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Probing the R-parity violating supersymmetric effects in the exclusive $c \to d/s\ell^+\nu_\ell$ decays

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Abstract

A lot of branching ratios of the exclusive $c \to d/s\ell^+\nu_\ell$ ($\ell = e, \mu$) decays have been quite accurately measured by CLEO-c, BELLE, BABAR, BES(I, II, III), ALEPH and MARKIII Collaborations. We probe the R-parity violating supersymmetric effects in the exclusive $c \to d/s\ell^+\nu_\ell$ decays. From the latest experimental measurements, we obtain new upper limits on the relevant R-parity violating coupling parameters within the decays, and many upper limits are obtained for the first time. Using the constrained new parameter spaces, we predict the R-parity violating effects on the observables, which have not been measured yet. We find that the R-parity violating effects due to slepton exchange could be large on the branching ratios of $D_{d/s} \to e^+\nu_e$ decays and the normalized forward-backward asymmetries of $D_{u/d} \to \pi/K\ell^+\nu_\ell$ as well as $D_s \to K\ell^+\nu_\ell$ decays, and the constrained squark exchange couplings have negligible effects in the exclusive $c \to d/s\ell^+\nu_\ell$ decays. Our results in this work could be used to probe new physics effects in the leptonic decays as well as the semileptonic decays, and will correlate with searches for direct supersymmetric signals at LHC and BESIII.

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1. Introduction

The $c \to d/s\ell^+\nu_\ell$ transitions have played a central role for the most precise measurements of CKM matrix elements V_{cd} and V_{cs} for a long time. These rare charmed decays also have received a lot of attention, since they are very promising for investigating the standard model (SM) and searching for new physics (NP) beyond it. The 26 charmed decays, $D^+ \to \ell^+\nu_\ell$, $D^0 \to \pi^-\ell^+\nu_\ell$, $D^+ \to \pi^0\ell^+\nu_\ell$, $D_s^+ \to K^0\ell^+\nu_\ell$, $D^0 \to \rho^-\ell^+\nu_\ell$, $D^+ \to \rho^0\ell^+\nu_\ell$, $D_s^+ \to K^{*0}\ell^+\nu_\ell$, $D_s^+ \to \ell^+\nu_\ell$, $D^0 \to K^-\ell^+\nu_\ell$, $D^+ \to K^0\ell^+\nu_\ell$, $D^0 \to K^{*-}\ell^+\nu_\ell$, $D^+ \to K^{*0}\ell^+\nu_\ell$ and $D_s^+ \to \phi\ell^+\nu_\ell$, are dominated by $c \to d/s\ell^+\nu_\ell$ transitions. Many Collaborations, such as BESIII [1–4], CLEO-c [5–12] and BELLE [13,14], BABAR [15,16], BESII [17], BES [18–21], ALEPH [22] and MARK-III [23], have studied the exclusive $c \to d/s\ell^+\nu_\ell$ decays, and a lot of branching ratios have been quite accurately measured by them. Present experimental measurements are in good agreement with the SM predictions, and they give us an opportunity to disprove NP or find bounds over NP models beyond the SM.

The exclusive $c \to d/s\ell^+\nu_\ell$ decays have been studied extensively in the SM and its various extensions (see for instance Refs. [24–33]). Among the NP models that survived electroweak data, one of the respectable options is the R-parity violating (RPV) supersymmetry (SUSY). The possible appearance of the RPV couplings [34,35], which will violate the lepton and baryon number conservation, has gained full attention in searching for SUSY [36–39]. In the present study, we will give a combined analysis of the semileptonic and leptonic D decays which involve $c \to d/s\ell^+\nu_\ell$ transitions. We will obtain new upper limits on relevant supersymmetric coupling products that satisfy all of the experimental data from the relevant charmed decays. Using the constrained new parameter spaces, we will predict the RPV effects on the branching ratios, the differential branching ratios and the normalized forward–backward (FB) asymmetries of charged leptons. Our results imply that the constrained RPV couplings due to slepton exchange have great effects on $\mathcal{B}(D_{d/s}^+ \to e^+\nu_e)$, and they could obviously enhance the allowed ranges of $\mathcal{A}_{FB}(D \to P\ell^+\nu_\ell)$.

This paper is schemed as follows: In Section 2, we introduce the theoretical frame of the exclusive $c \to d/s\ell^+\nu_\ell$ decays in SUSY without R-parity. In Section 3, we deal with the numerical results. We display the constrained parameter spaces which satisfy all the available experimental data, and then we use the constrained parameter spaces to predict the RPV effects on other quantities, which have not been measured yet. Section 4 contains our summary and conclusion.

2. The exclusive $c \to d/s\ell^+\nu_\ell$ decays in SUSY without R-parity

In the SM, the $c \to d/s\ell^+\nu_\ell$ processes are mediated by a virtual W boson exchange, and the relevant four fermion effective Hamiltonian is

$$\mathcal{H}_{eff}^{SM}(c \to d_k\ell_m^+\nu_{\ell_n}) = \frac{G_F}{\sqrt{2}}V_{cd_k}^*(\bar{d}_k\gamma_\mu(1-\gamma_5)c)(\bar{\nu}_{\ell_n}\gamma^\mu(1-\gamma_5)\ell_m). \tag{1}$$

In the most general superpotential of SUSY, the RPV superpotential is given by [34]

$$\mathcal{W}_{\not R_p} = \mu_i\hat{L}_i\hat{H}_u + \frac{1}{2}\lambda_{[ij]k}\hat{L}_i\hat{L}_j\hat{E}_k^c + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k^c + \frac{1}{2}\lambda''_{i[jk]}\hat{U}_i^c\hat{D}_j^c\hat{D}_k^c, \tag{2}$$

where $\hat{L}$ and $\hat{Q}$ are the SU(2)-doublet lepton and quark superfields, $\hat{E}^c$, $\hat{U}^c$ and $\hat{D}^c$ are the singlet superfields, while i, j and k are generation indices and c denotes a charge conjugate field. From Eq. (2), one can get the relevant R-parity breaking part of the Lagrangian of $c \to d_j\ell_m^+\nu_{\ell_n}$ [38,40]

