Anomalous Semileptonic B Decays and New Flavor Physics

N.G. Deshpande
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and X-G He arXiv 1608.04817)

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Semi-leptonic B decays: Experiment vs. Standard Model

- The BABAR reported values are:

$$R^{\rm exp}(D) = \frac{\mathcal{BR}(B \to D\tau\nu)}{\mathcal{BR}(B \to Dl\nu)} = 0.440 \pm 0.072$$
$$R^{\rm exp}(D^*) = \frac{\mathcal{BR}(B \to D^*\tau\nu)}{\mathcal{BR}(B \to D^*l\nu)} = 0.332 \pm 0.030$$

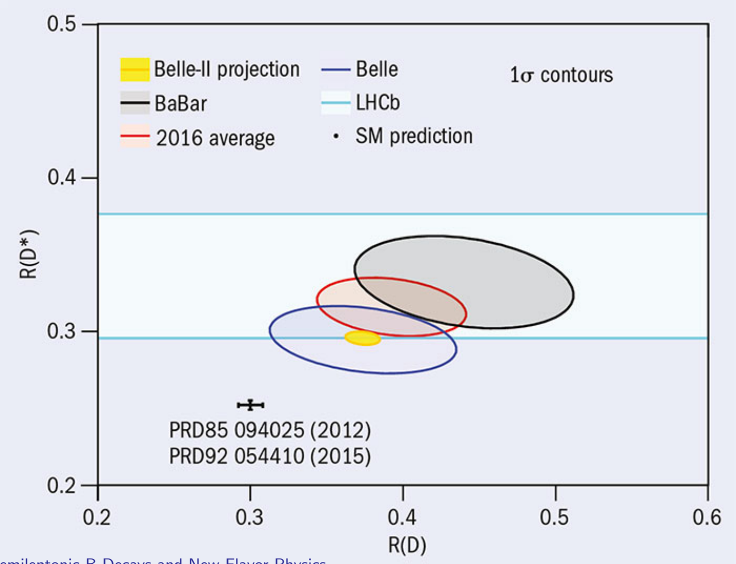
- Belle collaboration find :
  $R(D) = 0.375 \pm 0.069, R(D^*) = 0.293 \pm 0.04$
- LHCb find $R(D^*) = 0.336 \pm 0.042$
- Belle collaboration rate for the $B \to \tau\nu$ decay is

$$\mathcal{BR}(B \to \tau\nu) = (1.25 \pm 0.4) \times 10^{-4}.$$

- The expected SM values are:

$$R^{\rm SM}(D) = 0.297 \pm 0.017$$
$$R^{\rm SM}(D^*) = 0.252 \pm 0.003$$
$$\mathcal{BR}(B \to \tau\nu)^{\rm SM} = (0.753 \pm 0.1) \times 10^{-4}$$

Experimental situation and the future at Belle II)



Anomalies in $B \to K^* \mu^+ \mu^-$ Decay

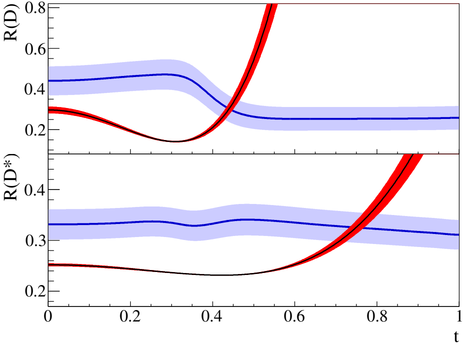
- LHCb analysis of 3 fb^{-1} data confirms 3 σ anomaly in two large K^*-recoil bins of angular observable P_5'.
- The observable $R_K = Br(B \to K\mu^+\mu^-)/Br(B \to Ke^+e^-)$ measured at LHCb in data in dilepton mass range 1 to 6 GeV^2 is $0.742^{+.09}_{-.074} \pm .036$ corresponding to 2.6σ deviation from SM value of 1
- Analysis of New Physics requires (based on Descotes-Genon,Hofer,Matias and Virto arXiv: 1605.06059)
  (a) $C_9^{NP} = -1.09$ or
  (b) $C_9^{NP} = -C_{10}^{NP} = -0.68$ or
  (c) $C_9^{NP} = -C_{9'}^{NP} = -1.06$
  all with almost same pull of 4.2 to 4.8

