Study of rare mesonic decays involving di-neutrinos in their final state

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Abstract

We have carried out phenomenological implication of R-parity violating (R_p) Minimal Supersymmetric Model (MSSM) via analyses of pure leptonic (M → ν¯ν) and semileptonic decays of pseudo-scalar mesons (M → Xνν). These analyses involve prediction of branching fraction of pure leptonic decays by using experimental limits/bounds derived from the study of semileptonic decays on R_p parameters. We have found, in general that R_p contribution dominates over the SM contribution i.e., by a factor of 10^2 for the semileptonic decays of K^0, 10 for the pure leptonic decays of K_L,S, while 10^2 & 10^4 in case of B_s and B_d respectively. This demonstrates the role of R_p as a viable model for the study of NP contribution in rare decays.

1 INTRODUCTION

Flavor changing neutral currents (FCNC) that mediate different flavored fermions (quarks) of the same charge are one of the most important tools searching for physics beyond the Standard Model (SM). This is due to their rarity owing to GIM mechanism[1]. Whereas, FCNC processes involving leptons are strictly forbidden in SM due to lepton family number conservation contrary to established experimental facts[2][3], such processes can only be accommodated through physics beyond the SM, named as New physics (NP). However, lepton flavor conserving processes can proceed through both universal and non-universal weak neutral current interactions. Here universal weak neutral current interactions correspond to the SM interactions, which are flavor as well as generation blind and Non-universal weak neutral current interaction represents NP interaction which are flavour as well as generation sensitive. Analyses of such type of processes are good for comparative study of different Models. In this paper, we have presented one class of such type of pure leptonic and semileptonic decays...
of pseudoscalar mesons involving di-neutrinos in their final state in the framework of SM and R-parity violating supersymmetric model.

Leptonic and semileptonic decays of beauty and strange mesons have played an important role in measuring parameters related to Cabibbo-Kobayashi-Maskawa (CKM), unitary angles and also in probing CP-violation\[^4\]. Many New Physics (NP) models like 2HDM \[^5\] and R\_p MSSM,\[^6\] have been explored in these processes\[^7\] as well. Super B-factories\[^8\] also hold a lot of potential in this regard. LHC B also holds a lot of promise for discovering prospects of new physics in B decays\[^9\].

The Minimal Supersymmetric Standard Model (MSSM) \[^10\] is the most economical version of SUSY. It is also the minimal extension of SM\[^10\]. MSSM allows processes that violate baryon and lepton number. It also allows LFV processes. R-parity, a discrete symmetry is imposed to prevent baryon number, lepton number and flavor violating processes. It is defined as \(R_p = (-1)^{3B+L+2S}\[^11\]. R-parity conservation is phenomenologically motivated and if relaxed carefully allows one to analyze rare and forbidden decays while maintaining the stability of matter\[^12\]. The R-parity violating gauge invariant and renormalizable superpotential is\[^11\]

\[
W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k + \mu_i H_u L_i, \tag{1}
\]

where \(i, j, k\) are generation indices, \(L_i\) and \(Q_i\) are the lepton and quark left-handed \(SU(2)_L\) doublets and \(E^c, D^c\) are the charge conjugates of the right-handed leptons and quark singlets, respectively. \(\lambda_{ijk}, \lambda'_{ijk}\) and \(\lambda''_{ijk}\) are Yukawa couplings. The term proportional to \(\lambda_{ijk}\) is antisymmetric in first two indices \([i, j]\) and \(\lambda''_{ijk}\) is antisymmetric in last two indices \([j, k]\), implying \(9(\lambda_{ijk}) + 27(\lambda'_{ijk}) + 9 \left(\lambda''_{ijk}\right) = 45\) independent coupling constants among which 36 are related to the lepton flavor violation (9 from \(LLE^c\) and 27 from \(LQD^c\)). We can rotate the last term away without affecting things of our interest.

In this scenario for detailed illustration we will use the pure and semileptonic rare decays of pseudoscalar mesons with missing energy i.e. \(B^0 \to \nu_\alpha \bar{\nu}_\beta, B^{\pm,0} \to M^{\pm,0} \nu_\alpha \bar{\nu}_\beta\) and \(B^X \to M^{\pm,0} \nu_\alpha \bar{\nu}_\beta\); where \(M = \pi, K\) and subscript \(X = S, C\). At the quark level all \(B^X \to M^{\pm,0} \nu_\alpha \bar{\nu}_\beta\) decays are represented by \(b \to q \nu_\alpha \bar{\nu}_\beta\) \((q = d, s)\), and (all these processes can be) divided into two categories on the bases of lepton flavors i.e.

1. lepton flavor conserving \((\alpha = \beta)\)
2. lepton flavor violating \((\alpha \neq \beta)\) decays.

The first type of decays \(b \to q \nu_\alpha \bar{\nu}_\alpha\) \((\alpha = e, \mu, \tau)\) are absent in the SM at tree level, however are induced by GIM mechanism\[^1\] at the quantum loop level\[^16\] which makes their effective strength very small, further suppression caused by the weak mixing angles of the quark flavor rotation matrix, called Cabibbo-Kobayashi-Maskawa (CKM) matrix \[^17\]. These two suppressions make FCNC decays very rare. Further-more these processes will provide indirect test of high energy scales through a low energy process. Such type of processes having only short distance dominant contribution whereas, long distance contribution
is subleading\[13\]. As we are taking pure and semileptonic decays, which can be accurately predicted in the standard model (SM) due to the fact that the only relevant hadronic operators are just the current operators whose matrix elements can be extracted from their respective leading decays \[15\].