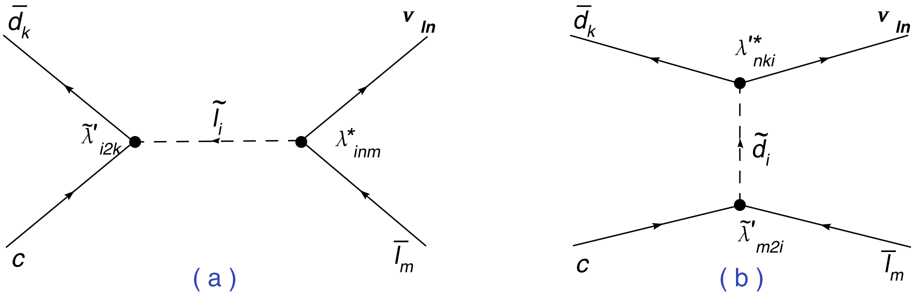

Fig. 1. The RPV contributions to the exclusive $\bar{c} \to \bar{d}_k \ell_m^+ \nu_{\ell_n}$ decays due to slepton and squark exchange.

$$\begin{aligned}\mathcal{L}_{eff}^{\not{R}_p}(c \to d_k \ell_m^+ \nu_{\ell_n}) = &-\sum_{i,j,k} \tilde{\lambda}'_{ijk} \left[\tilde{\ell}_{iL} \bar{d}_{kR} u_{jL} + \tilde{d}^*_{kR} \bar{\ell}^c_{iR} u_{jL} \right] \\ &+ \sum_{i,j,k} \lambda'_{ijk} \left[\tilde{d}^*_{kR} \bar{\nu}^c_{\ell_i R} d_{jL} \right] + \sum_{i,j,k} \lambda_{ijk} \left[\tilde{\ell}_{jL} \bar{\ell}_{kR} \nu_{\ell_i L} \right], \end{aligned} \tag{3}$$

with $\tilde{\lambda}'_{ijk} \equiv \sum_n V^*_{jn} \lambda'_{ink}$, and V_{jn} is the SM CKM matrix element [40]. Noted that (s)down–down–(s)neutrino vertices have the weak eigenbasis couplings λ', while charged (s)lepton–(s)down–(s)up vertices have the up quark mass eigenbasis couplings $\tilde{\lambda}'$. Very often in the literature (see e.g. [41–45]), one neglects the difference between λ' and $\tilde{\lambda}'$, based on the fact that diagonal elements of the CKM matrix dominate over nondiagonal ones.

In terms of Eq. (3), we can obtain the relevant four fermion effective Hamiltonian for the $c \to d_j \ell_m^+ \nu_{\ell_n}$ processes with RPV couplings due to the squark and slepton exchange

$$\begin{aligned}\mathcal{H}_{eff}^{\not{R}_p}(c \to d_k \ell_m^+ \nu_{\ell_n}) = &-\sum_i \frac{\lambda'^*_{nki} \tilde{\lambda}'_{m2i}}{8 m^2_{\tilde{d}_{iR}}} (\bar{d}_k \gamma_\mu (1-\gamma_5) c)(\bar{\nu}_{\ell_n} \gamma^\mu (1-\gamma_5) \ell_m) \\ &+ \sum_i \frac{\lambda^*_{inm} \tilde{\lambda}'_{i2k}}{4 m^2_{\tilde{\ell}_{iL}}} (\bar{d}_k (1-\gamma_5) c)(\bar{\nu}_{\ell_n} (1+\gamma_5) \ell_m). \end{aligned} \tag{4}$$

And the corresponding RPV Feynman diagrams for the $c \to d_k \ell_m^+ \nu_{\ell_n}$ processes are displayed in Fig. 1.

Then we can obtain the total effective Hamiltonian for $c \to d_k \ell_m^+ \nu_{\ell_n}$ in the RPV SUSY

$$\mathcal{H}_{eff}(c \to d_k \ell_m^+ \nu_{\ell_n}) = \mathcal{H}_{eff}^{SM}(c \to d_k \ell_m^+ \nu_{\ell_n}) + \mathcal{H}_{eff}^{\not{R}_p}(c \to d_k \ell_m^+ \nu_{\ell_n}). \tag{5}$$

Based on the effective Hamiltonian in Eq. (5), we will give the expressions of physical quantities for the RPV SUSY later in detail. In the following expressions and numerical analysis, we will keep the masses of the charged leptons, but ignore all neutrino masses.

2.1. $D^+_{d/s} \to \ell^+ \nu_\ell$ decays

Purely leptonic decays are the simplest and the cleanest decay modes of the pseudoscalar charged D^+ meson, and the decay amplitude of $D^+_{d_k} \to \ell^+ \nu_\ell$ can be obtained in the terms of Eq. (5)

$$\begin{aligned}
&\mathcal{M}^{\not{R}_p}(D^+_{d_k} \to \ell^+_m \nu_{\ell_n})\\
&\quad = <\ell^+_m \nu_{\ell_n}|\mathcal{H}_{eff}(c \to d_k \ell^+_m \nu_{\ell_n})|D^+_{d_k}>\\
&\quad = \left[\frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right] <0|\bar{d}_k \gamma_\mu (1-\gamma_5) c|D^+_{d_k}> (\bar{\nu}_{\ell_n}\gamma^\mu (1-\gamma_5)\ell_m)\\
&\qquad + \sum_i \frac{\lambda^*_{inm}\tilde{\lambda}'_{i2k}}{4m^2_{\tilde{\ell}_{iL}}} < 0|\bar{d}_k (1-\gamma_5) c|D^+_{d_k}>(\bar{\nu}_{\ell_n}(1+\gamma_5)\ell_m).
\end{aligned} \tag{6}$$

