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Study of pure and semileptonic decays of $\mathrm{D_s}$ meson within *R*-parity violating supersymmetric model

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Abstract: We present the comaprative study of semileptonic and leptonic decays of $\mathrm{D_s}$, $\mathrm{D^{\pm}}$ and $\mathrm{D^0}$ meson ($\mathrm{D\rightarrow M\, l^{+}_{\alpha}l^{-}_{\beta}}$, $\mathrm{D\rightarrow l^{+}_{\alpha}l^{-}_{\beta}}$, $\mathrm{D\rightarrow l^{+}_{\alpha}v_{\alpha}};\alpha,\beta=\mathrm{e},\mu$) within the framework of *R*-parity violating the ($\not{R}_{\mathrm{p}}$) Minimal Supersymmetric Standard Model (MSSM). The comparison shows that combination and product couplings, ($\lambda_{\beta i\alpha}\lambda'^{*}_{ij\mathrm{q}}$ or $\lambda'_{\beta\mathrm{q}k}\lambda'^{*}_{\alpha jk}$) contribution to the branching fractions of the said processes (under consideration) is consistent with or comparable to the experimental measurements in most of the cases. However, some cases exist where these contributions are highly suppressed. We identify such cases in our analysis and single out the important ones suitable for exploring in the future and current experiments.

Key words: supersymmtery, *R*-parity violating MSSM, leptonic decays, pseudo-scalar meson

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1 Introduction

Flavor changing neutral current (FCNC) processes in the lepton sector are strictly forbidden in SM, hence undoubtly, a hint for new physics (NP), while on the other hand, FCNC processes in the quark sector play a dual role: one in the erection of the Standard Model (SM) and the other, an efficient tool for physics beyond the SM [1]. These processes involve neutral meson mixing (oscillations), radiative decays [2], rare leptonic, semileptonic, lepton flavor and number conserving, and *CP* violating decays. All these mixings and decays are highly suppressed in SM, due to the Glashow, Ilopoulous and Maiani(GIM) mechanism. The GIM mechanism assures that there are no FCNC at the tree level and the leading contribution results through one loop (box or penguin) diagram, where quarks (up/down) could propagate in the loop and give tiny factor $\left(\dfrac{m_{\mathrm{q}}}{M_{\mathrm{W}}}\right)^2$ and the small Cabibbo-Kobayashi-Maskawa (CKM) angle provides the theoretical reason for the very small branching fraction and *CP* asymmetries in the SM [3], hence resulting in deviations from experimental data. These deviations become extraordinarily large when we deal with the processes involving only down type quarks (d, s, b) rather than up type quarks (u, c, t) propagating in the loop. The FCNC processes involving charm (D) meson decays [1], mixing and *CP*-violation [3] are among one of those golden channels, having extraordinarily large theory experimental discrepancy due to $\left(\dfrac{m_{\mathrm{d,s,b}}}{M_{\mathrm{W}}}\right)^2$ suppression, e.g for the process $\mathrm{D^0}\longrightarrow\mu^{+}\mu^{-}$ the best upper bound on Branching. Ratio (BR) is 1.3×10^{-6} at 90% C.L. from BaBar [4], while the world's best upper bound is 1.4×10^{-7} at 90% C.L. from Belle [5], while SM predicted that the BR of these decays is 4.76×10^{-20}, which is clear evidence for the large theoretical and experimental discrepancy and demands some NP.

Furthermore, the processes involving the D meson have proven to be an excellent laboratory for studying QCD (Quantum Chromo Dynamics) since the charm meson mass, O(2 GeV), is placed in the middle of the region of non-perturbative hadronic physics [6], thus providing very fertile ground for the study of NP.

An array of NP models was explored in the charm meson sector, particularly two Higgs doublet models Type-II (THDM-II) and Type-III (THDM-III) [7], a little Higgs model with T-parity [8], the Left-Right Symmetric Model (LR) [9] and the Minimal Supersymmetric Standard Model (MSSM) with explicit R-parity violation [10]. *R*-parity violating supersymmetric model accommodates and yields promising results, which are otherwise suppressed and cannot be accommodated by the SM. *R*-parity violating Yukawa couplings have been used to

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study the anomaly in the branching fraction of pure leptonic and semileptonic decays. Among those decays, currently, the most interesting one is the decay of charm mesons (D, $\mathrm{D}^{\pm}$, $\mathrm{D_s}$) due to hordes of data sample at the facilities of E687, E831 (Fermi-lab) [11], BES III (Beijing Spectrometer III), CDF, CLEO [11–13] Belle and BaBar [14].

The aim of this paper is to investigate, compare and advocate the two (pure leptonic) and three bodies (semileptonic) flavour conserving (FC) and flavour violating (FV) charm mesons processes, having the same quark substructures. The *R*-parity violating SUSY Model [15] allows FV processes at tree level through the same ($\mathrm{LQD^c}$) operator. This operator can lead to resonant slepton and sneutrino production, which otherwise proceeds through the box and penguin diagram through the exchange of down type quarks [11] within the Standard Model (SM) and are highly suppressed [14, 16]. In support of our argument, we consider the example of ($\mathrm{D_s^{\pm}\to K^{\pm}l_{\alpha}^{+}l_{\beta}^{-}}$, $\mathrm{D^0\to l_{\alpha}^{+}l_{\beta}^{-}}$, $\mathrm{D^{\pm}\to \pi^{\pm}l_{\alpha}^{+}l_{\beta}^{-}}$) and ($\mathrm{D^0\to\pi^{-}l_{\alpha}^{+}v_{\beta}}$, $\mathrm{D^{+}\to l_{\alpha}^{+}v_{\beta}}$), having the same subquark structure ($\mathrm{c\to ul_{\alpha}^{+}l_{\beta}^{-}}$) and ($\mathrm{c\to dl_{\alpha}^{+}v_{\beta}}$) respectively. The spectator quark model [17] is used to calculate the branching fraction of the above mentioned processes and compare them with the current experimental limits. As the outshoot, we get the limit on the *R*-parity violating Yukawa couplings.

Though *R*-parity ($R_{\rm p}=(-1)^{3B+L+2S}$) conserving the Minimal Supersymmetric Standard Model (MSSM) [15] is phenomenologically well motivated [18] even then *R*-parity violating MSSM, if relaxed carefully, has rich phenomenological implications [19]. This version of supersymmetry avoids any adhocism and satisfies all conditions of good theory, i.e. gauge invariance, renormalizability and anomaly free. This theory naturally accomodates lepton and baryon number and flavour violating terms, hence all FCNC (rare and forbidden decays) are accommodated at the tree level within *R*-parity violating MSSM [10] and thus it naturally provides the reason for significant enhancement in the branching fraction. So any significant deviation from the SM prediction is a clear hint to think about *R*-parity violating the SUSY model. This fact motivates us to study the leptonic and semileptonic decays of charm mesons within *R*-parity violating MSSM.

The *R*-parity violating gauge invariant and renormalizable superpotential is [18]

$$W_{\not{R}_{\rm p}}=\frac{1}{2}\lambda_{ijk}L_iL_jE_k^{\rm c}+\lambda'_{ijk}L_iQ_jD_k^{\rm c}+\frac{1}{2}\lambda''_{ijk}U_i^{\rm C}D_j^{\rm C}D_k^{\rm C}+\mu_iH_uL_i, \tag{1}$$

where i, j, k are the generation indices, L_i and Q_i are the lepton and quark left-handed $SU(2)_{\rm L}$ doublets and $E^{\rm c}$, $D^{\rm c}$ are the charge conjugates of the right-handed leptons and quark singlets, respectively. λ_{ijk}, λ'_{ijk} and λ''_{ijk} are the Yukawa couplings. The term proportional to λ_{ijk} is antisymmetric in the first two indices $[i,j]$ and λ''_{ijk} is antisymmetric in the 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 $\mathrm{LLE^c}$ and 27 from $\mathrm{LQD^c}$). We can rotate the last term away without affecting aspects of our interest, in order to ensure the stability of matter.