The second type of decays $b \rightarrow q \nu_\alpha \bar{\nu}_\beta$ ($(\alpha \neq \beta; \alpha, \beta = e, \mu, \tau)$ are strictly forbidden to all orders in the SM due to lepton flavour violation, so the only possible explanation for these type of processes is Non Standard/ New interactions. Hence one can say that these are the "golden channels" for the study of New Physics.

In this paper, we have analyzed above mentioned decays in the SM (first case) and then in $R_p$ violating MSSM. Our focus is to predict the branching fraction (in some cases) and NP parameters and to develop the relationship between the parameters of different models. In the forthcoming section, we will discuss these processes one by one.

2 $s \rightarrow d\nu_\alpha \bar{\nu}_\alpha$

The effective Hamiltonian for the semileptonic($K \rightarrow \pi\nu_\alpha \bar{\nu}_\alpha$, $K \rightarrow \pi^0\nu_\alpha \bar{\nu}_\alpha$) and pure leptonic $K_{L,S} \rightarrow \nu_\alpha \bar{\nu}_\alpha$ processes is given by\[14\]

\[
H_{\text{eff}} = \sum_l C_{SM}(\bar{s}d)_{V-A}(\bar{\nu}_l\nu_l)V_{\text{eff}}^{V-A}(2)
\]

In this case all leptons couple universally with the electroweak gauge bosons.

where

$$C_{SM} = \frac{G_F}{2\sqrt{2}\sin^2\theta_W}(V_{cs}^*V_{cd}X_{NL}^l + V_{ts}^*V_{td}X(x_t))$$

and

$$X(x_t) = X_0(x_t) + \frac{\alpha_S}{4\pi}X_1(x_t)$$

and

$$x_t = \frac{\tilde{m}_t(m_t)}{M_W}, \quad \mu_t = O(m_t).$$

In MSSM the relevant effective Lagrangian for the decay process $K \rightarrow \pi\nu_\alpha \bar{\nu}_\alpha$ is given by\[15\]

\[
L_{\text{eff}}^{R_p} (s \rightarrow d + \nu_\alpha + \bar{\nu}_\alpha) = \frac{4G_F}{\sqrt{2}} \left[ A_{\alpha\beta}^{sd} (\bar{\nu}_\alpha \gamma^\mu P_L\nu_\beta) (\bar{d}\gamma_\mu P_Rs) \right].
\]

Where $\alpha = e, \mu$. The first term in eq. (2) comes from the down squark exchange (where $d$ and $s$ are down type quarks). The dimensionless coupling constant $A_{\alpha\beta}^{sd}$ is given by

\[
A_{\alpha\beta}^{sd} = \frac{\sqrt{2}}{4G_F} \sum_{k=1}^{3} \frac{\lambda_{\alpha k1}^*\lambda_{\beta k2}^*}{2m_k^2}.
\]

The differential decay rate for semileptonic decay processes is given by

\[
\frac{d\Gamma}{dq^2} = \frac{1}{2\pi s^{3/2}} f_p^+(q^2) |f_p(q^2)|^2 |C_l|.
\]

3
where, $C_l = C_{SM} + C_{R_p}$ with $C_{R_p} = \frac{\lambda_{a1}^{\prime} \lambda_{a2}^{\prime \ast}}{m^2_{d_k}}$

The decay rate for pure leptonic decay processes is given by

$$\Gamma(s \to d\nu\bar{\nu}) = \frac{1}{8\pi} \frac{m_3^3}{m_K} \left| f_p(q^2) \right|^2 \left| \frac{2m_l}{m_K} C_l \right|^2 \tag{6}$$

### 3 $b \to d(s)\nu_\alpha \bar{\nu}_\alpha$

In MSSM, the relevant effective Lagrangian for the decay process $B \to \pi(K)\nu_\alpha\bar{\nu}_\alpha$ is given by [15]

$$L_{eff}^{\prime} (b \to d(s) + \nu_\alpha + \bar{\nu}_\alpha) = \frac{4G_F}{\sqrt{2}} \left[ A_{\alpha\alpha}^b (s) (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha) (\bar{b}\gamma_\mu P_R d(s)) \right]. \tag{7}$$

Where $\alpha = e, \mu$. The first term in eq. (2) comes from the down squark exchange (where $b$ and $d(s)$ are down type quarks). The dimensionless coupling constant $A_{\alpha\alpha}^b (s)$ is given by

$$A_{\alpha\alpha}^b (s) = \frac{\sqrt{2}}{4G_F} \sum_{k=1}^{3} \frac{\lambda_{a1}^{\prime}(1) \lambda_{a2}^{\prime \ast}}{2m_{d_k}}. \tag{8}$$

