

Right handed sneutrino effect on the $b \rightarrow c\bar{\nu}_l$ decays

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New Physics Beyond The SM

The SM provides a complete description of the three interactions is possible in terms of a well-defined gauge theory, based on the gauge symmetry group

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y.$$

- It does not incorporate the physics of general relativity, such as gravitation.
- The theory does not contain any viable dark matter particle that required for observational cosmology.
- It doesn't allow for neutrino masses \Rightarrow It can't be valid at energy scales above $M_{\text{seesaw}} \sim 10^{15}$ GeV.
- Gauge coupling unification: NP (SUSY) close to EW scale.

Therefore, the SM is only an effective low energy theory.

SUSY Models

- Minimal Supersymmetric Standard Model (MSSM) \Rightarrow minimal particle content compatible with the Standard Model particles and properties, based on the gauge symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- $U(1)_{B-L}$ extension of MSSM (BLSSM), based on the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$ where the MSSM is extended by:
 - ▶ two chiral singlet superfields $\eta_{1,2}$ with $B - L$ charge $= \pm 1$
 - ▶ three chiral singlet superfields $\hat{\nu}_i^c$ with $B - L$ charge $= -1$
- BLSSM with Inverse Seesaw (BLSSM-IS) mechanism is implemented by:
 - ▶ three singlet fermions S_1 with $B - L$ charge $= -2$
 - ▶ three singlet fermions S_2 with $B - L$ charge $= +2$
- The superpotential of this model is given by:

$$W = Y_u \hat{Q} \hat{H}_2 \hat{U}^c + Y_d \hat{Q} \hat{H}_1 \hat{D}^c + Y_e \hat{L} \hat{H}_1 \hat{E}^c + Y_\nu \hat{L} \hat{H}_2 \hat{\nu}^c + Y_S \hat{\nu}^c \hat{\chi}_1 \hat{S}_2 + \mu \hat{H}_1 \hat{H}_2 + \mu' \hat{\eta}_1 \hat{\eta}_2.$$

Right-handed sneutrinos and neutralinos

- Two right-handed sneutrinos could be light (of order few hundred GeV)
 - ▶ one from each of CP-even and CP-odd sneutrinos
- The neutralinos $\tilde{\chi}_i^0$ ($i = 1, \dots, 7$) in the BLSSM-IS are the physical (mass) superpositions where the lightest neutralino has the following decomposition:

$$\tilde{\chi}_1^0 = V_{11} \tilde{B} + V_{12} \tilde{W}^3 + V_{13} \tilde{H}_1^0 + V_{14} \tilde{H}_2^0 + V_{15} \tilde{B}' + V_{16} \tilde{\eta}_1 + V_{17} \tilde{\eta}_2.$$

- Here we analyze the SUSY contributions to $b \rightarrow c l \bar{\nu}_l$ transition ($l = e, \mu, \tau$)
- We are interesting in the processes $\tilde{B} \rightarrow D(D^*) l \bar{\nu}_l$ and $\tilde{B} \rightarrow J/\psi l \bar{\nu}_l$

Observables

- The observables $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are defined as:

$$\mathcal{R}(D) = \frac{\text{BR}(\bar{B} \rightarrow D \tau \bar{\nu}_\tau)}{\text{BR}(\bar{B} \rightarrow D l \bar{\nu}_l)}, \quad \mathcal{R}(D^*) = \frac{\text{BR}(\bar{B} \rightarrow D^* \tau \bar{\nu}_\tau)}{\text{BR}(\bar{B} \rightarrow D^* l \bar{\nu}_l)}$$

refers to either **electron** or **muon**

- Also, $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ can be defined as:

$$\mathcal{R}(D) = \frac{\Gamma(\bar{B} \rightarrow D \tau \nu_\tau)}{\Gamma(\bar{B} \rightarrow D l \nu_l)} = \frac{\int_{m_l^2}^{(m_B - m_D)^2} \frac{d\Gamma_\tau^D}{dq^2} dq^2}{\int_{m_l^2}^{(m_B - m_D)^2} \frac{d\Gamma_l^D}{dq^2} dq^2}$$

$$\mathcal{R}(D^*) = \frac{\Gamma(\bar{B} \rightarrow D^* \tau \nu_\tau)}{\Gamma(\bar{B} \rightarrow D^* l \nu_l)} = \frac{\int_{m_l^2}^{(m_B - m_{D^*})^2} \frac{d\Gamma_\tau^{D^*}}{dq^2} dq^2}{\int_{m_l^2}^{(m_B - m_{D^*})^2} \frac{d\Gamma_l^{D^*}}{dq^2} dq^2}$$