2 $(\mathrm{D^{+}},\mathrm{D_s})\to \mathrm{l_{\alpha}^{+}}\nu_{\beta}$ in $\not{R}_{\rm p}$ SUSY

The effective Lagrangian for the decays of $(\mathrm{D^{+}},\mathrm{D_s})\to \mathrm{l_{\alpha}^{+}}+\overline{\nu}_{\beta}$ in the quark mass basis is given as

$$L^{\rm eff}_{\not{R}_{\rm P}}(\mathrm{c}\longrightarrow \mathrm{q}+\mathrm{l}_{\alpha}^{+}+\overline{\nu}_{\beta})$$

$$=\frac{4G_{\rm F}V_{\rm cq}}{\sqrt{2}}\left[\begin{array}{c}A^{\rm cq}_{\alpha\beta}\left(\bar{c}\gamma^{\mu}P_{\rm L}q\right)\left(\bar{l}_{\alpha}\gamma_{\mu}P_{\rm L}\nu_{\beta}\right)\\ -B^{\rm cq}_{\alpha\beta}\left(\bar{c}P_{\rm R}q\right)\left(\bar{l}_{\alpha}P_{\rm L}\nu_{\beta}\right)\end{array}\right], \tag{2}$$

where α, β=e, μ and q=d, s. The tree diagram of the process is given as in Fig. 1. The dimensionless coupling constants $A^{\rm cq}_{\alpha\beta}$ and $B^{\rm cq}_{\alpha\beta}$ are given as,

$$\begin{aligned}A^{\rm cq}_{\alpha\beta}&=\frac{\sqrt{2}}{4G_{\rm F}V_{\rm cq}}\sum_{j,k=1}^{3}\frac{1}{2m^2_{\tilde{\rm d}^{\rm c}_k}}V_{{\rm c}j}\lambda'_{\beta{\rm q}k}\lambda'^{*}_{\alpha jk},\\ B^{\rm cq}_{\alpha\beta}&=\frac{\sqrt{2}}{4G_{\rm F}V_{\rm cq}}\sum_{i,j=1}^{3}\frac{1}{m^2_{\tilde{l}^{\rm c}_i}}V_{{\rm c}j}\lambda_{\beta i\alpha}\lambda'^{*}_{ij{\rm q}}.\end{aligned} \tag{3}$$

Thus the decay rate of the flavor conserving process $\mathrm{D^{+}\to l_{\alpha}^{+}}\overline{\nu}_{\alpha}$ is given by

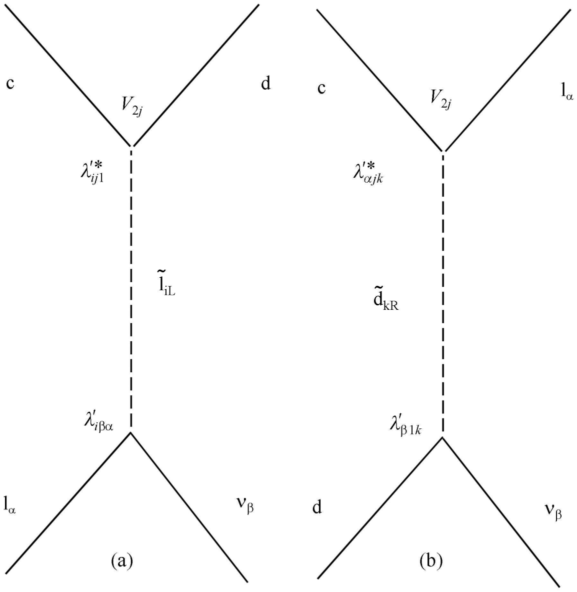

Fig. 1. The tree level diagram for ($\mathrm{D^0\to\pi^{-}l_{\alpha}^{+}v_{\beta}}$, $\mathrm{D^{+}\to l_{\alpha}^{+}v_{\beta}}$, $\mathrm{D^{+}\to\pi^{0}l_{\alpha}^{+}v_{\beta}}$) within the $R_{\rm p}$-violating MSSM.

$$\Gamma(\mathrm{D}^+\to \mathrm{l}_\alpha^+\overline{\nu}_\alpha) = \frac{1}{8\pi}G_\mathrm{F}^2|V_\mathrm{cq}|^2 f_\mathrm{D}^2 M_\mathrm{D}^3(1-\eta_\alpha^2)^2 \left|(1+A^\mathrm{cq}_{\alpha\alpha})\eta_\alpha - \left(\frac{M_\mathrm{D}}{m_\mathrm{c}+m_\mathrm{d,s}}\right)B^\mathrm{cq}_{\alpha\alpha}\right|^2,$$

where $\eta_\alpha=\frac{m_\alpha}{M_\mathrm{D}}$ is the mass of the charged lepton l, M_D is the mass of the charm meson, where f_M is the pseudoscalar meson decay constant. Here, the following PCAC (partial conservation of axial-vector current) relations have been used:

$$\langle 0|\overline{q}_\mathrm{c}\gamma^\mu\gamma_5 q_\mathrm{q}|M(p)\rangle = \mathrm{i}f_\mathrm{M}p^\mu_\mathrm{M}$$

$$\langle 0|\overline{q}_\mathrm{c}\gamma_5 q_\mathrm{q}|M(p)\rangle = \mathrm{i}f_\mathrm{M}\frac{M^2_\mathrm{M}}{m_{\mathrm{q_c}}+m_{\mathrm{q_q}}}. \qquad (4)$$

3 $\mathrm{D}\to(\pi,\mathrm{K})\mathrm{l}_\alpha^+\nu_\beta$ decay in $\not{R}_\mathrm{p}$ SUSY

The effective Lagrangian for the decays of $\mathrm{D}\to(\pi,\mathrm{K})\mathrm{l}_\alpha^+ +\nu_\beta$ in the quark mass basis is given as

$$L^\mathrm{eff}_{R_\mathrm{P}}(\mathrm{c}\longrightarrow \mathrm{q}+\mathrm{l}_\alpha^+ +\nu_\beta) = -\frac{4G_\mathrm{F}V_\mathrm{cq}}{\sqrt{2}}\begin{bmatrix} A^\mathrm{cq}_{\alpha\beta}(\bar{c}\gamma^\mu P_\mathrm{L}q)\left(\bar{l}_\alpha\gamma_\mu P_\mathrm{L}\nu_\beta\right) \\ -B^\mathrm{cq}_{\alpha\beta}(\bar{c}P_\mathrm{R}q)\left(\bar{l}_\alpha P_\mathrm{L}\nu_\beta\right)\end{bmatrix}, \qquad (5)$$

where α, β =e, μ and q=d, s. The tree diagram of the process is given as in Fig. 2. The dimensionless coupling constants $A^\mathrm{cq}_{\alpha\beta}$ and $B^\mathrm{cq}_{\alpha\beta}$ are given as,

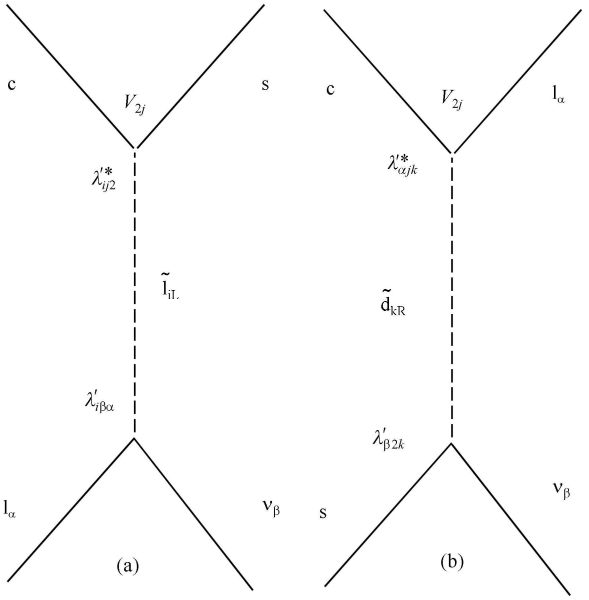

Fig. 2. The tree level diagram for ($\mathrm{D}^0\to\mathrm{K}^-\mathrm{l}_\alpha^+\nu_\beta$, $\mathrm{D}_\mathrm{s}^+\to\mathrm{l}_\alpha^+\nu_\beta$, $\mathrm{D}^+\to\mathrm{K}^0\mathrm{l}_\alpha^+\nu_\beta$ within the R_p-violating MSSM.