The differential decay rate for semileptonic decay processes is given by

$$\frac{d\Gamma}{dq^2} = \frac{1}{2\pi^3} \chi^{3/2}(1, r, s) m_B^3 \left| f_p(q^2) \right|^2 \left| C_l \right| \tag{9}$$

where

$$C_l = C_{SM} + C_{R_p}$$

with

$$C_{SM} = \frac{G_F}{2\sqrt{2} \sin^2 \theta_w} (V_{cb}^* V_{cd}(s)) X_{NL}^l + V_{tb}^* V_{td}(s) X(x_t))$$

with

$$X(x_t) = X_0 (x_t) + \frac{\mu_t}{m_t^2} X_t (x_t) \text{ and } x_t = \frac{\bar{m}_t^2}{m_t^2}, \mu_t = O(m_t).$$

and

$$C_{R_p} = \frac{\lambda_{a1}^{\prime}(1) \lambda_{a2}^{\prime \ast}}{m^2_{d_k}}$$

The decay rate for pure leptonic decay processes is given by

$$\Gamma (b \to d(s)\nu_\alpha \bar{\nu}_\alpha) = \frac{1}{8\pi} \frac{m_3^3}{m_B^3} \left| f_p(q^2) \right|^2 \left| \frac{2m_l}{m_B} C_l \right|^2 \tag{10}$$
4 Results And Discussions

We have carried out analysis of hypercharge changing two and three body decay processes of pseudoscalar mesons ($M \to X\nu\bar{\nu}; M \to \nu\bar{\nu}$) where $M = K, B$ and $X = \pi, K$. The feynman diagrams and table listing experimental data related to these processes are given in Fig. (1) and Table [I] respectively.

Figure 1: Feynman diagrams of (a) $b \to s\nu_{\alpha} \bar{\nu}_{\alpha}$ (b) $b \to d\nu_{\alpha} \bar{\nu}_{\alpha}$ (c) $s \to d\nu_{\alpha} \bar{\nu}_{\alpha}$
Table 1: Table listing the property of processes under discussion

| Process       | Experimental Measurement | SM Prediction | Bounds on New Physics Parameter |
|---------------|--------------------------|---------------|---------------------------------|
| $B \rightarrow \pi \nu \bar{\nu}$ | $< 9.8 \times 10^{-5}$   | 1.62x10^{-7}  | $< 1.79 \times 10^{-6}$         | $\leq 2\pi$ |
| $B_s^0 \rightarrow \nu \bar{\nu}$ | $6.13 \times 10^{-31}(e)$ | 4.57x10^{-27}(\mu) | 5.91x10^{-25}(\tau) | $\leq 2\pi$ |
| $B \rightarrow K \nu \bar{\nu}$ | $< 1.6 \times 10^{-5}$   | 4.40x10^{-6}  | $< 8.69 \times 10^{-7}$         | $\leq 2\pi$ |
| $B_d^0 \rightarrow \nu \bar{\nu}$ | $1.36 \times 10^{-30}(e)$ | 1.02x10^{-26}(\mu) | 1.32x10^{-23}(\tau) | $\leq 2\pi$ |
| $K^\pm \rightarrow \pi^\pm \nu \bar{\nu}$ | $(1.7 \pm 1.0) \times 10^{-10}$ | 8.23x10^{-11} | $(7.83 \pm 2.01) \times 10^{-9}(e)$ | $(7.83 \pm 2.01) \times 10^{-9}(\mu)$ | $(7.81 \pm 2.01) \times 10^{-9}(\tau)$ | $\leq 2\pi$ |
| $K_s^0 \rightarrow \nu \bar{\nu}$ | $7.24 \times 10^{-33}(e)$ | 5.40x10^{-29}(\mu) | 6.98x10^{-26}(\tau) | $\leq 2\pi$ |
| $K_L^0 \rightarrow \nu \bar{\nu}$ | $4.27 \times 10^{-33}(e)$ | 3.19x10^{-29}(\mu) | 4.06x10^{-26}(\tau) | $\leq 2\pi$ |
| $K^0 \rightarrow \pi^0 \nu \bar{\nu}$ (Bounds on New Physics parameter has been calculated numerically for their fit with SM prediction) | $< 2.6 \times 10^{-8}$ | 2.76x10^{-11} | $\leq 1.9 \times 10^{-9}$ | 15° |
|               |                          |               | $\leq 9.83 \times 10^{-10}$ | 30° |
|               |                          |               | $\leq 6.96 \times 10^{-10}$ | 45° |
|               |                          |               | $\leq 5.68 \times 10^{-10}$ | 60° |
|               |                          |               | $\leq 5.09 \times 10^{-10}$ | 75° |
|               |                          |               | $\leq 4.92 \times 10^{-10}$ | 90° |

First, we will discuss the results related to semileptonic decay processes followed by pure leptonic decays. We have plotted graphs in Figs. (2 and 3) for the study of process $K \rightarrow \pi \nu \bar{\nu}$. These plots relate the branching fraction of the said process with the magnitude and phase of New Physics(NP) parameters($z(\lambda^\prime_{i11} \lambda^\prime_{k22})$ and $\theta$). Plots in Fig. (2) represent the allowed region for NP parameters for a specific value of branching fraction at $\pm 1\sigma$ level. All four plots (comprising of Unpolarized(a) and Polarized(b-d)) show that the maximum magnitude of NP parameter oscillates w.r.t. its phase in general. The plot in Fig. (2a) shows a particular pattern at given error level at $-1\sigma$ level of measured branching fraction($0.7 \times 10^{-7}$). It clearly shows that only
a narrow range of phase of NP parameter ($|\theta| \leq \frac{\pi}{4}$) is allowed for given $-1 \sigma$ level. The bounds on the magnitude of NP parameter are given in Table [2]. Tables [2a and 2b] show the same pattern as observed in Figs. (2a and 3a) numerically. Since Yukawa couplings for R-parity violation are identical for the processes ($K \rightarrow \pi \nu_\alpha \bar{\nu}_\alpha$, $K^0 \rightarrow \pi^0 \nu_\alpha \bar{\nu}_\alpha$, $K_{L,S} \rightarrow \nu_\alpha \bar{\nu}_\alpha$), the maximum limits for $K \rightarrow \pi \nu_\alpha \bar{\nu}_\alpha$ are used for calculating NP contribution to branching fraction of other processes.