Experimental Results

The SM predictions for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are

- $\mathcal{R}(D)^{SM} = 0.299 \pm 0.003, \quad \mathcal{R}(D^*)^{SM} = 0.258$

The experimental values for $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ reported by the experimental collaborations and HFLAV group are

- $\mathcal{R}(D)^{Belle} = 0.375 \pm 0.064 \pm 0.026, \quad \mathcal{R}(D^*)^{Belle} = 0.283 \pm 0.018 \pm 0.014$
 $\mathcal{R}(D)^{Belle} = 0.307 \pm 0.037 \pm 0.016, \quad \mathcal{R}(D^*)^{Belle} = 0.293 \pm 0.038 \pm 0.015$
 $\mathcal{R}(D^*)^{Belle} = 0.270 \pm 0.035^{+0.028}_{-0.025}$
- $\mathcal{R}(D)^{BABAR} = 0.440 \pm 0.058 \pm 0.042, \quad \mathcal{R}(D^*)^{BABAR} = 0.332 \pm 0.024 \pm 0.018$
- $\mathcal{R}(D^*)^{LHCb} = 0.336 \pm 0.027 \pm 0.030$
 $\mathcal{R}(D^*)^{LHCb} = 0.283 \pm 0.019 \pm 0.029$
- $\mathcal{R}(D)^{HFLAV} = 0.339 \pm 0.026 \pm 0.019, \quad \mathcal{R}(D^*)^{HFLAV} = 0.295 \pm 0.010 \pm 0.010$
- The HFLAV results deviate from the SM expectations by 1.9σ and 3.2σ , respectively.
- These deviations, if confirmed, could be important hints for NP.

New physics effective operators

- The effective Hamiltonian for $b \rightarrow c l \bar{\nu}_l$ is given by

$$\begin{aligned} \mathcal{H}_{\text{eff}} = & \frac{4G_F V_{cb}}{\sqrt{2}} \left[(1 + g_{VL}) [\bar{c} \gamma_\mu P_L b] [\bar{l} \gamma_\mu P_L \nu_l] \right. \\ & + g_{VR} [\bar{c} \gamma_\mu P_R b] [\bar{l} \gamma_\mu P_L \nu_l] + g_{SL} [\bar{c} P_L b] [\bar{l} P_L \nu_l] \\ & \left. + g_{SR} [\bar{c} P_R b] [\bar{l} P_L \nu_l] + g_T [\bar{c} \sigma^{\mu\nu} P_L b] [\bar{l} \sigma_{\mu\nu} P_L \nu_l] \right] \end{aligned}$$

where $g_i = \frac{C_i^{\text{SUSY}}}{C_{\text{SM}}^{\text{SM}}}$, $C_{\text{SM}}^{\text{SM}} = \frac{4G_F V_{cb}}{\sqrt{2}}$, $P_{L,R} = (1 \mp \gamma_5)/2$.

Expressions of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

- After using the explicit formulae of the hadronic and leptonic amplitudes and upon fixing the SM parameters, we obtain

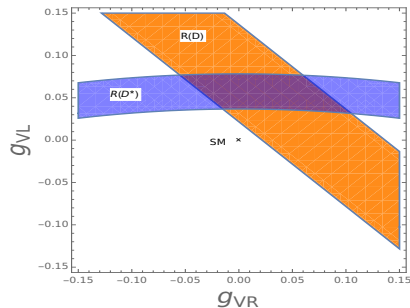
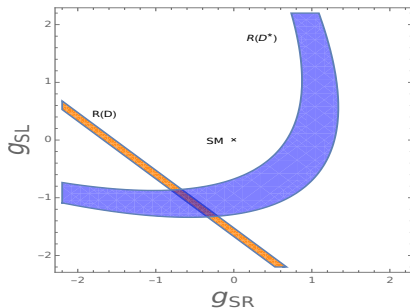
$$\begin{aligned} \mathcal{R}(D) = \mathcal{R}(D)^{\text{SM}} & \left[0.981 |g_{SR} + g_{SL}|^2 + |1 + g_{VL} + g_{VR}|^2 + 0.811 |g_T|^2 \right. \\ & \left. + 1.465 \text{Re}[(1 + g_{VL} + g_{VR})(g_{SR} + g_{SL})^*] + 1.074 \text{Re}[(1 + g_{VL} + g_{VR})g_T^*] \right] \end{aligned}$$