$$A^\mathrm{cq}_{\alpha\beta} = \frac{\sqrt{2}}{4G_\mathrm{F}V_\mathrm{cq}}\sum_{j,k=1}^{3}\frac{1}{2m^2_{\tilde{\mathrm{d}}^\mathrm{c}_\mathrm{k}}}V_{cj}\lambda'_{\beta\mathrm{q}k}\lambda'^*_{\alpha jk},$$

$$B^\mathrm{cq}_{\alpha\beta} = \frac{\sqrt{2}}{4G_\mathrm{F}V_\mathrm{cq}}\sum_{i,j=1}^{3}\frac{1}{m^2_{\tilde{\mathrm{l}}^\mathrm{c}_i}}V_{\mathrm{c}j}\lambda_{i\beta\alpha}\lambda'^*_{ij\mathrm{q}}. \qquad (6)$$

Thus the decay rate of $\mathrm{D}\to\mathrm{K}\mathrm{l}_\alpha^+\nu_\beta$ is given by [20]

$$\Gamma[\mathrm{c}\to\mathrm{q}\mathrm{l}_\alpha^+\nu_\beta] = \frac{m_\mathrm{D}^5}{192\pi^3}G_\mathrm{F}^2|V_\mathrm{cq}|^2(|A^\mathrm{cq}_{\alpha\beta}|^2+|B^\mathrm{cq}_{\alpha\beta}|^2). \qquad (7)$$

4 $\mathrm{D}^0\to\mathrm{l}_\alpha^\pm\mathrm{l}_\beta^\mp$ in $\not{R}_\mathrm{p}$ SUSY

The effective Lagrangian for the decays of $\mathrm{D}^0\to\mathrm{l}_\alpha^\pm\mathrm{l}_\beta^\mp$ in the quark mass basis is given as

$$L^\mathrm{eff}_{\not{R}_\mathrm{p}}(\mathrm{c}\longrightarrow\mathrm{u}+\mathrm{l}_\alpha^\pm+\mathrm{l}_\beta^\mp) = \frac{4G_\mathrm{F}}{\sqrt{2}}\left[A^\mathrm{cu}_{\alpha\beta}\left(\overline{l_\alpha}\gamma^\mu P_\mathrm{L}l_\beta\right)\left(\overline{u}\gamma_\mu P_\mathrm{R}c\right)\right], \qquad (8)$$

where α, β =e, μ. The tree diagram for the process is given as in Fig. 3. The dimensionless coupling constants $A^\mathrm{cu}_{\alpha\beta}$ are given by

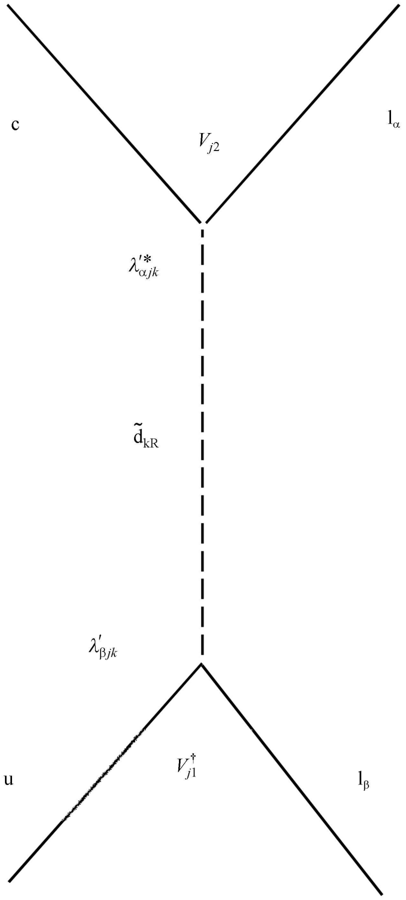

Fig. 3. The tree level diagram for ($\mathrm{D}^0\to\mathrm{e}^+\mathrm{e}^-$, $\mathrm{D}^0\to\mu^+\mu^-$, $\mathrm{D}_\mathrm{s}\to\mathrm{K}\mathrm{e}^+\mathrm{e}^-$) within the R_p-violating MSSM.

$$A^{\mathrm{cu}}_{\alpha\beta}=\frac{\sqrt{2}}{4G_{\mathrm{F}}}\sum_{m,n,i=1}^{3}\frac{V^{\dagger}_{n2}V_{1m}}{2m^2_{\tilde{\mathrm{d}}^{\mathrm{c}}_i}}\lambda'_{\beta ni}\lambda'^{*}_{\alpha mi}. \tag{9}$$

The decay rates of the processes $\mathrm{M}\rightarrow \mathrm{l}^{\pm}_{\alpha}\mathrm{l}^{\mp}_{\beta}$ are given by

$$\begin{aligned}&\Gamma\left[\mathrm{M(cu)}\rightarrow \mathrm{l}^{\pm}_{\alpha}\mathrm{l}^{\mp}_{\beta}\right]\\ &=\frac{1}{8\pi}G^2_{\mathrm{F}}f^2_{\mathrm{M}}M^3_{\mathrm{M}}\sqrt{1+\left(\eta^2_{\alpha}+\eta^2_{\beta}\right)^2-2\left(\eta^2_{\alpha}+\eta^2_{\beta}\right)}\\ &\times|A^{\mathrm{cu}}_{\alpha\beta}|^2[(\eta^2_{\alpha}+\eta^2_{\beta})-(\eta^2_{\alpha}-\eta^2_{\beta})^2]\end{aligned} \tag{10}$$

where $\eta_{\alpha}\equiv\dfrac{m_{\alpha}}{M_{\mathrm{M}}}$. m_{α} is the mass of the lepton, M_{M} is the mass of the meson, and f_{M} is the pseudoscalar meson decay constant, which is extracted from the leptonic decay of each pseudoscalar meson.

5 $\mathrm{D_s}\rightarrow \mathrm{Kl}^{-}_{\alpha}\mathrm{l}^{+}_{\beta}$ decay in $\not{R}_{\mathrm{p}}$ SUSY

In MSSM, the relevant effective Lagrangian for the decay process $\mathrm{D_s}\rightarrow \mathrm{Kl}^{-}_{\alpha}\mathrm{l}^{+}_{\beta}$ is given by [21]

$$L^{\mathrm{eff}}_{\not{R}_{\mathrm{p}}}\left(\mathrm{c}\longrightarrow \mathrm{u}+\mathrm{l}^{-}_{\alpha}+\mathrm{l}^{+}_{\beta}\right)=\frac{4G_{\mathrm{F}}}{\sqrt{2}}\left[A^{\mathrm{cu}}_{\alpha\beta}\left(\overline{l_{\alpha}}\gamma^{\mu}P_{\mathrm{L}}l_{\beta}\right)\left(\overline{u}\gamma_{\mu}P_{\mathrm{R}}c\right)\right], \tag{11}$$

where α, $\beta=\mathrm{e},\mu$. The first term in Eq. (2) comes from the up squark exchange (where c and u are the up type quarks). The dimensionless coupling constants $A^{\mathrm{cu}}_{\alpha\beta}$ are given by

$$A^{\mathrm{cu}}_{\alpha\beta}=\frac{\sqrt{2}}{4G_{\mathrm{F}}}\sum_{m,n,k=1}^{3}\frac{V^{\dagger}_{n2}V_{1m}}{2m^2_{\tilde{\mathrm{d}}^{\mathrm{c}}_k}}\lambda'_{\beta nk}\lambda'^{*}_{\alpha mk}. \tag{12}$$

The inclusive decay rate of the process is given by [20]

$$\Gamma\left[\mathrm{c}\rightarrow \mathrm{u}\ \mathrm{l}^{+}_{\alpha}\mathrm{l}^{-}_{\beta}\right]=\frac{m^5_{\mathrm{D}^{+}}}{192\pi^3}G^2_{\mathrm{F}}|A^{\mathrm{cu}}_{\alpha\beta}|^2. \tag{13}$$

6 Results and discussions

To summarize, we have analyzed the whole spectrum of pseudoscalar (charged and neutral) charm mesons involving pure leptonic and semileptonic leptonic (lepton flavor conserving as well as violating) two and three bodies decays. The technique we have adopted is to make a comparison between those processes represented by the same Feynman diagram in the R-parity violating SUSY Model, and hence having a common set of Yukawa coupling products ($\lambda'^{*}\lambda'$). The aim of this kind of analysis is to accommodate and pinpoint those decay channels, which are consistent with the experimental data when calculating in the R-parity violating SUSY model, as these decays cannot be accommodated by SM, for the reasons given in the introduction part. This type of analysis narrows down our searches for new physics.

