frac{m_{\tilde{d}_R}}{1\ \text{TeV}}\right)^2,$$

$$0.055 \left(\frac{m_{\tilde{d}_R}}{1\ \text{TeV}}\right)^2 \gtrsim (\lambda'_{33k}\lambda'^*_{22k} + \lambda'_{23k}\lambda'^*_{32k}) \gtrsim -0.055 \left(\frac{m_{\tilde{d}_R}}{1\ \text{TeV}}\right)^2.$$

Other flavor constraints

- There is one more one additional set of couplings $\lambda^{'*}_{2jk}\lambda^{'}_{2jk}$ in $C^{NP}_{\rm LL}$.
- $\lambda^{'*}_{22k}\lambda^{'}_{22k}$ and $\lambda^{'*}_{23k}\lambda^{'}_{23k}$ contribute to $D^0 \to \mu^+\mu^-$, while $\lambda^{'*}_{33k}\lambda^{'}_{33k}$ and $\lambda^{'*}_{23k}\lambda^{'}_{23k}$ can be constrained from data on $bb \to \tau\tau(\mu\mu)$.

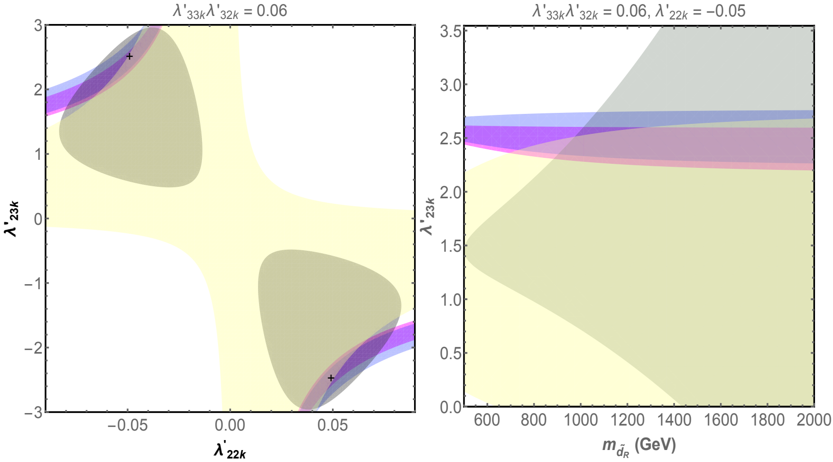
$$\lambda'^{*}_{22k}\lambda'_{22k} < 0.3 \left(m_{\tilde{d}_R}/1\ \text{TeV}\right)^2 ,$$

$$\lambda'^{*}_{23k}\lambda'_{23k} < \mathcal{O}(100) \left(m_{\tilde{d}_R}/1\ \text{TeV}\right)^2 ,$$

$$\lambda'^{*}_{33k}\lambda'_{33k}(\lambda'^{*}_{23k}\lambda'_{23k}) < \mathcal{O}(1)\,(m_{\tilde{u}_L}/1\ \text{TeV})^2 ,$$

Faroughy et al, Phys.Lett. B764 (2017) 126

Parameter space compatible with $b \to s\mu\mu$ data



Benchmark points: $m_{\tilde{u}} \sim 1$ TeV, $m_{\tilde{\nu}} \sim 600$ GeV and $m_{\tilde{d}} \sim 1.1$ TeV (for left plot)

For the above parameter space we find the range of $R_{K*,[0.045-1.1]}$ is [0.82-0.87] which is consistent with the LHCb measurement at the edge of 1σ.

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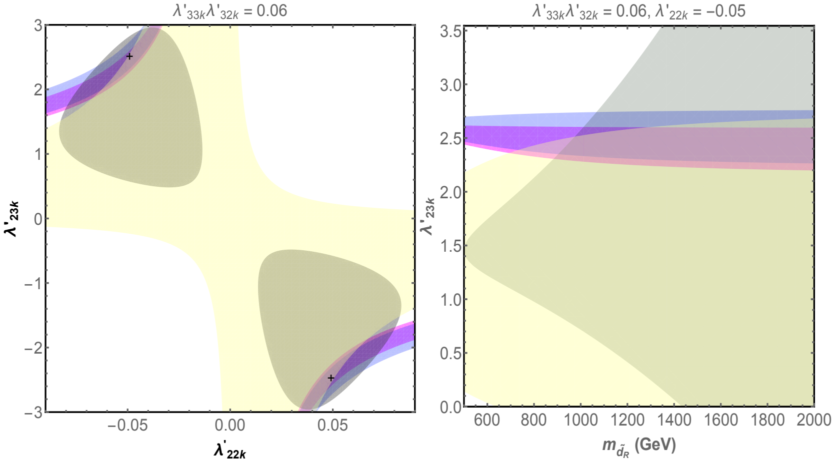