Charged Higgs Contributions to the Semi-leptonic Decays

$$R = R_{SM}(1 + 1.5 m_\tau \mathrm{Re}(g_{S_R} + g_{S_L}) + m_\tau^2 |g_{S_R} + g_{S_L}|^2)$$

$$R^* = R^*_{SM}(1 + 0.12 m_\tau \mathrm{Re}(g_{S_R} - g_{S_L}) + 0.05 m_\tau^2 |g_{S_R} - g_{S_L}|^2)$$

$$t = t_\beta / m_{H^+} (GeV^{-1})$$



General R-Parity Violating SUSY

- General Superpotential:

$$W_{\mathrm{RPV}} = \mu_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

- Imposing Z_3^B baryon symmetry leads to a proton stability and in the physical H_d basis

$$W = W_{\mathrm{MSSM}} + \frac{1}{2}\hat{\lambda}_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k^c + \hat{\lambda}'_{ijk}\hat{E}_i\hat{Q}_j\hat{D}_k^c$$

- Keeping only λ' term which is sufficient to explain the anomaly and has the correct structure to explain the q^2 distribution :

$$L = \lambda'_{ijk}\left[\tilde{\nu}_L^i \bar{d}_R^k d_L^j + \tilde{d}_L^j \bar{d}_R^k \nu_L^i + \tilde{d}_R^{k*} \bar{\nu}_L^{ci} d_L^j - \tilde{l}_L^i \bar{d}_R^k u_L^j - \tilde{u}_L^j \bar{d}_R^k l_L^i - \tilde{d}_R^{k*} \bar{l}_L^{ci} u_L^j\right],$$

Interactions of squark $\tilde{d}_R^k$ that lead to Semileptonic Decays

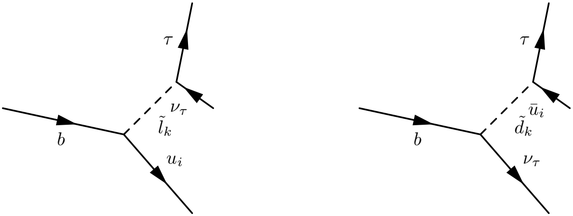
Working in the basis where down quarks are in their mass eigenstates, $Q^T = (V^{KM\dagger} u_L, d_l)$, one replaces u_L^j in the above by $(V^{KM\dagger} u_L)^j$. The leptons are in the weak basis. We will assume sfermions are in their mass eigenstate basis.

$$\mathcal{L}_{eff} = \frac{\lambda'_{ijk}\lambda'^{*}_{i'j'k}}{2m^2_{\tilde{d}_R^k}} \Big[\bar{\nu}_L^{i'}\gamma^\mu \nu_L^i \bar{d}_L^{j'}\gamma_\mu d_L^j + \bar{e}_L^{i'}\gamma^\mu e_L^i (\bar{u}_L V^{KM})^{j'}\gamma_\mu (V^{KM\dagger} u_L)^j - \nu_L^{i'}\gamma^\mu e_L^i \bar{d}_L^{j'}\gamma_\mu (V^{KM\dagger} u_L)^j - \bar{e}_L^{i'}\gamma^\mu \nu_L^i (\bar{u}_L V^{KM})^{j'}\gamma_\mu d_L^j \Big]$$

We assume flavor hierarchy for λ'_{ijk}

- We assume λ' for third generation is the largest because effects are more pronounced for third generation.
- We assume smaller λ' associated with second generation smaller because there are anomalies in B decays into muons
- We assume λ' associated with first generation are vanishingly small because no anomalies are known for particles associated with first generation
- To explain all anomalies we will be lead to $\lambda'_{333} \geq \lambda'_{233} \gg \lambda'_{323} \approx \lambda'_{223}$

Illustration of λ and λ' induced b-quark decays



A Simple Model

- Keeping only λ'_{333} for illustration we get

$$\mathcal{L}_{4f} \subset -V_{3m}^{\mathrm{KM}*}\left[\left(\frac{\lambda'_{333}\lambda'^{*}_{333}}{m^2_{\tilde{d}_3}}\right)(\bar{\tau}\gamma^\mu P_L \nu_\tau)(\bar{u}_m \gamma_\mu P_L b)\right] + \mathrm{h.c.}$$

- Due to $\Delta = \frac{\sqrt{2}}{4G_f}\frac{|\lambda'_{333}|^2}{2m^2_{\tilde{d}_3}}$ the enhancement to b decays is