Figures (4–11) and Tables 1–7 represent our analyses carried out in this paper. We have used the data from sources cite PDG, R. Barbie, BOUND for our analysis. The data are tabulated in Tables 1 and 2.

Table 1. Values of parameters used in calculations.

name	mass/GeV	life-time/s	form factor/GeV (pure leptonic decay)
D	1.869	1.04×10^{-12}	0.206
$\mathrm{D_s}$	1.968	5.01×10^{-13}	0.257
$\mathrm{D^0}$	1.865	4.10×10^{-13}	0.2
W	80.43		

Table 2. Values of CKM Matrix Elements used in calculations.

$$\begin{pmatrix} 0.974 & 0.226 & 0.0043 \\ 0.23 & 0.96 & 0.042 \\ 0.0074 & 0.36 & 0.999 \end{pmatrix}$$

Figure 4 gives the comparison between three different decay processes ($\mathrm{D}^{\pm}\rightarrow\pi^{\pm}\mathrm{e}^{+}\mathrm{e}^{-}$, $\mathrm{D}^{0}\rightarrow\mathrm{e}^{+}\mathrm{e}^{-}$ and $\mathrm{D}^{\pm}_{\mathrm{s}}\rightarrow\mathrm{K}^{\pm}\mathrm{e}^{+}\mathrm{e}^{-}$) in the frame work of $\not{R}_{\mathrm{p}}$ MSSM, which have the same Yukawa coupling ($\lambda'^{*}_{113}\lambda'_{123}$). Our analysis shows that among the above-mentioned processes only

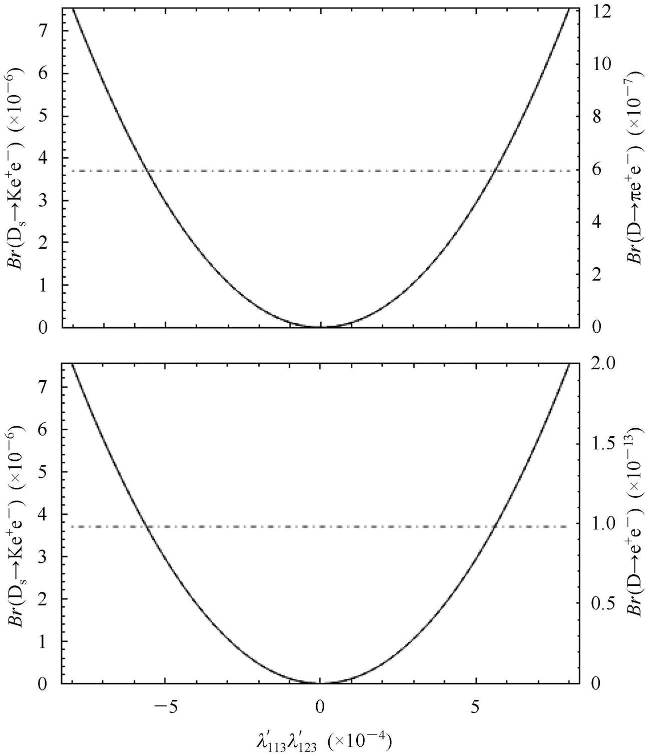

Fig. 4. A graph showing the relation between the branching fractions of leptonic and Semileptonic decays of charm meson. The dotted line shows the experimental bound on $\mathrm{D}^{\pm}_{\mathrm{s}}\rightarrow\mathrm{Ke^{+}e^{-}}$. $\lambda'_{123}\lambda'^{*}_{113}$ is expressed in units of $1/(m_{\tilde{\mathrm{d}}_{\mathrm{iL}}}/100\ \mathrm{GeV})^2$.

$D_s^{\pm} \rightarrow K^{\pm}e^{+}e^{-}$ and $D^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$ are in good agreement with the experimental limits, whereas $D^0 \rightarrow e^{+}e^{-}$ is highly suppressed when compared with the current experimental data. So these two processes ($D_s^{\pm} \rightarrow K^{\pm}e^{+}e^{-}$ and $D^{\pm} \rightarrow \pi^{\pm}e^{+}e^{-}$) are favorable for the study of NP, especially in $\not{R}_p$ MSSM.

The processes ($D^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$, $D^0 \rightarrow \mu^{+}\mu^{-}$, $D_s \rightarrow K^{\pm}\mu^{+}\mu^{-}$) having Yukawa coupling products ($\lambda'^{*}_{213}\lambda'_{223}$) are compared in Fig. 5. This comparison shows that the $\not{R}_p$ MSSM contribution to $D^0 \rightarrow \mu^{+}\mu^{-}$ is three times smaller than the current experimental limits but still better than the SM. This is significantly much better than the $D^0 \rightarrow e^{+}e^{-}$ due to the fact that the branching fraction of the pure leptonic decay depends directly on the square of the lepton to meson mass ratio. A comparison between $D^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ and $D_s^{\pm} \rightarrow K^{\pm}\mu^{+}\mu^{-}$ shows that the $\not{R}_p$ MSSM contribution to these processes is comparable to the experimental limits. So these decay channels ($D^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$, $D^0 \rightarrow \mu^{+}\mu^{-}$, $D_s \rightarrow K^{\pm}\mu^{+}\mu^{-}$) are promising for the study of $\not{R}_p$ MSSM.

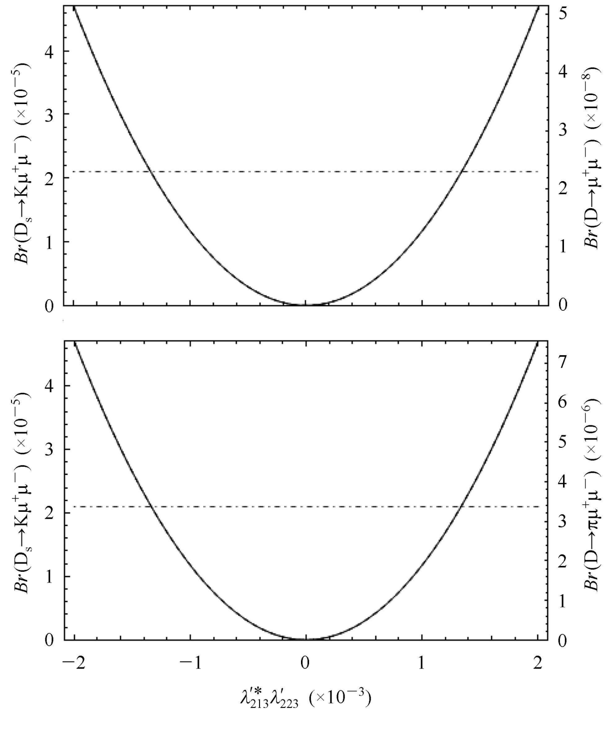

Fig. 5. A graph showing the relation between branching fractions of leptonic and semileptonic decays of charm meson. The dotted line shows the experimental bound on ($D_s^{\pm} \rightarrow K\mu^{+}\mu^{-}$). $\lambda'_{232}\lambda'^{*}_{231}$ is expressed in units of $1/(m_{\tilde{d}_{iL}}/100\ \mathrm{GeV})^2$.