Fig. (4) shows the relationship between the branching fraction of the process ($K^0 \rightarrow \pi^0 \nu_\alpha \bar{\nu}_\alpha$), magnitude and phase of New Physics (NP) parameters ($|z(\lambda'_{ik1} \lambda'_{ik2})|$ and $\theta$). These plots comprise of the allowed region for NP parameters for a specific value of branching fraction at $\pm 1 \sigma$ level. All four plots (comprising of Unpolarized(a) and Polarized(b-d)) show that the maximum magnitude of NP parameter follows a catenary (hanging chain) pattern, with the bottom level smoothing with decreasing error levels. The bounds on the magnitude of NP parameter and possible NP contribution are in Table [3], which shows that \( R_\mu \) MSSM enhances SM contribution by order of magnitude \( \sim 10^2 \), but an order of \( \sim 10^2 \) below experimental limits.

Figs. (5 and 6) relate the branching fraction of the process ($B \rightarrow \pi \nu_\alpha \bar{\nu}_\alpha$), with the magnitude and phase of NP parameters ($|z(\lambda'_{ik1} \lambda'_{ik2})|$ and $\theta$). Graphs in Fig. (5) illustrate the allowed region for NP parameters for a specific value of branching fraction at $\pm 1 \sigma$ level. All four plots (comprising of Unpolarized(a) and Polarized(b-d)) show that the maximum magnitude of NP parameter oscillates gently w.r.t. its phase in general. Similarly, plots in Fig. (6) represent the variation of branching fraction w.r.t. the magnitude of NP parameter ($|z(\lambda'_{ik1} \lambda'_{ik2})|$). All four plots demonstrate the gentle oscillation behavior as observed in Fig. (5) with sharply distinct curves for different values of phases of NP parameter ($\theta$). The bounds on the magnitude of NP parameter are given in Table [6].

Plots in Fig. (7) describe the branching fraction of the process ($B \rightarrow K \nu_\alpha \bar{\nu}_\alpha$) with the magnitude and phase of NP parameters ($|z(\lambda'_{ik1} \lambda'_{ik2})|$ and $\theta$). Graphs in Fig. (7) depict the allowed region for NP parameters for a specific value of branching fraction bounded by the experimental limit, while plots in Fig. (3) represent the variation of branching fraction w.r.t. the magnitude of NP parameter ($|z(\lambda'_{ik1} \lambda'_{ik2})|$). All four plots (comprising of Unpolarized(a) and Polarized(b-d)) show that the maximum magnitude of NP parameter oscillates w.r.t. its phase in general. The plot in Fig. (2a) shows a particular pattern below given limiting branching fraction ($\leq 4 \times 10^{-6}$). This particular pattern shows that only a narrow range of phase ($\theta$) of NP parameter is allowed in that case.

For pure leptonic decays of strange mesons involving neutrinos ($K_{L,S} \rightarrow \nu_\alpha \bar{\nu}_\alpha$), there is no experimental data available. Therefore, we use limits derived from ($K \rightarrow \pi \nu_\alpha \bar{\nu}_\alpha$) to calculate NP contribution to these processes. The bounds on the magnitude of NP parameter and possible NP contribution are given in Tables [4 and 5] for the decay of $K_{S,L}$ respectively, which shows that $R_\mu$ MSSM enhances SM contribution by order $\sim 10$ for $K_{S,L}$.

For pure leptonic decays of beauty involving neutrinos ($B_{d,s} \rightarrow \nu_\alpha \bar{\nu}_\alpha$), there
is no experimental data available for these processes, we use limits derived from $(B \to (\pi,K)\nu_\alpha \bar{\nu}_\alpha)$ to calculate NP contributions to these processes. The bounds on the magnitude of NP parameter and possible NP contribution are given in Tables [8 and 9] for the decay of $B_{d,s}$ respectively, which shows that $R_p$ MSSM enhances SM contribution by order of magnitude $\sim 10$ for $B_s$ and $10^4$ for $B_d$. 
Table 2: Bounds on NP Parameter \( |z(\lambda'_{ijk}\lambda'_{lmn})| \) for \( K \to \pi\nu_\alpha\bar{\nu}_\alpha, \alpha (Br_{SM}) \) are (a) UnPolarized \( (8.63 \times 10^{-11}) \) (b) e \( (2.89 \times 10^{-11}) \) (c) \( \mu (2.89 \times 10^{-11}) \) (d) \( \tau (2.85 \times 10^{-11}) \). Experimental limits are \((1.7 \pm 1.0) \times 10^{-10}\)
Figure 2: Allowed region of general New Physics (NP) Parameter $(z, \theta)$ for $K \rightarrow \pi \nu_\alpha \bar{\nu}_\alpha$, $\alpha$ are (a) UnPolarized (b) $e$ (c) $\mu$ (d) $\tau$. The three contours belong to branching fraction at $[0.7, 1.7, 2.7]$
Figure 3: Variations of branching fraction w.r.t NP Parameter (|z(λ′_{ijk} λ′_{lmm})|, θ) for K → πν_α ν_α, α are (a) UnPolarized (b) e (c) μ (d) τ. The three bounds belong to branching fraction at [0.7, 1.7, 2.7]
Table 3: Bounds on NP Parameter (derived from $K \to \pi \nu_{\alpha} \pi_{\alpha}$, $\alpha$) $[|\chi_{m,\alpha}^\nu|, \theta]$ for $K^0 \to \nu^0 \nu_{\alpha} \pi_{\alpha}, (Br_{SM})$ are (a) UnPolarized ($2.94 \times 10^{-11}$) and ($9.78 \times 10^{-12}$) for (b) e (c) $\mu(d)\tau$. Experimental bound on the process is ($2.6 \times 10^{-8}$).