After using the definitions of D meson decay constant [46]

$$< 0|\bar{d}_k \gamma_\mu \gamma_5 c|D^+(p)>= i f_D p_\mu, \tag{7}$$

and

$$< 0|\bar{d}_k \gamma_5 c|D^+(p)>= -i f_D \mu_{D_q}, \tag{8}$$

where $\mu_{D_{d_k}} \equiv \frac{m^2_{D_{d_k}}}{\bar{m}_c + \bar{m}_{d_k}}$ and $\bar{m}_q$ is the current quark mass at m_c scale, we get the branching ratio for $D^+_{d/s} \to \ell^+ \nu_\ell$

$$\begin{aligned}
\mathcal{B}^{\not{R}_p}(D^+_{d_k} \to \ell^+_m \nu_{\ell_n}) = &\left|\frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}} + \sum_i \frac{\lambda^*_{inm}\tilde{\lambda}'_{i2k}}{4m^2_{\tilde{\ell}_{iL}}} \frac{\mu_{D_{d_k}}}{m_{\ell_m}}\right|^2\\
&\times \frac{\tau_{D_{d_k}}}{4\pi} f^2_{D_{d_k}} m_{D_{d_k}} m^2_{\ell_m} \left[1 - \frac{m^2_{\ell_m}}{m^2_{D_{d_k}}}\right]^2.
\end{aligned} \tag{9}$$

2.2. $D \to P\ell^+\nu_\ell$ $(P = \pi, K)$ decays

In the terms of Eq. (5), $D \to P\ell^+\nu_\ell$ decay amplitude can be written as

$$\begin{aligned}
&\mathcal{M}^{\not{R}_p}(D \to P\ell^+_m \nu_{\ell_n})\\
&\quad = \langle P\ell^+_m \nu_{\ell_n}|\mathcal{H}_{eff}(c \to d_k \ell^+_m \nu_{\ell_n})|D\rangle\\
&\quad = \left[\frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right] \langle P|\bar{d}_k \gamma_\mu (1-\gamma_5) c|D\rangle (\bar{\nu}_{\ell_n}\gamma^\mu (1-\gamma_5)\ell_m)\\
&\qquad + \sum_i \frac{\lambda^*_{inm}\tilde{\lambda}'_{i2k}}{4m^2_{\tilde{\ell}_{iL}}} \langle P|\bar{d}_k (1-\gamma_5) c|D\rangle (\bar{\nu}_{l_n}(1+\gamma_5)\bar{\ell}_m).
\end{aligned} \tag{10}$$

Using the $D \to P$ transition form factors [48]

$$c_P \left\langle P(p)\left|\bar{d}_k \gamma_\mu c\right| D(p_D)\right\rangle = f^P_+(s)(p+p_D)_\mu + \left[f^P_0(s) - f^P_+(s)\right] \frac{m^2_D - m^2_P}{s} q_\mu, \tag{11}$$

$$c_P \left\langle P(p)\left|\bar{d}_k c\right| D(p_D)\right\rangle = f^P_0(s) \frac{m^2_D - m^2_P}{\bar{m}_c - \bar{m}_{d_k}}, \tag{12}$$

with the factor c_P accounts for the flavor content of particles ($c_P=\sqrt{2}$ for π^0, and $c_P=1$ for π^-, K^0, K^-), $s=q^2$ ($q=p_D-p$), and the definitions of $f^P_{0,+}(s)$ can be found in Ref. [48], the differential branching ratio for $D\to P\ell^+_m\nu_{\ell_n}$ is

$$\frac{d\mathcal{B}^{\not{R}_p}(D\to P\ell^+_m\nu_{\ell_n})}{ds\,d\cos\theta}=\frac{\tau_D\sqrt{\lambda_P}}{2^7\pi^3m_D^3c_P^2}\left(1-\frac{m^2_{\ell_m}}{s}\right)^2\left[N_0^P+N_1^P\cos\theta+N_2^P\cos^2\theta\right], \tag{13}$$

with

$$\begin{aligned}N_0^P=&\left|\frac{G_F}{\sqrt{2}}V^*_{cd_k}-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right|^2[f_+^P(s)]^2\lambda_P+\left|\frac{G_F}{\sqrt{2}}V^*_{cd_k}-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right.\\&\left.+\sum_i\frac{\lambda^*_{inm}\tilde{\lambda}'_{i2k}}{4m^2_{\tilde{\ell}_{iL}}}\frac{s}{m_{\ell_m}(\bar{m}_c-\bar{m}_{d_k})}\right|^2m^2_{\ell_m}[f_0^P(s)]^2\frac{(m_D^2-m_P^2)^2}{s},\end{aligned} \tag{14}$$

$$\begin{aligned}N_1^P=&\left\{\left|\frac{G_F}{\sqrt{2}}V^*_{cd_k}-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right|^2+Re\left[\left(\frac{G_F}{\sqrt{2}}V^*_{cd_k}-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right)^\dagger\right.\right.\\&\left.\left.\times\sum_i\frac{\lambda^*_{inm}\tilde{\lambda}'_{i2k}}{4m^2_{\tilde{\ell}_{iL}}}\frac{s}{m_{\ell_m}(\bar{m}_c-\bar{m}_{d_k})}\right]\right\}2m^2_{\ell_m}f_0^P(s)f_+^P(s)\sqrt{\lambda_P}\frac{(m_D^2-m_P^2)}{s},\end{aligned} \tag{15}$$

$$N_2^P=-\left|\frac{G_F}{\sqrt{2}}V^*_{cd_k}-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right|^2[f_+^P(s)]^2\lambda_P\left(1-\frac{m^2_{\ell_m}}{s}\right), \tag{16}$$

where θ is the angle between the momentum of D meson and the charged lepton in the c.m. system of $\ell-\nu$, and the kinematic factor $\lambda_M=m_D^4+m_M^4+s^2-2m_D^2m_M^2-2m_D^2s-2m_M^2s$.

Here, we give the definition of the normalized forward–backward asymmetry of charged lepton, which is more useful from the experimental point of view,

$$\bar{\mathcal{A}}_{FB}=\frac{\int_0^{+1}\frac{d^2\mathcal{B}}{ds\,d\cos\theta}d\cos\theta-\int_{-1}^{0}\frac{d^2\mathcal{B}}{ds\,d\cos\theta}d\cos\theta}{\int_0^{+1}\frac{d^2\mathcal{B}}{ds\,d\cos\theta}d\cos\theta+\int_{-1}^{0}\frac{d^2\mathcal{B}}{ds\,d\cos\theta}d\cos\theta}. \tag{17}$$

Explicitly, for $D\to P\ell^+\nu_\ell$ the normalized FB asymmetry is

$$\bar{\mathcal{A}}_{FB}(D\to P\ell^+\nu_\ell)=\frac{N_1^P}{2N_0^P+2/3N_2^P}. \tag{18}$$