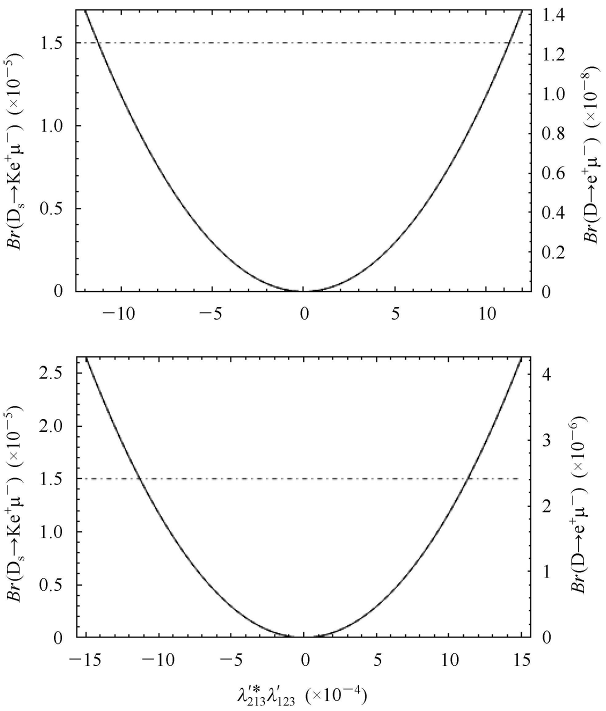

Fig. 6. A graph showing the relation between the branching fractions of leptonic and semileptonic decays of charm mesons. The dotted line shows the experimental bound on $D_s^{\pm} \rightarrow Ke^{+}\mu^{-}$. $\lambda'_{123}\lambda'^{*}_{213}$ is expressed in units of $1/(m_{\tilde{d}_{iL}}/100\ \mathrm{GeV})^2$.

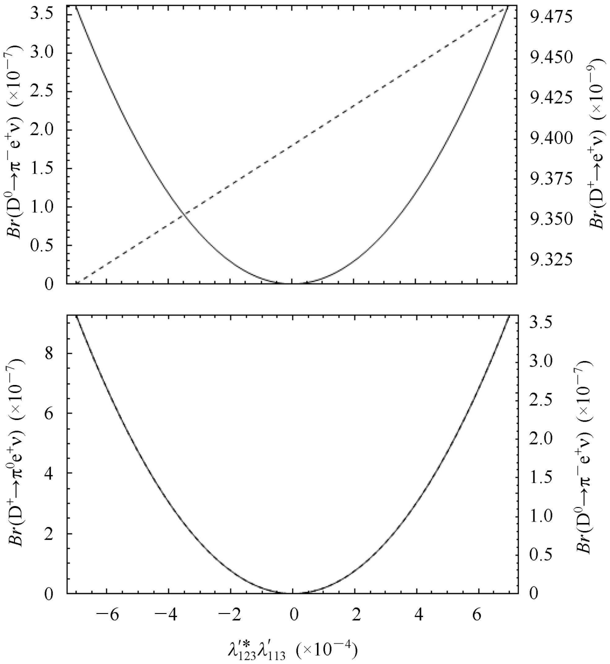

Fig. 7. A graph showing the relation between the branching fractions of leptonic and semileptonic decays of charm mesons. The dotted line represents a variation of $Br(D \rightarrow e^{+}\nu_e)$. $\lambda'_{113}\lambda'^{*}_{123}$ is expressed in the units of $1/(m_{\tilde{d}_{iL}}/100\ \mathrm{GeV})^2$.

A comparison between different processes ($D^{\pm} \rightarrow \pi^{\pm}e^{+}\mu^{-}$, $D^0 \rightarrow e^{+}\mu^{-}$ and $D_s^{\pm} \rightarrow K^{\pm}e^{+}\mu^{-}$), which have a common set of Yukawa coupling products ($\lambda'^{*}_{213}\lambda'_{123}$) is given in Fig. 6. This comparison shows that the decay processes $D_s^\pm \to K^\pm e^+ \mu^-$ (compatible) and $D^\pm \to \pi^\pm e^+ \mu^-$ (comparable) are promising enough to be explored for signs of the $\not{R}_p$ MSSM.

Further, a comparison between ($D^0 \to \pi^- e^+ \nu_e$, $D^+ \to e^+ \nu_e$ and $D^\pm \to \pi^0 e^+ \nu_e$) which have a common set of Yukawa coupling products ($\lambda'^*_{133}\lambda'_{113}$ and $\lambda'^*_{321}\lambda_{131}$) is delineated in Figs. 7, 8. This comparison shows that the $\not{R}_p$ MSSM contribution to $D^+ \to e^+ \nu_e$ is mostly made by sneutrino exchange Yukawa couplings ($\lambda'^*_{321}\lambda_{131}$) and is compatible with the current experimental limits. So this is the only favorable process for the study of the $\not{R}_p$ MSSM.

A comparison between processes ($D^0 \to \pi^- \mu^+ \nu_\mu$ and $D^+ \to \mu^+ \nu_\mu$) having a common set of Yukawa coupling product ($\lambda'^*_{233}\lambda'_{213}$ and $\lambda'^*_{321}\lambda_{232}$) is elucidated in Fig. 9. The contribution to $Br(D^+ \to \mu^+ \nu_\mu)$ from squark Yukawa couplings ($\lambda'^*_{233}\lambda'_{213}$) is comparable with SM and experimental limits, while the contribution of slepton exchange Yukawa couplings ($\lambda'^*_{321}\lambda_{232}$) terms is also compatible with $D^+ \to \mu^+ \nu_\mu$.

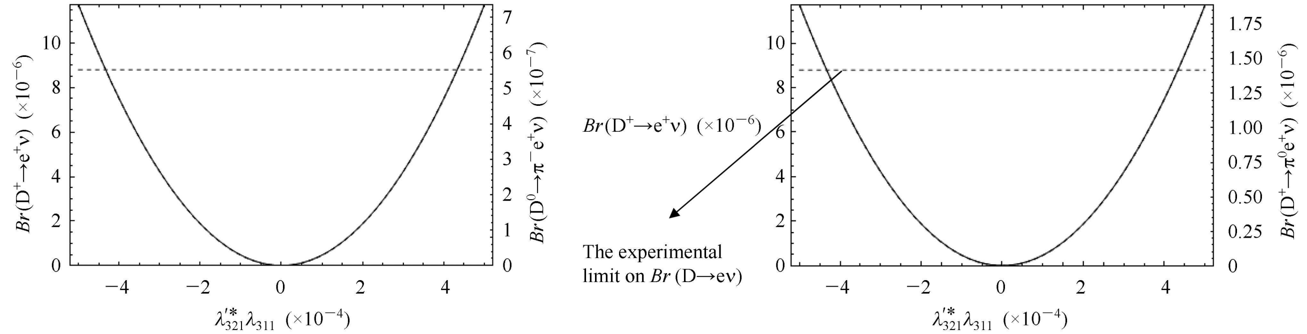

Fig. 8. A graph showing the relation between the branching fractions of leptonic and semileptonic decays of charm mesons. $\lambda_{311}\lambda'^*_{321}$ is expressed in units of $1/(m_{\tilde{l}_{iL}}/100\ \text{GeV})^2$.