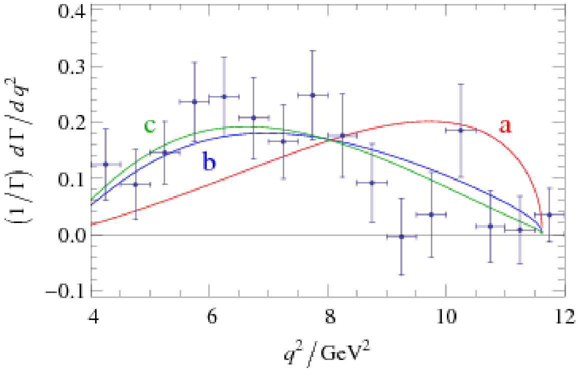
$$L_{\mathrm{EFF}} = -\frac{4G_f}{\sqrt{2}}\sum_{m=1,2} V_{3m}^{\mathrm{KM}}\left[1+\Delta\right](\bar{u}_m\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

Consequences of the simple model

$$-\left[\frac{4G_f}{\sqrt{2}}\right]^{-1} L_{\mathrm{EFF}} = V_{bc}^{\mathrm{KM}}\left[1+\Delta\right](\bar{c}\gamma^{\mu}P_L b)(\bar{\tau}\gamma^{\mu}P_L\nu_{\tau})$$
$$+V_{bu}^{\mathrm{KM}}\left[1+\Delta\right](\bar{u}\gamma^{\mu}P_L b)(\bar{\tau}\gamma^{\mu}P_L\nu_{\tau})$$

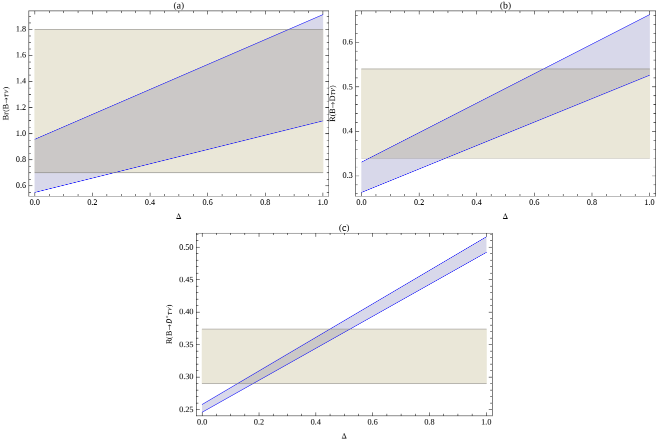
- $r(D, D^*) = Br(\bar{B} \to D\tau\bar{\nu})/Br(\bar{B} \to D\tau\bar{\nu})_{SM}$
  $= Br(\bar{B} \to D^*\tau\bar{\nu})/Br(\bar{B} \to D^*\tau\bar{\nu})_{SM} \approx 1 + 2\Delta.$
- $r(\rho, \pi) = Br(\bar{B} \to \rho\tau\bar{\nu})/Br(\bar{B} \to \rho\tau\bar{\nu})_{SM}$
  $= Br(\bar{B} \to \pi\tau\bar{\nu})/Br(\bar{B} \to \pi\tau\bar{\nu})_{SM}$
  $= Br(\bar{B} \to \tau\bar{\nu})/Br(\bar{B} \to \tau\bar{\nu})_{SM} \approx 1 + 2\Delta.$

q^2 Distribution of $B \to D^* \tau \nu$ Decay(Freytsis et.al)

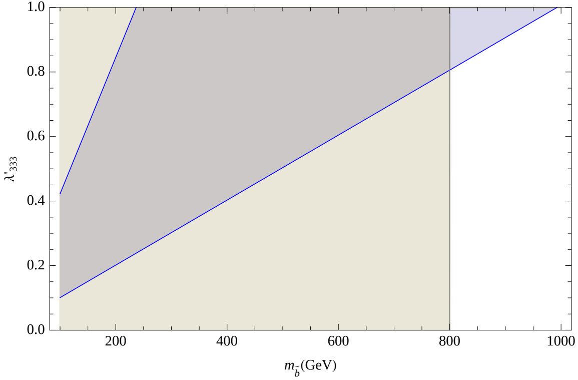


(a) right-handed vector (b) left-handed vector (c) scalar

Constraints on Δ

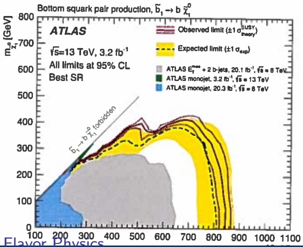


LHC Prospects and Constraints



- Large $\lambda'_{333} \Rightarrow$ R-parity violating decays $\tilde{t} \to bl^+$ and $\tilde{b} \to b\nu$ compete with the standard SUSY ones. LHC limits on $\tilde{b} \to b\chi_0$ apply to $\tilde{b} \to b\nu$ decay rate for mass $m_{\chi_0} = 0$