| $\theta$ | $|\chi_{m,\alpha}^\nu|$ | NP | Interference | Combined |
|---------|-------------------|----|-------------|----------|
| 0       | 4.465 ± 0.209     | 0. x0 | 0. x0 | 0.003 ± 0.0 |
| 30      | 3.024 ± 0.265     | 2.04 ± 0.462 | -2.44 ± 0.462 | 0.031 ± 0.036 |
| 60      | 4.229 ± 0.216     | 0.321 ± 0.419 | -0.955 ± 0.419 | 0.116 ± 0.046 |
| 90      | 2.977 ± 0.225     | 5.201 ± 0.451 | -5.328 ± 0.451 | 0.082 ± 0.046 |
| 120     | 2.230 ± 0.225     | 2.209 ± 0.451 | -2.25 ± 0.451 | 0.042 ± 0.025 |
| 150     | 1.927 ± 0.225     | 0.166 ± 0.419 | -0.555 ± 0.419 | 0.015 ± 0.015 |
| 180     | 1.94 ± 0.225      | 0. x0 | 0. x0 | 0.033 ± 0.025 |
| 210     | 2.278 ± 0.225     | 0.724 ± 0.451 | -0.796 ± 0.451 | 0.002 ± 0.025 |
| 240     | 3.06 ± 0.225      | 4.05 ± 0.451 | -4.233 ± 0.451 | 0.023 ± 0.025 |
| 270     | 4.357 ± 0.225     | 11.621 ± 0.451 | -11.541 ± 0.451 | 0.002 ± 0.025 |
| 300     | 3.078 ± 0.225     | 7.75 ± 0.451 | -7.495 ± 0.451 | 0.058 ± 0.057 |
| 330     | 3.466 ± 0.225     | 3.36 ± 0.451 | -3.44 ± 0.451 | 0.023 ± 0.025 |
| 360     | 3.465 ± 0.209     | 0. x0 | 0. x0 | 0.003 ± 0.0 |

| $\theta$ | $|\chi_{m,\alpha}^\nu|$ | NP | Interference | Combined |
|---------|-------------------|----|-------------|----------|
| 0       | 8.026 ± 0.831     | 0. x0 | 0. x0 | 0.001 ± 0.0 |
| 30      | 7.085 ± 1.169     | 2.757 ± 1.422 | -2.719 ± 1.422 | 0.039 ± 0.027 |
| 60      | 5.671 ± 1.079     | 5.585 ± 1.369 | -5.515 ± 1.369 | 0.071 ± 0.041 |
| 90      | 4.406 ± 1.079     | 4.843 ± 1.729 | -4.762 ± 1.729 | 0.062 ± 0.048 |
| 120     | 3.618 ± 1.166     | 2.582 ± 2.166 | -2.544 ± 2.166 | 0.034 ± 0.026 |
| 150     | 3.267 ± 1.165     | 0.722 ± 0.622 | -0.713 ± 0.622 | 0.013 ± 0.009 |
| 180     | 3.282 ± 1.167     | 0. x0 | 0. x0 | 0.001 ± 0.0 |
| 210     | 3.666 ± 1.169     | 0.833 ± 0.736 | -0.879 ± 0.736 | 0.005 ± 0.005 |
| 240     | 4.499 ± 1.168     | 3.759 ± 1.863 | -3.732 ± 1.863 | 0.020 ± 0.024 |
| 270     | 3.753 ± 1.165     | 3.706 ± 2.185 | -3.665 ± 2.185 | 0.062 ± 0.048 |
| 300     | 7.189 ± 1.166     | 8.497 ± 4.306 | -8.429 ± 4.306 | 0.068 ± 0.038 |
| 330     | 8.068 ± 1.165     | 3.499 ± 1.536 | -3.475 ± 1.536 | 0.025 ± 0.013 |
| 360     | 8.026 ± 1.167     | 0. x0 | 0. x0 | 0.001 ± 0.0 |