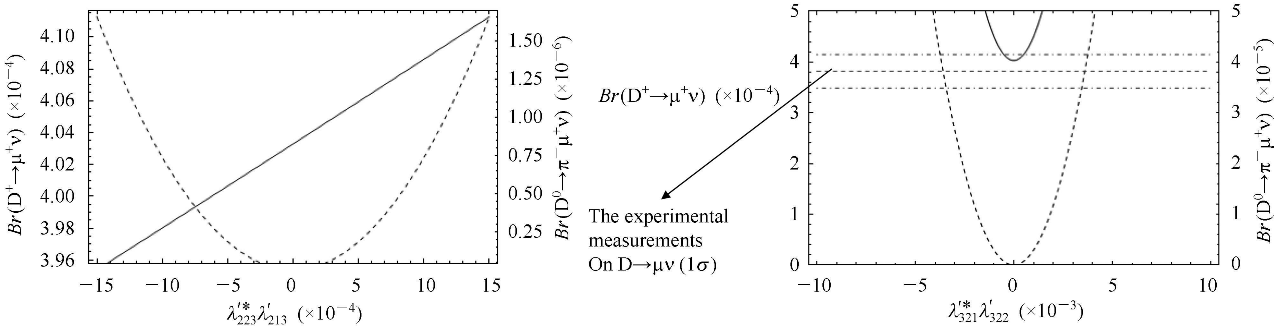

Fig. 9. A graph showing the relation between branching fractions of leptonic and semileptonic decays of charm mesons. The dotted line shows the variation of $Br(D^0 \to \pi^- \mu^+ \nu_\mu)$. $\lambda_{322}\lambda'^*_{321}$ is expressed in units of $1/(m_{\tilde{l}_{iL}}/100\ \text{GeV})^2$. $\lambda'_{213}\lambda'^*_{223}$ is expressed in units of $1/(m_{\tilde{d}_{iL}}/100\ \text{GeV})^2$.

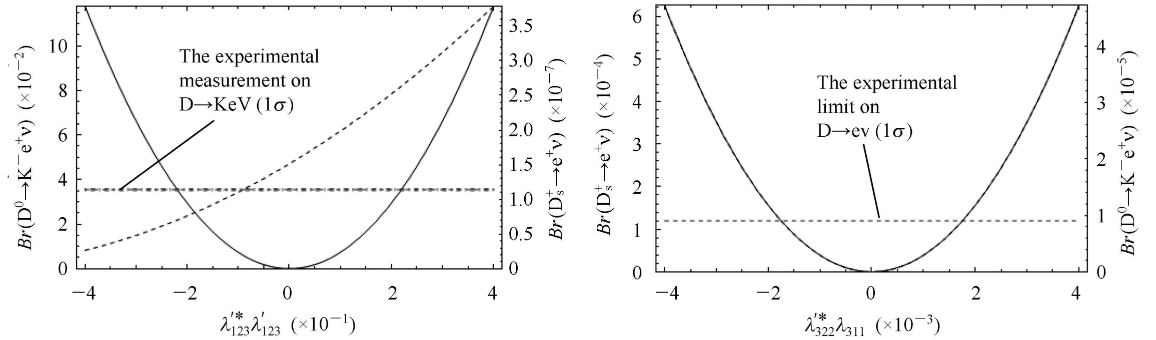

Fig. 10. A graph showing the relation between branching fractions of leptonic and semileptonic decays of charm mesons. The dotted line shows the variation of $Br(D^+ \to e^+ \nu_e)$. $\lambda_{311}\lambda'^*_{332}$ is expressed in units of $1/(m_{\tilde{l}_{iL}}/100\ \text{GeV})^2$. $\lambda'_{123}\lambda'^*_{123}$ is expressed in units of $1/(m_{\tilde{d}_{iL}}/100\ \text{GeV})^2$.

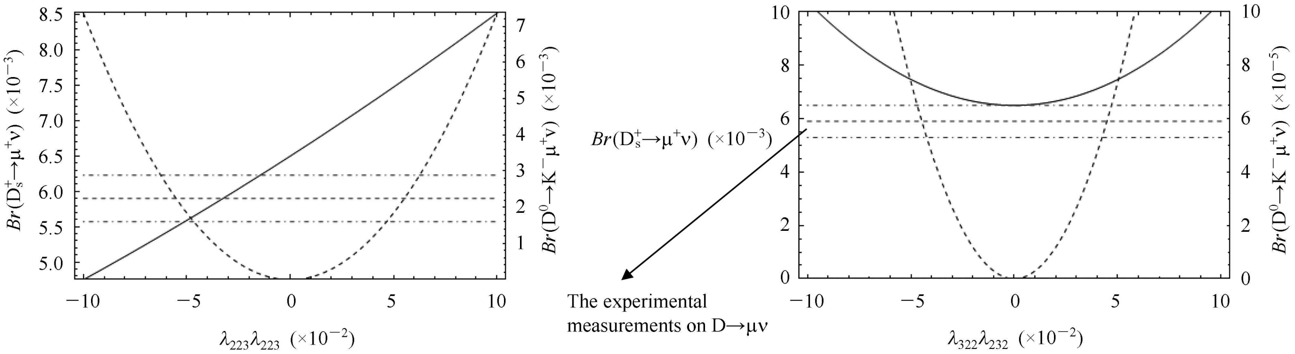

Fig. 11. A graph showing the relations between branching fractions of leptonic and semileptonic decays of charm mesons. The dotted line shows the variation of $Br(D_s^+ \to \mu^+\nu_\mu)$. $\lambda'_{223}\lambda'^*_{223}$ is expressed in units of $1/(m_{\tilde{d}_{iL}}/100\ \mathrm{GeV})^2$.

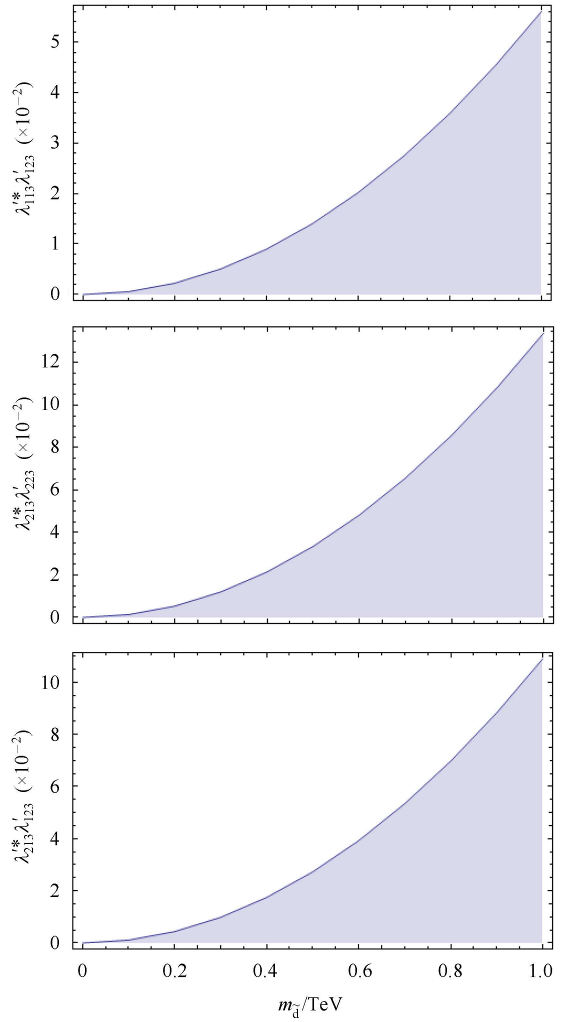

Fig. 12. The evolution of Yukawa couplings $\lambda'\lambda'$ w.r.t. squark mass.