ATLAS 13 TeV limit on bottom squark



Loop Contributions to $b \to s\mu^+\mu^-$ From New Physics

New physics contributes to $b \to sl\bar{l}$ can be parametrized as $H_{eff}^{NP} = \sum C_i^{NP} O_i$.
Some of the most studied operators O_i are

$$O_9 = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_L b\bar{\mu}\gamma_\mu\mu \;, \qquad O_9' = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_R b\bar{\mu}\gamma_\mu\mu \;,$$
$$O_{10} = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_L b\bar{\mu}\gamma_\mu\gamma_5\mu \;, \quad O_{10}' = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_R b\bar{\mu}\gamma_\mu\gamma_5\mu \;, (1)$$

where $P_{L,R} = (1 \mp \gamma_5)/2$.
The SM predictions are $C_9^{SM} \approx -C_{10}^{SM} = 4.1$.

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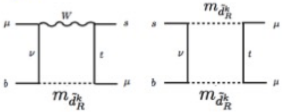
Loop contribution to b-> s $\mu^+\mu^-$

One needs to include one loop contributions. At one loop level, exchanging $\tilde{d}_R^k$ in the loop, contributions with $C_9^{NP} = -C_{10}^{NP}$ can be gener



$$C_9^{NP,ll'} \approx \frac{m_q^2}{8\pi}\frac{1}{m^2_{\tilde{d}_R^k}}\lambda'_{lbk}\lambda'^*_{l'mk}\frac{V_{qm}V^*_{ts}}{V_{tb}V^*_{ts}} - \frac{\sqrt{2}}{64\pi\alpha G_F}\frac{\ln(m^2_{\tilde{d}_R^k}/m^2_{\tilde{d}_R^{k'}})}{m^2_{\tilde{d}_R^k}-m^2_{\tilde{d}_R^{k'}}}\lambda'_{ibk}\lambda'^*_{isk'}\lambda'_{ljk'}\lambda'^*_{l'jk}\frac{1}{V_{tb}V^*_{ts}},$$

With $\lambda'_{1jk} = 0$ and $\lambda'_{i1k} = 0$

$$C_9^{NP,ll'} \approx \frac{m_t^2}{8\pi}\frac{1}{m^2_{\tilde{d}_R^k}}\lambda'_{l3k}\lambda'^*_{l'3k}$$

$$-\frac{\sqrt{2}}{64\pi\alpha G_F}\frac{1}{m^2_{\tilde{d}_R^3}}(\lambda'_{23k}\lambda'^*_{22k} + \lambda'_{33k}\lambda'^*_{32k})(\lambda'_{l2k}\lambda'^*_{l'2k} + \lambda'_{l3k}\lambda'^*_{l'3k})\frac{1}{V_{tb}V^*_{ts}}$$

$$= (10^{-3}\lambda'_{l3k}\lambda'^*_{l'3k} + 2.0(\lambda'_{23k}\lambda'^*_{22k} + \lambda'_{33k}\lambda'^*_{32k})(\lambda'_{l2k}\lambda'^*_{l'2k} + \lambda'_{l3k}\lambda'^*_{l'3k}))\frac{(1\text{TeV})^2}{m^2_{\tilde{d}_R^3}}.$$

Constraint on λ' from $D^0 \to \mu\mu$ Decay

$$H_{eff} = -\frac{1}{2m^2_{\tilde{d}^k_R}} C^k_{D\mu\mu} \mu_L \gamma_\mu \mu_L \bar{u}_L \gamma^\mu c_L \ ,$$

$$C^k_{D\mu\mu} = \lambda'_{2jk} \lambda'^*_{2j'k} V_{1j'} V^*_{2j}$$
$$= (\lambda'_{21k} V^*_{21} + \lambda'_{22k} V^*_{22} + \lambda'_{23k} V^*_{23})(\lambda'^*_{21k} V_{11} + \lambda'^*_{22k} V_{12} + \lambda'^*_{23k} V_{13}) \ .$$