2.3. $D\to V\ell^+\nu_l$ ($V=\rho,K^*,\phi$) decays

From Eq. (5), $D\to V\ell^+\nu_\ell$ decay amplitude can be written as

$$\begin{aligned}&\mathcal{M}^{\not{R}_p}(D\to V\ell^+_m\nu_{\ell_n})\\&=\langle V\ell^+_m\nu_{\ell_n}|\mathcal{H}_{eff}(c\to d_k\ell^+_m\nu_{\ell_n})|D\rangle\end{aligned}$$

$$= \left[\frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki} \tilde{\lambda}'_{m2i}}{8 m^2_{\tilde{d}_{iR}}} \right] \left\langle V \middle| \bar{d}_k \gamma_\mu (1-\gamma_5) c \middle| D \right\rangle (\bar{\nu}_{\ell_n} \gamma^\mu (1-\gamma_5) \ell_m)$$

$$+ \sum_i \frac{\lambda^*_{inm} \tilde{\lambda}'_{i2k}}{4 m^2_{\tilde{\ell}_{iL}}} \left\langle V \middle| \bar{d}_k (1-\gamma_5) c \middle| D \right\rangle (\bar{\nu}_{\ell_n} (1+\gamma_5) \ell_m). \tag{19}$$

In terms of the $D \to V$ form factors [48]

$$c_V \left\langle V(p,\varepsilon^*) \middle| \bar{d}_k \gamma_\mu (1-\gamma_5) c \middle| D(p_D) \right\rangle$$

$$= \frac{2V^V(s)}{m_D + m_V} \epsilon_{\mu\nu\alpha\beta} \varepsilon^{*\nu} p_D^\alpha p^\beta$$

$$- i \left[\varepsilon^*_\mu (m_D + m_V) A_1^V(s) - (p_D + p)_\mu (\varepsilon^* . p_D) \frac{A_2^V(s)}{m_D + m_V} \right]$$

$$+ i q_\mu (\varepsilon^* . p_D) \frac{2 m_V}{s} [A_3^V(s) - A_0^V(s)], \tag{20}$$

$$c_V \left\langle V(p,\varepsilon^*) \middle| \bar{d}_k \gamma_5 c \middle| D(p_D) \right\rangle = -i \frac{\varepsilon^* . p_D}{m_D} \frac{2 m_D m_V}{\bar{m}_c + \bar{m}_{d_k}} A_0^V(s), \tag{21}$$

where $c_V = \sqrt{2}$ for ρ^0, $c_V = 1$ for ρ^-, K^{*0}, K^{*-}, ϕ, the definitions of $V^V(s)$ and $A_i^V(s)$ can be found in Ref. [48], and ε^* is the polarization of vector meson, we have

$$\frac{d\mathcal{B}^{\not{R}_p}(D \to V \ell^+_m \nu_{\ell_n})}{ds\, d\cos\theta} = \frac{\tau_D \sqrt{\lambda_V}}{2^7 \pi^3 m_D^3 c_V^2} \left(1 - \frac{m^2_{\ell_m}}{s}\right)^2 \left[N_0^V + N_1^V \cos\theta + N_2^V \cos^2\theta \right], \tag{22}$$

with

$$N_0^V = \left| \frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki} \tilde{\lambda}'_{m2i}}{8 m^2_{\tilde{d}_{iR}}} \right|^2 \Bigg\{ [A_1^V(s)]^2 \left(\frac{\lambda_V}{4 m_V^2} + (m^2_{\ell_m} + 2s) \right) (m_D + m_V)^2$$

$$+ [A_2^V(s)]^2 \frac{\lambda_V^2}{4 m_V^2 (m_D + m_V)^2} + [V^V(s)]^2 \frac{\lambda_V}{(m_D + m_V)^2} (m^2_{\ell_m} + s)$$

$$- A_1^V(s) A_2^V(s) \frac{\lambda_V}{2 m_V^2} (m_D^2 - s - m_V^2) \Bigg\}$$

$$+ \left| \frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki} \tilde{\lambda}'_{m2i}}{8 m^2_{\tilde{d}_{iR}}} + \sum_i \frac{\lambda^*_{inm} \tilde{\lambda}'_{i2k}}{4 m^2_{\tilde{\ell}_{iL}}} \frac{s}{m_{\ell_m} (\bar{m}_c + \bar{m}_{d_k})} \right|^2 [A_0^V(s)]^2 \frac{m^2_{\ell_m}}{s} \lambda_V, \tag{23}$$

$$N_1^V = \Bigg\{ \left| \frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki} \tilde{\lambda}'_{m2i}}{8 m^2_{\tilde{d}_{iR}}} \right|^2$$

$$+ Re \left[\left(\frac{G_F}{\sqrt{2}} V^*_{cd_k} - \sum_i \frac{\lambda'^*_{nki} \tilde{\lambda}'_{m2i}}{8 m^2_{\tilde{d}_{iR}}} \right)^\dagger \sum_i \frac{\lambda^*_{inm} \tilde{\lambda}'_{i2k}}{4 m^2_{\tilde{\ell}_{iL}}} \frac{s}{m_{\ell_m} (\bar{m}_c + \bar{m}_{d_k})} \right] \Bigg\}$$

$$\times\left[A_0^V(s)A_1^V(s)\frac{m_{\ell_m}^2(m_D+m_V)(m_D^2-m_V^2-s)\sqrt{\lambda_V}}{sm_V}\right.$$

$$\left.-A_0^V(s)A_2^V(s)\frac{m_{\ell_m}^2\lambda_V^{3/2}}{sm_V(m_D+m_V)}\right]$$

$$+\left|\frac{G_F}{\sqrt{2}}V_{cd_k}^*-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right|^2 A_1^V(s)V^V(s)4s\sqrt{\lambda_V}, \tag{24}$$

$$N_2^V=-\left|\frac{G_F}{\sqrt{2}}V_{cd_k}^*-\sum_i\frac{\lambda'^*_{nki}\tilde{\lambda}'_{m2i}}{8m^2_{\tilde{d}_{iR}}}\right|^2\left(1-\frac{m_{\ell_m}^2}{s}\right)\lambda_V\left\{[A_1^V(s)]^2\frac{(m_D+m_V)^2}{4m_V^2}\right.$$