Figure 10 displays a comparison between $D^0 \to K^-e^+\nu_e$ and $D_s^+ \to e^+\nu_e$ having a common set of couplings $(\lambda'^*_{123}\lambda'_{123})$. This comparison shows that $\not{R}_p$ MSSM contribution by squark exchange Yukawa couplings $(\lambda'_{123}\lambda'^*_{123})$ to $D^+ \to e^+\nu_e$ is suppressed but competes with

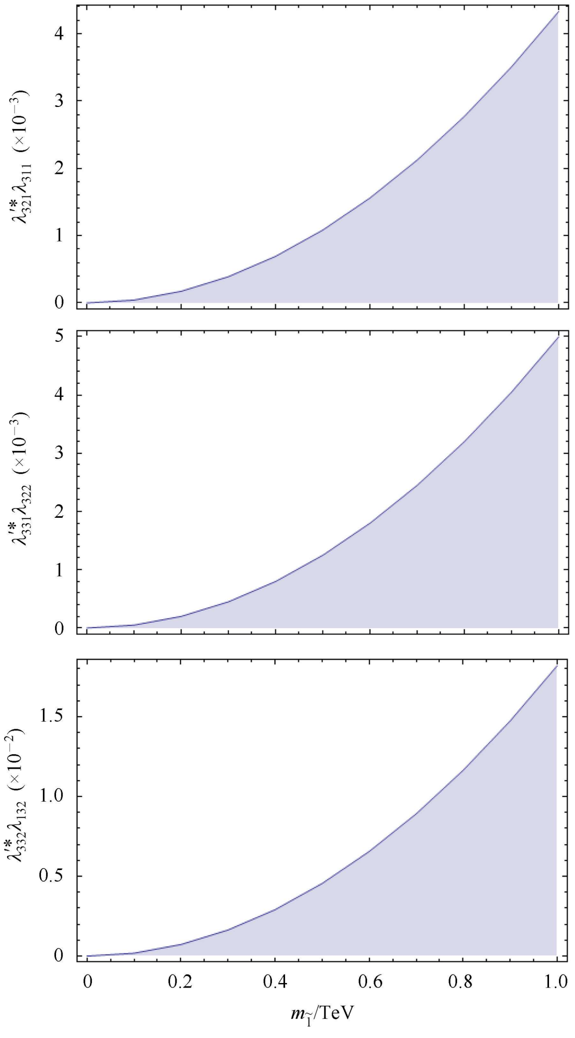

Fig. 13. The evolution of Yukawa couplings $\lambda'\lambda$ w.r.t. slepton mass.

Table 3. A table showing the comparison between the branching fractions of decay processes of charmed mesons ($D_s^{\pm}$, D^0, $D^{\pm}$). (a) Bounds on $|\lambda'^{*}_{131}\lambda'_{132}|$ ($< 5.61\times10^{-4}$) have been obtained from the experimental limits on $Br(D_s^{\pm}\to K^{\pm}e^+e^-)$; (b) Bounds on $|\lambda'^{*}_{231}\lambda'_{232}|$ ($<1.34\times10^{-3}$) have been obtained from the experimental limits on $Br(D_s^{\pm}\to K^{\pm}\mu^+\mu^-)$; (c) Bounds on $|\lambda'^{*}_{231}\lambda'_{132}|$ ($<1.09\times10^{-3}$) have been obtained from the experimental limits on $Br(D_s^{\pm}\to K^{\pm}e^+\mu^-)$.

process	subquark process	branching fraction	branching fraction	branching fraction
		(experimental)	SM	($\not{R}_p$ contribution)
$D^0\to e^+e^-$		$<7.9\times10^{-8}$	1.52×10^{-24}	$\leqslant2.1\times10^{-13}$
$D_s^{\pm}\to K^{\pm}e^+e^-$	$c\to u\ e^+e^-$	$<3.7\times10^{-6}$	4.3×10^{-8}	$\leqslant3.7\times10^{-6}$
$D^{\pm}\to\pi^{\pm}e^+e^-$		$<1.1\times10^{-6}$	2×10^{-6}	$\leqslant0.6\times10^{-6}$
$D^0\to\mu^+\mu^-$		$<1.4\times10^{-7}$	4.76×10^{-20}	$\leqslant0.5\times10^{-7}$
$D_s^{\pm}\to K^{\pm}\mu^+\mu^-$	$c\to u\ \mu^+\mu^-$	$<2.1\times10^{-5}$	4.3×10^{-8}	$\leqslant2.1\times10^{-5}$
$D^{\pm}\to\pi^{\pm}\mu^+\mu^-$		$<3.9\times10^{-6}$	1.9×10^{-6}	$\leqslant3.4\times10^{-6}$
$D^0\to e^+\mu^-$		$<2.6\times10^{-7}$		$\leqslant0.26\times10^{-7}$
$D_s^{\pm}\to K^{\pm}e^+\mu^-$	$c\to u\ e^+\mu^-$	$<1.4\times10^{-5}$		$\leqslant1.4\times10^{-5}$
$D^{\pm}\to\pi^{\pm}e^+\mu^-$		$<2.9\times10^{-6}$		$\leqslant2.4\times10^{-6}$

Table 4. A table showing the comparison between the branching fractions of decay processes of charmed mesons ($D_s^{\pm}$, D^0, $D^{\pm}$). Squark Yukawa couplings products are normalized as $1/(m_{\tilde{d}^c_k}/100\ \text{GeV}^2$. Bounds on $|\lambda'_{123}\lambda'^{*}_{123}|$ ($< 2.22\times10^{-1}$) have been calculated from $Br(D^{\pm}\to K^-e^+\nu_e)$. Bounds on $|\lambda'_{223}\lambda'^{*}_{223}|$ ($< 1.45\times10^{-2}$) have been calculated from $Br(D_s^+\to\mu^+\nu_\mu)$.

processes	subquark process	branching fraction	branching fraction	branching fraction
		(experimental)	SM	($\not{R}_p$ contribution)
$D^0\to\pi^-e^+\nu_e$		$(2.89\pm0.08)\times10^{-3}$		$<2.0\times10^{-7}$
$D^+\to e^+\nu_e$	$(c\to d\ e^+\nu_e)$	$<8.8\times10^{-6}$	1.18×10^{-8}	$<9.4\times10^{-9}$
$D^+\to\pi^0e^+\nu_e$		$(4.05\pm0.18)\times10^{-3}$		$<5\times10^{-7}$
$D^0\to\pi^-\mu^+\nu_\mu$	$(c\to d\ \mu^+\nu_\mu)$	$(2.37\pm0.24)\times10^{-3}$		$<1.5\times10^{-6}$
$D^+\to\mu^+\nu_\mu$		$(3.82\pm0.33)\times10^{-4}$	5×10^{-4}	$<3.96\times10^{-4}$
$D^0\to K^-e^+\nu_e$	$(c\to s\ e^+\nu_e)$	$(3.55\pm0.04)\%$	3.639%	$<3.55\%$
$D_s^+\to e^+\nu_e$		$<1.2\times10^{-4}$	1.5×10^{-7}	$<3.8\times10^{-7}$
$D^0\to K^-\mu^+\nu_\mu$	$(c\to s\ \mu^+\nu_\mu)$	$(3.30\pm0.13)\%$	3.559%	$<0.193\%$
$D_s^+\to\mu^+\nu_\mu$		$(5.90\pm0.33)\times10^{-3}$	6.5×10^{-3}	$<5.90\times10^{-3}$

Table 5. A table showing the comparison between the branching fractions of decay processes of charmed mesons ($D_s^{\pm}$, D^0, $D^{\pm}$). Slepton Yukawa couplings products are normalized as $1/(m_{\tilde{d}^c_k}/100\ \text{GeV}^2)$. Bounds on $|\lambda'^{*}_{321}\lambda_{311}|$ ($<4.33\times10^{-4}$) have been calculated from $Br(D^+\to e^+\nu_e)$. Bounds on $|\lambda'^{*}_{3j1}\lambda_{322}|$ ($<5.0\times10^{-4}$) have been calculated from $Br(D^+\to\mu^+\nu_\mu)$. Bounds on $|\lambda'^{*}_{332}\lambda_{311}|$ ($<1.82\times10^{-3}$) have been calculated from $Br(D_s^+\to e^+\nu_e)$.