| $\theta$ | $|\chi_{m,\alpha}^\nu|$ | NP | Interference | Combined |
|---------|-------------------|----|-------------|----------|
| 0       | 8.026 ± 1.167     | 0. x0 | 0. x0 | 0.001 ± 0.0 |
| 30      | 7.085 ± 1.169     | 2.748 ± 1.418 | -2.732 ± 1.418 | 0.038 ± 0.027 |
| 60      | 5.671 ± 1.079     | 5.582 ± 1.369 | -5.513 ± 1.369 | 0.071 ± 0.041 |
| 90      | 4.418 ± 1.079     | 4.856 ± 1.729 | -4.795 ± 1.729 | 0.062 ± 0.043 |
| 120     | 3.631 ± 1.166     | 2.603 ± 2.118 | -2.568 ± 2.118 | 0.036 ± 0.021 |
| 150     | 3.282 ± 1.165     | 0.727 ± 0.625 | -0.715 ± 0.625 | 0.013 ± 0.009 |
| 180     | 3.281 ± 1.167     | 0. x0 | 0. x0 | 0.001 ± 0.0 |
| 210     | 3.668 ± 1.169     | 0.830 ± 0.736 | -0.876 ± 0.736 | 0.005 ± 0.005 |
| 240     | 4.515 ± 1.168     | 3.782 ± 1.869 | -3.753 ± 1.869 | 0.028 ± 0.024 |
| 270     | 5.002 ± 1.165     | 7.745 ± 4.309 | -7.684 ± 4.309 | 0.062 ± 0.043 |
| 300     | 7.189 ± 1.166     | 8.489 ± 4.299 | -8.421 ± 4.299 | 0.060 ± 0.038 |
| 330     | 8.054 ± 1.165     | 3.487 ± 1.536 | -3.464 ± 1.536 | 0.024 ± 0.013 |
| 360     | 8.009 ± 1.167     | 0. x0 | 0. x0 | 0.001 ± 0.0 |
Figure 4: Allowed regions of general New Physics (NP) Parameter \((z, \theta)\) for \(K^0 \rightarrow \pi^0 \nu_\alpha \bar{\nu}_\alpha\), \(\alpha\) are (a) UnPolarized (b) e (c) \(\mu(d)\)\(\tau\). The three contours belong to branching fraction at \([0.3, 1.3, 2.6]\)
Figure 5: Variations of NP contribution w.r.t NP Parameter ($|\lambda'_{ijk} \lambda'_{lmn}|, \theta$) for
$K^0 \rightarrow \pi^0 \nu_\alpha \bar{\nu}_\alpha \bar{\nu}_\alpha$, $\alpha$ is (a) UnPolarized (b) e (c) $\mu$ (d) $\tau$.
Table 4: Bounds on NP Parameter ($|z(\lambda'_{ijk}\lambda'_{lmn})|$, $|$ and $|$ for $B \rightarrow \pi\nu\alpha$, $\alpha$ ($Br_{SM}$) are (a) UnPolarized ($1.73 \times 10^{-7}$) and ($5.76 \times 10^{-8}$) for (b) e (c) $\mu(d)$ $\tau$. Experimental bound on the process is ($9.8 \times 10^{-5}$).
Figure 6: Allowed regions of general New Physics (NP) Parameter \((z, \theta)\) for 
\(B \to \pi \nu_\alpha \overline{\nu}_\alpha, \alpha\) are (a) UnPolarized (b) e (c) \(\mu(d)\tau\). The three contours belong to branching fraction at \([1.4 − 9.8]\)
Figure 7: Variation of branching fraction w.r.t. NP Parameter ($|z(\lambda'_{ijk}\lambda'_{lmn})|, \theta$) for $B \to \pi \nu_\alpha \overline{\nu}_\alpha$, $\alpha$ is (a) UnPolarized (b) $e$ (c) $\mu$ (d) $\tau$. Experimental bound on the process is $(9.8 \times 10^{-5})$. 
Table 5: Bounds on NP Parameter \( |\varepsilon(\lambda'_{ijk}^\alpha \lambda_{mn}^\alpha)| \times 10^{-7} \) for \( B \rightarrow K\nu_\alpha \vec{\nu}_\alpha, \alpha \) (\(B_{SM}\)) are (a) UnPolarized \((4.69 \times 10^{-6})\) and \((1.56 \times 10^{-6})\) for (b) e (c) \(\mu(d)\tau\). Experimental bound on the process is \((1.60 \times 10^{-5})\)
Figure 8: Allowed regions of general New Physics (NP) Parameter \((z, \theta)\) for \(B \to K \nu_\alpha \bar{\nu}_\alpha\), \(\alpha\) are (a) UnPolarized (b) e (c) \(\mu(d)\tau\). The three contours belong to branching fraction at \([0.4 - 1.6]\)
Figure 9: Variations of branching fraction w.r.t. NP Parameter \( |z(\lambda'_{ijk} \lambda'_{lmn})|, \theta \) for \( B \to K\nu_\alpha \tau_\alpha \). \( \alpha \) are (a) UnPolarized (b) e (c) \( \mu \) (d) \( \tau \). Experimental bound on the process is \((1.60 \times 10^{-5})\).
Table 6: Bounds on NP Parameter (derived from $K \rightarrow \pi\nu\tau_\alpha (\nu)$) for $K_s \rightarrow \nu_\alpha \nu_\alpha$, $\alpha$ ($Br_{SM}$) are (a) UnPolarized (7.27×10^{-27}) (b) e (7.58×10^{-33}) (c) $\mu$ (5.66×10^{-29}) (d) $\tau$ (7.27×10^{-27}).