$$+[V^V(s)]^2\frac{s}{(m_D+m_V)^2}+[A_2^V(s)]^2\frac{\lambda_V}{4m_V^2(m_D+m_V)^2}$$

$$\left.-A_1^V(s)A_2^V(s)\frac{m_D^2-m_V^2-s}{2m_V^2}\right\}. \tag{25}$$

The normalized FB asymmetry of $D\to V\ell^+\nu_\ell$ can be written as

$$\bar{A}_{FB}(D\to V\ell^+\nu_\ell)=\frac{N_1^V}{2N_0^V+2/3N_2^V}. \tag{26}$$

3. Numerical results and discussions

In this section, we summarize our numerical results and analysis of RPV couplings in the exclusive $c\to d/s\ell^+\nu_\ell$ decays. The relevant physical inputs needed for the computation are as follow. The masses, the mean lives and the CKM matrix elements are taken from PDG [47]. The calculations for relevant form factors have been improved significantly, for instance Refs. [48–53]. We use the reliable predictions for hadronic form factors in Ref. [48], in which includes all relevant form factors we considered. The meson decay constants of D^+ and D_s in Ref. [54] are used to compute the leptonic branching ratio. To be conservative, the form factors with 10% uncertainties at $q^2=0$ as well as the input parameters and the experimental bounds at 68% confidence level (CL) (i.e. within 1σ error) and 90% CL (i.e. within 1.64σ error) will be used to constrain parameters of the relevant new couplings.

The total theoretical uncertainties of relevant semileptonic decay (differential) branching ratios are calculated straightforward: propagating each uncertainty for every physical constant as reported in PDG [47]. The theoretical uncertainties mainly coming from the form factors. The branching ratios will have around 5%, 30%, 46% uncertainties if considering 5%, 10%, 15% uncertainties of the form factors at $q^2=0$, respectively. We can believe that the normalized FB asymmetries could be much more accurate than that for the branching ratios, since many uncertainties could be canceled in the ratios.

As mentioned in last section, both squark and slepton exchange couplings contribute to exclusive $c\to d/s\ell^+\nu_\ell$ decays. For the squark exchange couplings, $|\lambda'_{11i}\lambda'_{12i}|$ and $|\lambda'_{21i}\lambda'_{22i}|$, which appear in exclusive $c\to d\ell^+\nu_\ell$ decays, are strongly constrained from $K^+\to\pi^+\nu\bar{\nu}$ decay [55], $|\lambda'_{12i}\lambda'_{12i}|$ and $|\lambda'_{22i}\lambda'_{22i}|$, which appear in exclusive $c\to s\ell^+\nu_\ell$ decays, are strongly constrained

Table 1
Branching ratios of the exclusive $c \to d e^+ \nu_e$ decays are in units of 10^{-3} except for branching ratio of $D_d^+ \to e^+ \nu_e$ is in units of 10^{-8}. For the experimental data, "a line" shown in the last column denotes the experimental measurements with 1σ error, and "b line" shown in the last column denotes the corresponding 90% CL experimental range. For the theoretical predictions in the third and forth columns, "a line" and "b line" denote the theoretical predictions by using the input parameters with 1σ and 1.64σ errors, respectively. In the forth column, "SUSY w/$\lambda^*_{i11}\tilde{\lambda}'_{i21}$" denotes the SUSY predictions considering the $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ coupling effects. Since there is no the 68% CL experimental upper limit of $\mathcal{B}(D_d^+ \to e^+ \nu_e)$, we have used their 90% CL experimental upper limit to constrain $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ coupling. The similar in Tables 3, 4, 5.

Observable	Exp. data	SM predictions	SUSY w/$\lambda^*_{i11}\tilde{\lambda}'_{i21}$	
$\mathcal{B}(D_d^+ \to e^+ \nu_e)$	$\cdots$	$[0.91,\ 1.13]$	< 880	a
	< 880	$[0.84, 1.21]$	< 880	b
$\mathcal{B}(D_u^0 \to \pi^- e^+ \nu_e)$	2.89 ± 0.08	$[2.79, 4.23]$	$[2.95, 2.97]$	a
	$[2.76, 3.02]$	$[2.40, 4.72]$	$[2.85, 3.02]$	b
$\mathcal{B}(D_d^+ \to \pi^0 e^+ \nu_e)$	4.05 ± 0.18	$[3.61, 5.50]$	$[3.87, 3.90]$	a
	$[3.75, 4.35]$	$[3.09, 6.15]$	$[3.75, 3.98]$	b
$\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e)$	3.7 ± 1.0	$[2.58, 3.98]$	$[2.70, 3.96]$	a
	$[2.06, 5.34]$	$[2.20, 4.48]$	$[2.21, 4.49]$	b
$\mathcal{B}(D_u^0 \to \rho^- e^+ \nu_e)$	1.9 ± 0.4	$[1.30, 2.20]$	$[1.50, 2.00]$	a
	$[1.24, 2.56]$	$[1.06, 2.53]$	$[1.24, 2.24]$	b
$\mathcal{B}(D_d^+ \to \rho^0 e^+ \nu_e)$	2.2 ± 0.4	$[1.68, 2.85]$	$[1.95, 2.60]$	a
	$[1.54, 2.86]$	$[1.37, 3.28]$	$[1.58, 2.86]$	b
$\mathcal{B}(D_s^+ \to K^{*0} e^+ \nu_e)$	1.8 ± 0.7	$[1.44, 2.38]$	$[1.45, 2.36]$	a
	$[0.65, 2.95]$	$[1.17, 2.76]$	$[1.18, 2.78]$	b

from charged current universality and $D \to K\ell\nu$ [56]. The effects of the squark exchange couplings on exclusive $c \to d/s\ell^+\nu_\ell$ decays are almost negligible because of the lacking the $1/m_\ell$ enhancement, and they will not provide any significant effect on the branching ratios and the normalized FB asymmetries of exclusive $c \to d/s\ell^+\nu_\ell$ decays. So we will only focus on the slepton exchange coupling effects on exclusive $c \to d/s\ell^+\nu_\ell$ decays when we study the effects due to SUSY without R-parity in this work.