$$\begin{aligned} \mathcal{R}(D^*) = \mathcal{R}(D^*)^{\text{SM}} & \left[0.025 |g_{SR} - g_{SL}|^2 + |1 + g_{VL}|^2 + |g_{VR}|^2 + 16.739 |g_T|^2 \right. \\ & + 0.094 \text{Re}[(1 + g_{VL} + g_{VR})(g_{SR} - g_{SL})^*] + 6.513 \text{Re}[g_{VR}g_T^{*}] \\ & \left. - 4.457 \text{Re}[(1 + g_{VL})g_T^*] - 1.748 \text{Re}[(1 + g_{VL})g_{VR}^*] \right] \end{aligned}$$

- The above expressions provide the explicit dependence of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ on the Wilson coefficients

$b \rightarrow c \tau \bar{\nu}_\tau$ Sensitivity to New Physics

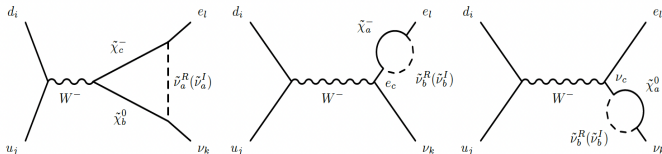
- In case of a dominant scalar contribution, $\mathcal{R}(\mathcal{D}^*)$ cannot be significantly larger than the SM expectation unless $g_{SR} - g_{SL}$ is larger than one (i.e., $C_S^{NP} > C_{SM}$), which is not possible



- The allowed regions in the (g_{SL}, g_{SR}) and (g_{VL}, g_{VR}) planes by the 1σ experimental results on $\mathcal{R}(\mathcal{D})$ and $\mathcal{R}(\mathcal{D}^*)$

Right Handed Sneutrino effect on $b \rightarrow c l \bar{\nu}_l$ decays

- BLSSMIS provides new contributions from the penguins and lepton self energy diagrams involving the right-handed sneutrinos
- The first diagram represents the dominant contributions and the relevant Wilson coefficient



Right Handed Sneutrino effect on $b \rightarrow c l \bar{\nu}_l$ decays

- The relevant Wilson coefficient can be found as

$$C_{VL}^{\tilde{\nu}^{R(l)}} = \frac{\Gamma_{\tilde{\chi}_k^0 \nu_l \tilde{\nu}_i^{R(l)}}^L \Gamma_{\tilde{l} \tilde{\chi}_j^- \tilde{\nu}_i^{R(l)}}^R \Gamma_{\tilde{c} b W^-}^L}{16\pi^2 M_{W^\pm}^2} \left[\Gamma_{\tilde{\chi}_j^+ \tilde{\chi}_k^0 W^-}^{R(l)} m_{\tilde{\chi}_j^-} m_{\tilde{\chi}_k^0} C_0(m_{\tilde{\chi}_k^0}^2, m_{\tilde{\chi}_j^-}^2, m_{\tilde{\nu}_i^{R(l)}}^2) \right. \\ \left. - \Gamma_{\tilde{\chi}_j^+ \tilde{\chi}_k^0 W^-}^L (B_0(m_{\tilde{\chi}_j^-}^2, m_{\tilde{\chi}_k^0}^2) - 2C_{00}(m_{\tilde{\chi}_k^0}^2, m_{\tilde{\chi}_j^-}^2, m_{\tilde{\nu}_i^{R(l)}}^2)) \right. \\ \left. + m_{\tilde{\nu}_i^{R(l)}}^2 C_0(m_{\tilde{\chi}_k^0}^2, m_{\tilde{\chi}_j^-}^2, m_{\tilde{\nu}_i^{R(l)}}^2) \right]$$

- For our numerical analysis, $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ are defined as.