| Bounds on NP Parameter | Branching Fraction | Bounds on NP Parameter | Branching Fraction |
|------------------------|--------------------|------------------------|--------------------|
| $|\lambda_{ijk}\lambda_{lmn}|<10^{-3}$ | HP | Interference | Combined | $|\lambda_{ijk}\lambda_{lmn}|<10^{-3}$ | HP | Interference | Combined |
| 0 | 8.026±1.87 | 6.29±2.78 | 2.09±2.62 | 1.99±0.46 | 8.026±1.87 | 6.29±2.78 | 2.09±2.62 | 1.99±0.46 |
| 30 | 1.032±2.655 | 1.595±1.94 | -0.745±0.469 | 1.91±1.272 | 1.032±2.655 | 1.595±1.94 | -0.745±0.469 | 1.91±1.272 |
| 60 | 6.278±1.59 | 2.157±1.32 | 2.055±1.37 | 6.928±1.92 | 6.278±1.59 | 2.157±1.32 | 2.055±1.37 | 6.928±1.92 |
| 120 | 1.233±2.56 | 0.601±2.26 | -0.808±1.159 | 0.509±2.15 | 1.233±2.56 | 0.601±2.26 | -0.808±1.159 | 0.509±2.15 |
| 150 | 1.54±2.85 | 0.464±2.55 | 0.339±1.56 | 0.215±1.74 | 1.54±2.85 | 0.464±2.55 | 0.339±1.56 | 0.215±1.74 |
| 210 | 1.278±1.06 | 0.626±1.31 | 1.312±1.56 | 2.654±1.34 | 1.278±1.06 | 0.626±1.31 | 1.312±1.56 | 2.654±1.34 |
| 240 | 1.06±1.33 | 0.107±1.74 | 1.763±1.34 | 2.487±1.34 | 1.06±1.33 | 0.107±1.74 | 1.763±1.34 | 2.487±1.34 |
| 270 | 2.59±0.92 | 2.289±1.34 | 2.545±1.34 | 3.16±0.92 | 2.59±0.92 | 2.289±1.34 | 2.545±1.34 | 3.16±0.92 |
| 300 | 1.075±0.72 | 7.035±2.02 | -0.476±0.421 | 2.27±1.1 | 1.075±0.72 | 7.035±2.02 | -0.476±0.421 | 2.27±1.1 |
| 330 | 2.046±0.33 | 2.748±2.71 | 1.87±1.73 | 2.12±0.45 | 2.046±0.33 | 2.748±2.71 | 1.87±1.73 | 2.12±0.45 |
| 360 | 2.465±0.21 | 2.69±2.62 | 1.10±1.02 | 4.515±3.709 | 2.465±0.21 | 2.69±2.62 | 1.10±1.02 | 4.515±3.709 |
Figure 10: Variations of NP contribution w.r.t. NP Parameter $\langle |\lambda'_{ijk}\lambda'_{lmn}|, \theta \rangle$ for $K_S \rightarrow \nu_\alpha \bar{\nu}_\alpha$, $\alpha$ are (a) UnPolarized (b) $e$ (c) $\mu$ (d) $\tau$. 

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Table 7: Bounds on NP Parameter (derived from $K \to \pi^0 \nu \nu$, $\alpha$) ($|\lambda_{ijk} \lambda_{lmn}|^2 \theta$) for $K_L \to \nu \nu$, $\alpha$ ($Br_{SM}$) are (a) UnPolarized ($4.29 \times 10^{-27}$) (b) e ($4.48 \times 10^{-33}$) (c) $\mu$ ($3.34 \times 10^{-29}$) (d) $\tau$ ($4.26 \times 10^{-27}$).
Figure 11: Variations of NP contribution w.r.t. NP Parameter \( (|\lambda'_{ijk}\lambda'_{lmn}|, \theta) \) for \( K_L \rightarrow \nu_\alpha \bar{\nu}_\alpha, \alpha \) are (a) UnPolarized (b) e (c) \( \mu \) (d) \( \tau \).
| $\sigma$ | $|\mathcal{L}_{\mathcal{L}}|_{10^{-2}}$ | $\lambda_{ij}^{\nu_{\alpha}}|_{10^{-2}}$ | Branching Fraction ($|x| \times 10^{-25}$) | $\lambda_{ij}^{\nu_{\alpha}}|_{10^{-2}}$ | $\lambda_{ij}^{\nu_{\alpha}}|_{10^{-2}}$ | Branching Fraction ($|x| \times 10^{-25}$) |
|------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|
| 0    | 1.164           | 3.325           | 0.269          | 3.6             | 0               | 1.164           | 3.325           | 0.269          | 3.6             |
| 30   | 1.023           | 3.413           | 0.151          | 3.57            | 30              | 1.023           | 3.413           | 0.151          | 3.57            |
| 60   | 1.056           | 3.555           | -0.23          | 3.328           | 60              | 1.056           | 3.555           | -0.23          | 3.328           |
| 120  | 1.123           | 3.709           | -0.23          | 3.495           | 120             | 1.123           | 3.709           | -0.23          | 3.495           |
| 150  | 1.093           | 3.884           | 0.165          | 4.014           | 150             | 1.093           | 3.884           | 0.165          | 4.014           |
| 180  | 1.101           | 3.905           | 0.289          | 4.2             | 180             | 1.101           | 3.905           | 0.289          | 4.2             |
| 210  | 1.084           | 3.964           | 0.186          | 4.2             | 210             | 1.084           | 3.964           | 0.186          | 4.2             |
| 240  | 1.062           | 3.612           | -0.016         | 3.626           | 240             | 1.062           | 3.612           | -0.016         | 3.626           |
| 330  | 1.037           | 3.207           | -0.253         | 3.061           | 330             | 1.037           | 3.207           | -0.253         | 3.061           |
| 360  | 1.064           | 3.325           | -0.181         | 3.15            | 360             | 1.064           | 3.325           | -0.181         | 3.15            |