3.1. The exclusive $c \to d e^+ \nu_e$ decays

RPV coupling product $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ due to slepton exchange contributes to seven exclusive $c \to d e^+ \nu_e$ decay modes, $D_d^+ \to e^+\nu_e$, $D_u^0 \to \pi^- e^+ \nu_e$, $D_d^+ \to \pi^0 e^+ \nu_e$, $D_s^+ \to K^0 e^+ \nu_e$, $D_u^0 \to \rho^- e^+ \nu_e$, $D_d^+ \to \rho^0 e^+ \nu_e$ and $D_s^+ \to K^{*0} e^+ \nu_e$. All relevant semileptonic branching ratios of the exclusive $c \to d e^+ \nu_e$ decays have been accurately measured by BESIII [1–3], CLEO-c [5–8] and Belle [13], furthermore, the pureleptonic branching ratio of $D_d^+ \to e^+ \nu_e$ is upperlimited by CLEO-c [9]. Their average values with 1σ error bars from PDG [47] and corresponding experimental ranges at 90% CL are given in the second column of Table 1. Moreover, the SM prediction values with 10% uncertainties for the form factors at $q^2 = 0$ as well as with 1σ and 1.64σ error ranges for the input parameters are listed in the third column of Table 1. We can see that the both branching ratios by using the inputs within 1σ or 1.64σ errors have no big difference, these small differences mainly come from different error bars of relevant CKM matrix

Table 2

Bounds for the relevant RPV coupling products due to the mass of the corresponding slepton is 500 GeV and previous bounds are listed for comparison. "a" and "b" denote the bounds with the experimental measurements and theoretical predictions at 68% and 90% CL, respectively.

Couplings	Our bounds		Previous bounds
$\lvert\lambda_{i11}\lambda'_{i21}\rvert$	0.010^a 0.010^b	from $c \to d e^+ \nu_e$	$i = 2, 0.22$ [56] $i = 3, 0.81$ [56]
$\lvert\lambda_{i22}\lambda'_{i21}\rvert$	$\ldots^a$ 0.142^b	from $c \to d \mu^+ \nu_\mu$	$i = 1, 3.8 \times 10^{-5}$ [57] $i = 3, 0.91$ [56]
$\lvert\lambda_{i11}\lambda'_{i22}\rvert$	0.042^a 0.045^b	from $c \to s e^+ \nu_e$	$i = 2, 0.26$ [56] $i = 3, 0.81$ [56]
$\lvert\lambda_{i22}\lambda'_{i22}\rvert$	0.552^a 0.602^b	from $c \to s \mu^+ \nu_\mu$	$i = 1, 0.053$ [56] $i = 3, 0.91$ [56]

elements, the branching ratios will have about 1% uncertainties if considering the CKM matrix element V_{cd} within 1σ error, and the main uncertainties of relevant branching ratios come from the form factors. The theoretical predictions of relevant branching ratios are consistent with experimental data at the present level of precision, and we can constrain the relevant NP parameter spaces by these D decays.

The 68% CL or 90% CL experimental data of the exclusive $c \to d e^+ \nu_e$ decays give very strong constraint on the modulus of $\lambda^*_{i11}\tilde{\lambda}'_{i21}$, but the RPV weak phase of $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ is not obviously constrained by current experimental measurements. The bound on $|\lambda^*_{i11}\tilde{\lambda}'_{i21}|$ is listed in the second line of Table 2. Our bound on the direct quadric couplings $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ is derived for the first time. For comparison, previous bounds, which are calculated from the products of two single couplings in [56], are also listed. Our bound on $|\lambda^*_{i11}\tilde{\lambda}'_{i21}|$ from the exclusive $c \to d e^+ \nu_e$ decays is much stronger than previous one from the products of two single couplings.

Now we will analyze the constrained RPV effects in the exclusive $c \to d e^+ \nu_e$ decays. Using the constrained parameter spaces from the exclusive $c \to d e^+ \nu_e$ decays, we can predict the constrained RPV effects on the branching ratios, the differential branching ratios and the normalized FB asymmetries of charged leptons. The numerical results for the branching ratios are listed in the last column of Table 1, and the constrained RPV effects of $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ at 90% CL in the exclusive $c \to d e^+ \nu_e$ decays are displayed in Fig. 2. Comparing the RPV SUSY predictions to the SM ones or experimental bounds given in Table 1 and in Fig. 2, we give some remarks as follows. For the slepton exchange coupling $\lambda^*_{i11}\tilde{\lambda}'_{i21}$, since its contribution to $\mathcal{B}(D_d^+ \to e^+ \nu_e)$ is increased by m_D/m_e, as shown in Fig. 2(a–b), $\mathcal{B}(D_d^+ \to e^+ \nu_e)$ can be extremely enhanced or reduced by the constrained $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ coupling, and it is very sensitive to both modulus and weak phase of $\lambda^*_{i11}\tilde{\lambda}'_{i21}$, furthermore, $|\lambda^*_{i11}\tilde{\lambda}'_{i21}|$ is tightly upper-limited by the experimental measurement of $\mathcal{B}(D_d^+ \to e^+ \nu_e)$. The constrained slepton exchange coupling $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ has no obvious contribution to the six semileptonic decay branching ratios. From the forth column of Table 1, one can find that present accurate experimental measurements of $\mathcal{B}(D_u^0 \to \pi^- e^+ \nu_e)$ and $\mathcal{B}(D_d^+ \to \pi^0 e^+ \nu_e)$ give very strong bounds on the semileptonic decay branching ratio predictions with $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ coupling. As for the differential branching ratios and the normalized FB asymmetries of relevant semileptonic D decays, slepton exchange RPV contributions to $D_u^0 \to \pi^- e^+ \nu_e$, $D_d^+ \to \pi^0 e^+ \nu_e$ and $D_s^+ \to K^0 e^+ \nu_e$ ($D_u^0 \to \rho^- e^+ \nu_e$, $D_d^+ \to \rho^0 e^+ \nu_e$ and $D_s^+ \to K^{*0} e^+ \nu_e$) are very similar to each other. We would take $D_u^0 \to \pi^- e^+ \nu_e$ and $D_u^0 \to \rho^- e^+ \nu_e$ as examples (the similar