processes	subquark process	branching fraction	branching fraction	branching fraction
		(experimental)	SM	($\not{R}_p$ contribution)
$D^0\to\pi^-e^+\nu_e$		$(2.89\pm0.08)\times10^{-3}$		$<1.51\times10^{-6}$
$D^+\to e^+\nu_e$	$(c\to u\ e^+\nu_e)$	$<8.8\times10^{-6}$	1.18×10^{-8}	$<8.8\times10^{-6}$
$D^+\to\pi^0e^+\nu_e$		$(4.05\pm0.18)\times10^{-3}$		$<1.42\times10^{-6}$
$D^0\to\pi^-\mu^+\nu_\mu$	$(c\to d\ \mu^+\nu_\mu)$	$(2.37\pm0.24)\times10^{-3}$		$<7.41\times10^{-7}$
$D^+\to\mu^+\nu_\mu$		$(3.82\pm0.33)\times10^{-4}$	5×10^{-4}	$<3.82\times10^{-4}$
$D^0\to K^-e^+\nu_e$	$(c\to s\ e^+\nu_e)$	$(3.55\pm0.04)\%$		$<9.79\times10^{-6}$
$D_s^+\to e^+\nu_e$		$<1.2\times10^{-4}$	1.5×10^{-7}	$<1.2\times10^{-4}$
$D^0\to K^-\mu^+\nu_\mu$	$(c\to s\ \mu^+\nu_\mu)$	$(3.30\pm0.13)\%$		$<1.54\times10^{-4}$
$D_s^+\to\mu^+\nu_\mu$		$(5.90\pm0.33)\times10^{-3}$	6.5×10^{-3}	$<6.23\times10^{-3}$

Table 6. A comparison of bounds on R-parity violating Yukawa couplings calculated from the analysis with the old bounds available in the literature.

processes	subquark process	Yukawa couplings	bounds (New)	bounds (old)
$\mathrm{D_s^\pm \to K^\pm e^+ e^-}$	$(\mathrm{c \to d\ e^+ e^-})$	$\lvert\lambda'^*_{113}\lambda'_{123}\rvert$	$<5.61\times10^{-4}$	$<8\times10^{-4}$
$\mathrm{D^+ \to e^+ \nu_e}$	$(\mathrm{c \to d\ e^+ \nu_e})$	$\lvert\lambda'^*_{321}\lambda_{311}\rvert$	$<8.8\times10^{-6}$	
$\mathrm{D_s^\pm \to K^\pm e^+ \mu^-}$	$(\mathrm{c \to u\ e^+ \mu^-})$	$\lvert\lambda'^*_{213}\lambda'_{123}\rvert$	$<1.09\times10^{-3}$	$<2.8\times10^{-3}$
$\mathrm{D^0 \to K^- e^+ \nu_e}$	$(\mathrm{c \to s\ e^+ \nu_e})$	$\lvert\lambda'^*_{123}\lambda'_{123}\rvert$	$<2.22\times10^{-1}$	
$\mathrm{D_s^+ \to e^+ \nu_e}$	$(\mathrm{c \to s\ e^+ \nu_e})$	$\lvert\lambda'^*_{332}\lambda_{311}\rvert$	$<1.82\times10^{-3}$	
$\mathrm{D_s^\pm \to K^\pm \mu^+ \mu^-}$	$(\mathrm{c \to u\ \mu^+ \mu^-})$	$\lvert\lambda'^*_{213}\lambda'_{223}\rvert$	$<1.34\times10^{-3}$	$<4.0\times10^{-3}$
$\mathrm{D^+ \to \mu^+ \nu_\mu}$	$(\mathrm{c \to d\ \mu^+ \nu_\mu})$	$\lvert\lambda'^*_{321}\lambda_{322}\rvert$	$<5.0\times10^{-4}$	$<1.01\times10^{-2}$
$\mathrm{D_s \to K e^+ \mu^-}$	$(\mathrm{c \to d\ e^+ \mu^-})$	$\lvert\lambda'^*_{213}\lambda'_{123}\rvert$	$<1.09\times10^{-3}$	$<9.0\times10^{-3}$
$\mathrm{D_s^+ \to \mu^+ \nu_\mu}$	$(\mathrm{c \to s\ \mu^+ \nu_\mu})$	$\lvert\lambda'^*_{223}\lambda'_{223}\rvert$	$<1.45\times10^{-2}$	$<1.0\times10^{-2}$

Table 7. A list of decay processes that are either favorable or unfavorable for the study of $\not{R}_\mathrm{p}$ MSSM.

	favorable	unfavorable
processes	$\mathrm{D^0 \to \mu^+ \mu^-}$	$\mathrm{D^0 \to e^+ e^-}$
	$\mathrm{D^+ \to e^+ \nu_\mu}$	$\mathrm{D^0 \to e^+ \mu^-}$
	$\mathrm{D^+ \to \mu^+ \nu_\mu}$	$\mathrm{D^0 \to \pi^- e^+ \nu_e}$
	$\mathrm{D_s^+ \to e^+ \nu_\mu}$	$\mathrm{D^0 \to \pi^- \mu^+ \nu_\mu}$
	$\mathrm{D_s^+ \to \mu^+ \nu_\mu}$	$\mathrm{D^+ \to \pi^0 e^+ \nu_e}$
	$\mathrm{D^0 \to K^- e^+ \nu_e}$	$\mathrm{D^0 \to K^- \mu^+ \nu_\mu}$
	$\mathrm{D_s^\pm \to K^\pm e^+ e^-}$	
	$\mathrm{D_s^\pm \to K^\pm \mu^+ \mu^-}$	
	$\mathrm{D_s^\pm \to K^\pm e^+ \mu^-}$	
	$\mathrm{D^\pm \to \pi^\pm e^+ e^-}$	
	$\mathrm{D^\pm \to \pi^\pm \mu^+ \mu^-}$	
	$\mathrm{D^\pm \to \pi^\pm e^+ \mu^-}$	

the SM predictions. The contribution by slepton exchange Yukawa couplings ($\lambda'^*_{322}\lambda_{311}$) to $\mathrm{D^+ \to e^+\nu_e}$ is compatible with the experimental bounds and much better than the SM predictions. The $\not{R}_\mathrm{p}$ MSSM contribution by slepton exchange Yukawa couplings ($\lambda'_{123}\lambda'^*_{123}$) to $\mathrm{D^0 \to K^- e^+ \nu_e}$ is compatible with the experimentally measured branching fraction. These two decay processes are favorable for studying the competition between $\not{R}_\mathrm{p}$ MSSM and SM.

Further, a comparison between $\mathrm{D^0 \to K^-\mu^+\nu_\mu}$ and $\mathrm{D_s^+ \to \mu^+\nu_\mu}$ is displayed in Fig. 11. This comparison shows that $\not{R}_\mathrm{p}$ MSSM contribution to $\mathrm{D_s^+ \to \mu^+\nu_\mu}$ is consistent with available experimental data and also with SM. Therefore, this decay process is most favorable for the study of $\not{R}_\mathrm{p}$ MSSM.

Figures 12, 13 show the evolution effect of Yukawa couplings w.r.t corresponding sparticle masses.

Tables 1–3 summarize new bounds on the branching fraction of the pseudoscalar charm meson decay and compared with Ref. [22]. Furthermore, the bounds on the Yukawa couplings can be compared with the bounds from [19], [23].

Table 4 shows a comparison between the $\not{R}_\mathrm{p}$ MSSM Yukawa couplings that are calculated from our analysis and the ones already available in the literature. The comparison shows that the majority of bounds used in our analysis are compatible with the ones existing in the literature, except the bound on $\lambda'_{321}\lambda_{322}$, which is more stringent than the old one. Table 5 comprises a summary of Tables 1–3. It lists those decay processes that are favorable or not for the study of $\not{R}_\mathrm{p}$ MSSM.

Summarizing, we have analyzed the decay processes ($\mathrm{D_s^\pm \to K^\pm l_\alpha^+ l_\beta^- (\nu_\alpha)}$, $\mathrm{D^0 \to l_\alpha^+ l_\beta^-}$, $\mathrm{D^\pm \to \pi^\pm l_\alpha^+ l_\beta^- (\nu_\alpha)}$) and compared their branching fractions against a common parameter $\lambda'_{\beta n1}\lambda'^*_{\alpha m2}$ and $\lambda_{\beta n1}\lambda'^*_{\alpha m2}$. The analysis distinguishes important processes to be studied at various accelerator facilities like the Beijing Electron Positron Collider (BEPC), Fermilab and CLEO detector [11, 13, 24].

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