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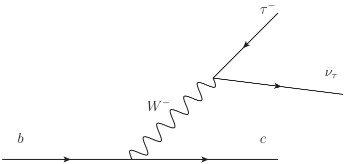
Comments on $R_{D(*)}$

- $\sim 4\,\sigma$ deviation from the SM in the ratio

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



Feynman diag. in the SM

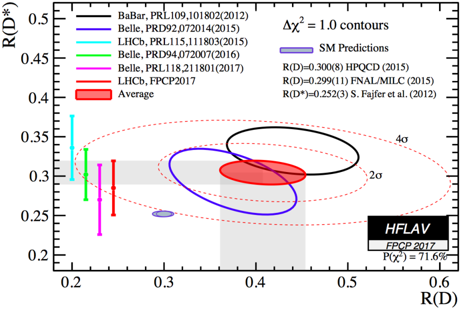


Fig. from http://www.slac.stanford.edu/xorg/hfag/

$$R_D^{\mathrm{SM}} = 0.300 \pm 0.008, \qquad R_D^{\mathrm{Exp.}} = 0.407 \pm 0.039 \pm 0.024,$$
$$R_{D*}^{\mathrm{SM}} = 0.252 \pm 0.003, \qquad R_{D*}^{\mathrm{Exp.}} = 0.304 \pm 0.013 \pm 0.007,$$

Comments on $R_{D^{(*)}}$

- $\mathcal{L}_{\rm int}^{\not R}$ contains $\sim \tilde{d}_R^{k*}\bar{\nu}_L^{ci} d_L^j - \tilde{d}_R^{k*}\bar{\ell}_L^{ci} u_L^j$ allowing for tree level contribution to $b \to c(u)\ell\nu$ transitions via the exchange of $\tilde{d}_R^k$.
- The minimal setup to explain these excesses is by invoking new physics in tau mode only (λ'_{3ik} only) and having muon and electron modes SM like. (N. Deshpande's and Bhupal Dev's talk)
- In this scenario, for region of the parameter space above consistent with R_K and R_{K*} we find that ratios R_D and R_{D*} to be almost SM like, while being in agreement with other $b \to c(u)\ell\nu$ data.

Conclusions

- We have explored the possibility of addressing these anomalies in the framework of R-parity violating interaction.
- We find that the tree level contributions to $b \to s\mu^+\mu^-$ transition are not enough to simultaneously yield $R_K < 1$ and $R_{K*} < 1$
- Beyond tree level, one-loop contributions generated by the exchange of $\tilde{d}_R$ and $\tilde{u}_L, \tilde{\nu}_L$ can lead to $R_K < 1$ and $R_{K*} < 1$ simultaneously consistent with the flavor constraints.
- The lower bin measurement of $R_{K*,[0.045-1.1]}$ can be partially resolved.
- A simultaneous explanation of LFU ratios related to $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ remains a challenge in this scenario.

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- Beyond tree level, one-loop contributions generated by the exchange of $\tilde{d}_R$ and $\tilde{u}_L, \tilde{\nu}_L$ can lead to $R_K < 1$ and $R_{K*} < 1$ simultaneously consistent with the flavor constraints.
- The lower bin measurement of $R_{K*,[0.045-1.1]}$ can be partially resolved.
- A simultaneous explanation of LFU ratios related to $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ remains a challenge in this scenario.

Thank you

Back-up

For benchmark point:
$\lambda'_{22k} = -0.05$, $\lambda'_{23k} = 2.49$,
$\lambda'_{32k} = 0.04$, $\lambda'_{33k} = 1.42$
with $m_{\tilde{d}} = 1.1$ TeV, $m_{\tilde{u}} = 1$ TeV and $m_{\tilde{\nu}} = 0.6$ TeV

$C_{LL}^{\mathrm{NP}\mu} = -1.14$, $R_K = 0.74$, $R_{K*,[1.1-6.0]} = 0.73$, and $R_{K*,[0.045-1.1]} = 0.84$,

$r(B \to D^{(*)}\tau\nu)$ and $r(B \to \tau\nu)$ to be ~ 1.04,

$R_{\bar{B}\to K(K*)\nu\bar{\nu}} = 1.12$, $R_\tau(c) = 1.08$, $R_\mu(c) = 1.09$,