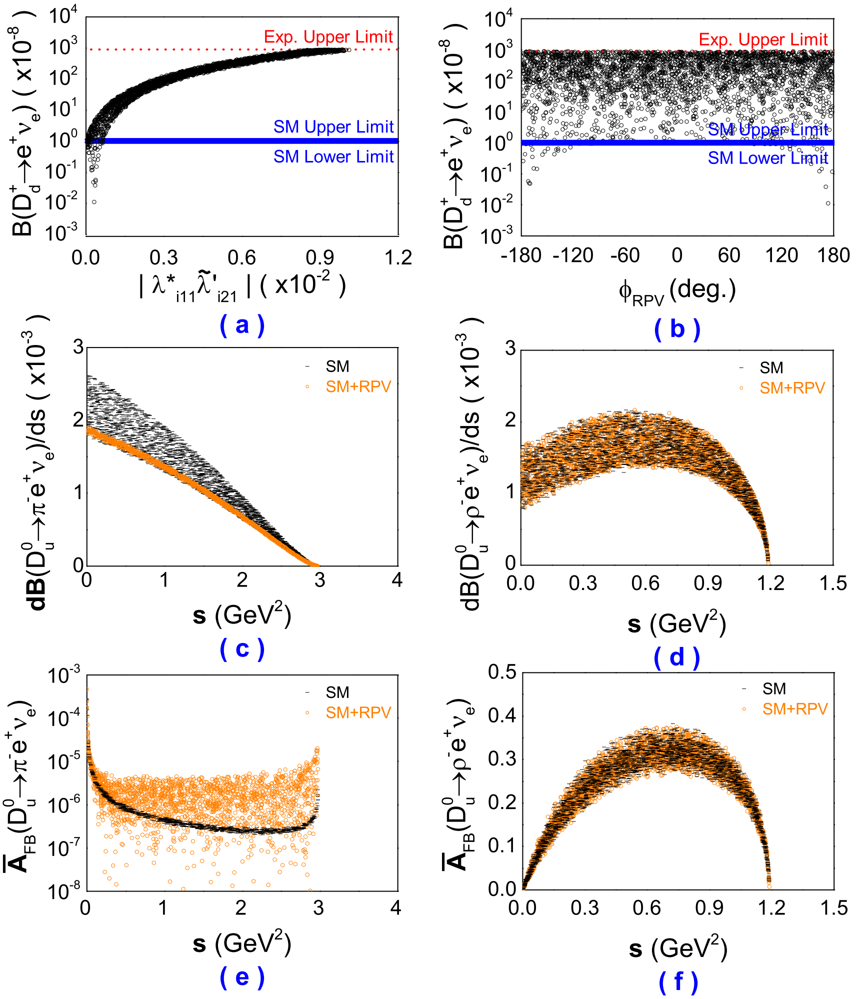

Fig. 2. The constrained effects of RPV coupling $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ due to the slepton exchange a 90% CL in the exclusive $c \to de^+\nu_e$ decays.

in the subsections of the exclusive $c \to d\mu^+\nu_\mu, \bar{s}e^+\nu_e, \bar{s}\mu^+\nu_\mu$ decays), which are shown by Fig. 2(c, e) and Fig. 2(d, f), respectively. We can see that present accurate experimental measurements of $\mathcal{B}(D^0_u \to \pi^- e^+\nu_e)$ and $\mathcal{B}(D^+_d \to \pi^0 e^+\nu_e)$ also give very strong bounds on their differential branching ratios, the constrained $\lambda^*_{i11}\tilde{\lambda}'_{i21}$ coupling let the differential branching ratios close to their SM upper limits. Nevertheless, other differential branching ratios (including $d\mathcal{B}(D^+_s \to K^0 e^+\nu_e)/ds$) are not constrained so much by present experimental measurements given in Table 1. The RPV predictions of the four differential branching ratios of $D^+_s \to K^0 e^+\nu_e$, $D^0_u \to \rho^- e^+\nu_e$, $D^+_d \to \rho^0 e^+\nu_e$ and $D^+_s \to K^{*0} e^+\nu_e$ decays can not be distinguished from their SM ones at all s range. As displayed in Fig. 2(e), the constrained slepton exchange coupling has quite large effects on the normalized FB asymmetries of $D^0_u \to \pi^- e^+\nu_e$, $D^+_d \to \pi^0 e^+\nu_e$ and $D^+_s \to K^0 e^+\nu_e$ decays, but these values are very tiny.

Table 3
Branching ratios of the exclusive $c \to d\mu^+\nu_\mu$ decays (in units of 10^{-3}) except for $\mathcal{B}(D_d^+ \to \mu^+\nu_\mu)$ (in units of 10^{-4}).

Observable	Exp. data	SM predictions	SUSY w/$\lambda^*_{i22}\tilde{\lambda}'_{i21}$	
$\mathcal{B}(D_d^+ \to \mu^+\nu_\mu)$	3.82 ± 0.33	[3.84, 4.82]	$\cdots$	*a*
	[3.28, 4.36]	[3.54, 5.11]	[3.28, 4.36]	*b*
$\mathcal{B}(D_u^0 \to \pi^-\mu^+\nu_\mu)$	2.37 ± 0.24	[2.76, 4.14]	$\cdots$	*a*
	[1.98, 2.76]	[2.36, 4.64]	[2.34, 2.76]	*b*
$\mathcal{B}(D_d^+ \to \pi^0\mu^+\nu_\mu)$	$\cdots$	[3.57, 5.39]	$\cdots$	*a*
	$\cdots$	[3.05, 6.05]	[3.02, 3.64]	*b*
$\mathcal{B}(D_s^+ \to K^0\mu^+\nu_\mu)$	$\cdots$	[2.52, 3.87]	$\cdots$	*a*
	$\cdots$	[2.15, 4.37]	[2.16, 4.34]	*b*
$\mathcal{B}(D_u^0 \to \rho^-\mu^+\nu_\mu)$	$\cdots$	[1.26, 2.10]	$\cdots$	*a*
	$\cdots$	[1.03, 2.41]	[1.33, 2.35]	*b*
$\mathcal{B}(D_u^0 \to \rho^-\mu^+\nu_\mu)$	2.4 ± 0.4	[1.62, 2.70]	$\cdots$	*a*
	[1.74, 3.06]	[1.33, 3.14]	[1.74, 3.05]	*b*
$\mathcal{B}(D_s^+ \to K^{*0}\mu^+\nu_\mu)$	$\cdots$	[1.38, 2.27]	$\cdots$	*a*
	$\cdots$	[1.15, 2.61]	[1.18, 2.54]	*b*

Noted that the RPV effects on purely leptonic decays $D^+_{d/s} \to e^+\nu$, which no experimental limits existed at that time, has been considered in Ref. [33]. Here the helicity unsuppressed s-channel contributions mediated by combinations of $\lambda\lambda'$ were focused, and only single coupling bounds in Ref. [56] were used. They found that quite large RPV contributions to $\mathcal{B}(D^+_{d/s} \to e^+\nu)$ could occur if the neutrino is ν_τ. Just lepton flavor violating processes are not considered in this paper.