λ'_{23k} is only very loosely constrained from $D^0 \to \mu + \mu^-$. If just λ'_{21k} or λ'_{22k} is non-zero, they are constrained as

$$\lambda'_{21k} \lambda'^*_{21k} \frac{(1\text{TeV})^2}{m^2_{\tilde{d}^k_R}}, \lambda'_{22k} \lambda'^*_{22k} \frac{(1\text{TeV})^2}{m^2_{\tilde{d}^k_R}} < 0.28 \ .$$

Constraint on λ' from $K \to \pi\nu\nu$ and $B \to K\nu\nu$ Decays

The contribution is given by the interaction:

$$\frac{\lambda'_{ijk}\lambda'^{*}_{i'j'k}}{2m^2_{\tilde{d}^k_R}}\bar{\nu}^{i'}_L\gamma^\mu\nu^i_L\bar{d}^{j'}_L\gamma_\mu d^j_L$$

For $K \to \pi\nu\bar{\nu}$, the ratio of $R_{K\to\pi\nu\bar{\nu}} = \Gamma_{RPV}/\Gamma_{SM}$ is given by:

$$R_{K\to\pi\nu\bar{\nu}} = \sum_{i=,e,\mu,\tau}\frac{1}{3}\left|1+\frac{\Delta^{RPV}_{\nu_i\bar{\nu}_i}}{X_0(x_t)V_{ts}V^*_{td}}\right|^2 + \frac{1}{3}\sum_{i\neq i'}\left|\frac{\Delta^{RPV}_{\nu_i\bar{\nu}_{i'}}}{X_0(x_t)V_{ts}V^*_{td}}\right|^2 ,$$

$$\Delta^{RPV}_{\nu_i\bar{\nu}_{i'}} = \frac{\pi s^2_W}{\sqrt{2}G_F\alpha}\left|\frac{\lambda'_{i2k}\lambda'^{*}_{i'1k}}{2m^2_{\tilde{d}^k_R}}\right|^2 , X_0(x) = \frac{x(2+x)}{8(x-1)} + \frac{3x(x-2)}{8(x-1)^2}\ln x ,$$

where $x_t = m_t^2/m_W^2$.

Constraint on λ' from $K \to \pi\nu\nu$ and $B \to K\nu\nu$ Decays continued

Using $Br(K \to \pi\nu\nu) = (1.7 \pm 1.1) \times 10^{-10}$, at 2σ level:
we find $\lambda'_{i2k}\lambda'^{*}_{i'1k} \leq 10^{-3}(m^2_{d^k_R}/(1\text{TeV})^2)$.

We will set $\lambda'^{*}_{i1k} = 0$, so that this process is not affected at tree level.
The expressions for $R_{\bar{B}\to\pi\nu\bar{\nu}}$ and $R_{\bar{B}\to K(K^*)\nu\bar{\nu}}$ of $\bar{B} \to \pi\nu\bar{\nu}$ and $\bar{B} \to K(K^*)\nu\bar{\nu}$ can be obtained f by replacing $V_{ts}V^*_{td}$ to $V_{tb}V^*_{td}$ and $V_{tb}V^*_{ts}$, respectively.
From $B \to K\nu\nu$ we find experimentally $\Gamma_{RPV}/\Gamma_{SM} \leq 4.3$
we find $\lambda'_{33k}\lambda'_{32k} \leq 0.07$
We will impose this constraint.

Best Fit Values for non vanishing $\lambda^{'}$ and predictions

Assume $m_{\tilde{d}} = 1\,TeV$
$\lambda'_{22k} = -1.35 \times 10^{-2}$
$\lambda'_{23k} = 1.88, \quad \lambda'_{32k} = -1.80 \times 10^{-2}\,, \;\; \lambda'_{33k} = 3.35\,.$

With this set of values, we have
$r(\bar{B} \to D^{(*)}\nu\bar{\tau})_{ave} = 1.265\,, \;\; C_9^{NP} = -0.604\,,$
$r(\bar{B} \to \tau\bar{\nu}) = 1.274 = r(\bar{B} \to \rho\bar{\tau}\nu)\,,$
$R_{\bar{B}\to K(K^*)\nu\bar{\nu}} = 4.238\,, \;\; R_\mu^{SM}(c) = 1.098\,.$

Here $r(\bar{B} \to D^{(*)}\nu\bar{\tau})_{ave} = Br(B \to D^{(*)}\nu\tau)_{EXPT}/Br(B \to \nu\tau)_{SM}$
and similarly for $r(\bar{B} \to \rho\nu\bar{\tau})$
$R_\mu^{SM}(c) = Br(B \to D^{(*)}\mu\nu)/Br_{SM}(B \to D^*\mu\nu)$