$$\mathcal{R}(D) = \frac{\Gamma_\tau^D}{\Gamma_e^D}, \quad \mathcal{R}(D^*) = \frac{\Gamma_\tau^{D^*}}{\Gamma_e^{D^*}},$$

Right Handed Sneutrino effect on $b \rightarrow cl\bar{\nu}_l$ decays

$\mathcal{R}(\mathcal{D})$ and $\mathcal{R}(\mathcal{D}^*)$ are constrained by:

- The leptonic decays of W boson

$$\frac{\Gamma(W \rightarrow \tau\nu)}{\Gamma(W \rightarrow e\nu)} = 1.043 \pm 0.024, \quad \frac{\Gamma(W \rightarrow \tau\nu)}{\Gamma(W \rightarrow \mu\nu)} = 1.07 \pm 0.026$$

- τ decays

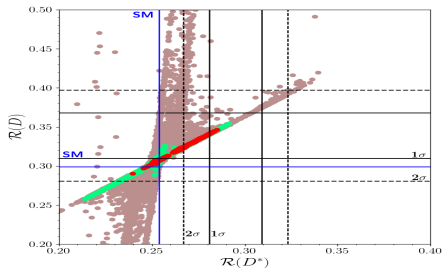
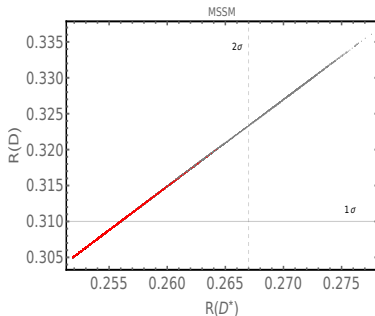
$$\frac{\Gamma(\tau \rightarrow \mu\nu_\tau\nu_\mu)}{\Gamma(\tau \rightarrow e\nu_\tau\nu_e)} = 0.979 \pm 0.004$$

- SUSY mass bounds

- The rare $B_s \rightarrow X_s\gamma$ and $B_s \rightarrow \mu^+\mu^-$ decay modes

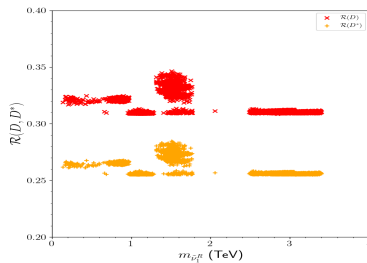
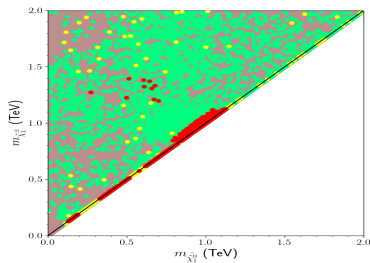
- The current limits on the LFV processes as $l_i \rightarrow l_j\gamma$

Right Handed Sneutrino effect on $b \rightarrow cl\bar{\nu}_l$ decays



- The correlation between $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, (left) in the MSSM and (right) in the BLSSMIS. Here, all points are compatible with EWSB. Green points also satisfy the SUSY mass bounds and the constraints from $B_s \rightarrow \mu^+ \mu^-$ and $B_s \rightarrow X_s \gamma$.
- The red points form a subset of the green ones they are also consistent with LFV and LFU constraints. The horizontal (vertical) black solid and dashed lines show the 1σ and 2σ ranges of the experimental measurements of $\mathcal{R}(D)$ ($\mathcal{R}(D^*)$), respectively, while the blue line indicates the SM value.

Right Handed Sneutrino effect on $b \rightarrow c l \bar{\nu}_l$ decays



- $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ in correlation with the lightest chargino and neutralino (left) as well as right-handed sneutrino (right) masses. In the $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ plane. The colors are the same.

Conclusion

- We analyzed the SUSY implications in the flavor violating processes $B \rightarrow D l \bar{\nu}_l$ and $B \rightarrow D^* l \bar{\nu}_l$
- We have found that the BLSSM-IS is able to explain within 1σ the (averaged) measured values of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$, in presence of experimental constraints on its EW, SUSY and flavour sectors, notably including those from LFU and LFV observables.
- Our results might then be taken as a circumstantial evidence of SUSY. They might pave the way to its direct discovery as they point to spectra in the sparticle sector of the BLSSMIS that can be accessed at Run 3.

Thank you