Table 8: Bounds on NP Parameter (derived from $B \to \pi \nu_{\alpha} \nu_{\alpha}$) ($|\lambda_{ij}^{\nu_{\alpha}}|_{10^{-2}}$) for $B_d \to \nu_{\alpha} \nu_{\alpha}$ ($B_{SM}$) are (a) UnPolarized ($6.35 \times 10^{-25}$) (b) e ($6.53 \times 10^{-31}$) (c) $\mu$ ($4.87 \times 10^{-27}$) (d) $\tau$ ($6.3 \times 10^{-25}$).
Figure 12: Variations of NP contribution w.r.t. NP Parameter ($|\lambda'_{ijk} \lambda'_{lmn}| \theta$) for $B_d \rightarrow \nu_{\alpha} \tau_{\alpha}, \alpha$ are (a) UnPolarized (b) $e$ (c) $\mu$ (d) $\tau$.
Table 9: Bounds on NP Parameter (derived from $B \rightarrow K\nu_\alpha \nu_\alpha$, $\alpha$ (|$\lambda_{ijk}^\prime \lambda_{lmn}^\prime$), $\theta$) for $B_s \rightarrow \nu_\alpha \bar{\nu}_\alpha$, $\alpha$ ($Br_{SM}$) are (a) UnPolarized ($1.41 \times 10^{-23}$) (b) $e$ ($1.45 \times 10^{-29}$) (c) $\mu$ ($1.08 \times 10^{-25}$) (d) $\tau$ ($1.4 \times 10^{-21}$).

| Parameter | Bound | Branching Fraction ($\times 10^{-23}$) | Parameter | Bound | Branching Fraction ($\times 10^{-29}$) |
|-----------|-------|----------------------------------------|-----------|-------|-------------------------------|
| $\sigma$ | $|\lambda_{ijk}^\prime \lambda_{lmn}^\prime|_{10^{-23}}$ | | $\sigma$ | $|\lambda_{ijk}^\prime \lambda_{lmn}^\prime|_{10^{-29}}$ | |
| 0        | 0.5319 | 1.145 -0.092 0.402 | 0        | 8.7539 | 2.56 -1.216 1.469 |
| 30       | 0.5112 | 0.988 -0.115 1.014 | 30       | 8.3927 | 2.36 -0.183 2.323 |
| 60       | 0.4436 | 0.642 0.576 1.357 | 60       | 7.6629 | 1.86 0.296 3.001 |
| 90       | 0.3239 | 0.341 0.195 0.639 | 90       | 6.3556 | 1.24 0.16 2.629 |
| 120      | 0.2395 | 0.181 -0.26 0.062 | 120      | 5.7388 | 0.97 -0.612 0.503 |
| 150      | 0.0202 | 0.118 -0.18 0.079 | 150      | 4.7829 | 0.77 -0.471 0.444 |
| 180      | 0.0266 | 0.101 0.144 0.386 | 180      | 4.5656 | 0.71 0.357 1.232 |
| 210      | 0.0232 | 0.095 0.223 0.467 | 210      | 4.7829 | 0.77 0.386 1.501 |
| 240      | 0.0235 | 0.181 -0.104 0.218 | 240      | 5.3788 | 0.97 -0.248 0.896 |
| 270      | 0.0239 | 0.095 0.432 0.903 | 270      | 6.3359 | 1.14 -0.666 0.659 |
| 300      | 0.0236 | 0.062 0.014 0.787 | 300      | 7.4629 | 1.46 0.026 2.033 |
| 330      | 0.0239 | 0.098 0.741 1.877 | 330      | 8.3927 | 2.36 1.159 3.664 |
| 360      | 0.0249 | 1.145 0.229 1.515 | 360      | 8.7539 | 2.56 0.352 3.057 |

Table 9: Bounds on NP Parameter (derived from $B \rightarrow K\nu_\alpha \nu_\alpha$, $\alpha$ (|$\lambda_{ijk}^\prime \lambda_{lmn}^\prime$), $\theta$) for $B_s \rightarrow \nu_\alpha \bar{\nu}_\alpha$, $\alpha$ ($Br_{SM}$) are (a) UnPolarized ($1.41 \times 10^{-23}$) (b) $e$ ($1.45 \times 10^{-29}$) (c) $\mu$ ($1.08 \times 10^{-25}$) (d) $\tau$ ($1.4 \times 10^{-21}$).
Summarizing, we have carried out the study of semileptonic and pure leptonic decays of pseudoscalar mesons within $\mathcal{R}_p$ MSSM. It enhances the SM contribution for all the involved processes as discussed in the context of decays of $K^0$, $K_{S,L}$, and $B_{s,d}$. This makes $\mathcal{R}_p$ MSSM a viable model for checking the contribution of NP in rare decays.

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