Consequences for $B \to K^* \tau^+ \tau^-$ and $B \to K^* \tau^\pm \mu^\mp$

The loops generating $b \to s\mu^+\mu^-$ interaction will also induce $b \to s\tau^+\tau^-, s\tau^\pm\mu^\mp$ interactions.

$$r^{\tau^+\mu^-} = \frac{C_9^{NP,\tau^+\mu^-}}{C_9^{NP,\mu^+\mu^-}} = \frac{\lambda'_{32k}\lambda'^*_{22k} + \lambda'_{33k}\lambda'^*_{23k}}{|\lambda'_{22k}|^2 + |\lambda'_{23k}|^2} \sim 1.80 \, ,$$

$$r^{\mu^+\tau^-} = \frac{C_9^{NP,\mu^+\tau^-}}{C_9^{NP,\mu^+\mu^-}} = \frac{\lambda'_{23k}\lambda'^*_{33k} + \lambda'_{22k}\lambda'^*_{32k}}{|\lambda'_{22k}|^2 + |\lambda'_{23k}|^2} \sim 1.80 \, ,$$

$$r^{\tau^+\tau^-} = \frac{C_9^{NP,\tau^+\tau^-}}{C_9^{NP,\mu^+\mu^-}} = \frac{|\lambda'_{33k}|^2 + |\lambda'_{32k}|^2}{|\lambda'_{22k}|^2 + |\lambda'_{23k}|^2} \sim 3.20 \, .$$

Present experimental upper limit is 2.25×10^{-3} for $\bar{B} \to K\tau^+\tau^-$. $\bar{B} \to K\tau^+\tau^-, K\tau^\pm\mu^\mp$ will be a spectacular confirmation of this theory.

$B_s - \bar{B}_s$ mixing and $b \to s\gamma$

$$C_{B_s} = \frac{\langle B_s | H_{eff}^{NP} | \bar{B}_s \rangle}{\langle B_s | H_{eff}^{SM} | \bar{B}_s \rangle}$$

$$= 1 + \frac{s_W^2}{\sqrt{2}\pi\alpha G_F S_0(x_t)} \frac{m_W^2}{m_{\tilde{d}_R^k}^2} \left(\frac{\lambda'_{23k}\lambda'^*_{22k} + \lambda'_{33k}\lambda'^*_{32k}}{V_{tb}V_{ts}^*} \right)^2 = 1.077 \, ,$$

$$C_{7\gamma} = C_{7\gamma}^{SM} + \left(\frac{v}{12 m_{\tilde{d}_R^k}} \right)^2 \frac{\lambda'_{23k}\lambda'^*_{22k} + \lambda'_{33k}\lambda'^*_{32k}}{V_{tb}V_{ts}^*} = C_{7\gamma}^{SM} - 0.001$$

The R-parity violating contribution to $C_{7\gamma}$ is small and can be neglected. The contribution to C_{B_s} is at a few percent level which is close to the central value of recent global fit.

CONCLUSIONS

We conclude that by a judicious choice of RPV couplings it is possible to reconcile both $R(D^{(*)})$ and $b \to s\mu^+\mu^-$ anomalies. In addition we are lead to unique predictions.

- $r(\rho, \pi) = Br(\bar{B} \to \rho\tau\bar{\nu})/Br_{SM}(\bar{B} \to \rho\tau\bar{\nu}) = Br(\bar{B} \to \pi\tau\bar{\nu})/Br_{SM}(\bar{B} \to \pi\tau\bar{\nu}) = Br(\bar{B} \to \tau\bar{\nu})/Br_{SM}(\bar{B} \to \tau\bar{\nu}) \approx 1.27$.
- Anomalies in $b \to s\tau^+\tau^-$ and $b \to s\tau^\pm\mu^\mp$ are large with $C_9^{NP,\tau\bar{\tau}}/C_9^{NP,\mu\bar{\mu}} \approx 3.18$, $C_9^{NP,\tau^\pm\mu^\mp}/C_9^{SM,\mu\bar{\mu}} \approx 1.78$
- The value for $R_{\bar{B}\to K(K^*)\nu\bar{\nu}}$ is close to its 90% C.L. upper bound of 4.3. Observation of this process at this level will be a confirmation of this model.
- The model requires $\tilde{d}_R^k$ squark should have a mass not much larger than 1 TeV. Such a low mass should be able to be detected at the LHC soon.