3.2. The exclusive $c \to d\mu^+\nu_\mu$ decays

Two RPV coupling products, $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ due to slepton exchange and $\lambda'^*_{21i}\tilde{\lambda}'_{22i}$ due to squark exchange, contribute to seven exclusive $c \to d\mu^+\nu_\mu$ decay modes, $D_d^+ \to \mu^+\nu_\mu$, $D_u^0 \to \pi^-\mu^+\nu_\mu$, $D_d^+ \to \pi^0\mu^+\nu_\mu$, $D_s^+ \to K^0\mu^+\nu_\mu$, $D_u^0 \to \rho^-\mu^+\nu_\mu$, $D_d^+ \to \rho^0\mu^+\nu_\mu$ and $D_s^+ \to K^{*0}\mu^+\nu_\mu$. Three relevant branching ratios of the exclusive $c \to d\mu^+\nu_\mu$ decays have been measured by BESIII [4], CLEO-c [8,9], Belle [13] and BES [18], and their average values with 1σ error from PDG [47] and corresponding experimental range at 90% CL are given in the second column of Table 3. The SM prediction values with 10% uncertainties for the form factors at $q^2 = 0$ as well as with 1σ and 1.64σ error ranges for the input parameters are listed in the third column of Table 3.

At 68% CL, $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ coupling is ruled out by present experimental measurements. Our bound for $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ from the 90% CL experimental data is demonstrated in Fig. 3, and both modulus and weak phase of $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ are strongly constrained by the experimental measurements of $\mathcal{B}(D_u^0 \to \pi^-\mu^+\nu_\mu)$ and $\mathcal{B}(D_d^+ \to \rho^0\mu^+\nu_\mu)$. The bound on $|\lambda^*_{i22}\tilde{\lambda}'_{i21}|$ is listed in the third line of Table 2, and previous bounds are listed for comparing. We get $|\lambda^*_{i22}\tilde{\lambda}'_{i21}| \leq 0.142$ with 500 GeV sfermion mass. The bound on the direct quadric couplings $|\lambda^*_{322}\tilde{\lambda}'_{321}|$ is obtained for the first time, and it's stronger than one from the products of two single couplings in [56]. The RPV coupling $\lambda^*_{122}\lambda'_{121}$

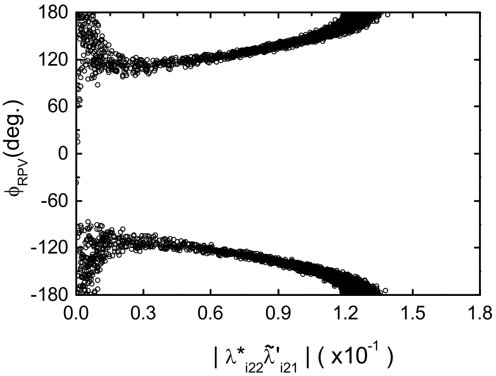

Fig. 3. The allowed RPV parameter spaces from the exclusive $c \to d\mu^+\nu_\mu$ decays at 90% CL with 500 GeV sfermion mass.

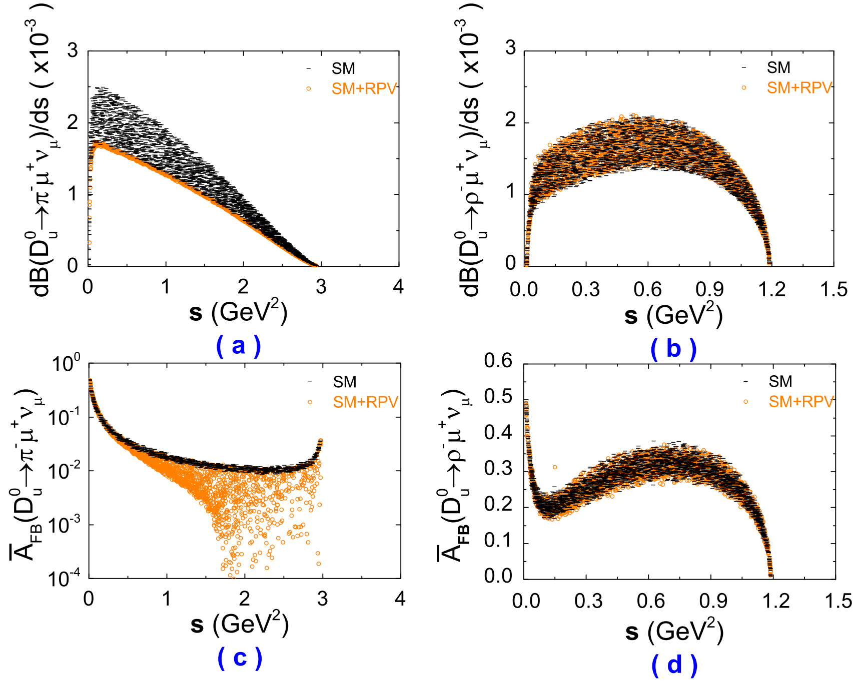

Fig. 4. The constrained effects of RPV coupling $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ due to the slepton exchange at 90% CL in the exclusive $c \to d\mu^+\nu_\mu$ decays.

could strongly contribute to $K_L \to \mu^+\mu^-$ decay, and one got that $|\lambda^*_{122}\lambda'_{121}| < 3.8 \times 10^{-5}$ from $\mathcal{B}(K_L \to \mu^+\mu^-)$ [57], which is 10^4 better than our one from the exclusive $c \to d\mu^+\nu_\mu$ decays.

Now we discuss the constrained RPV effects in the exclusive $c \to d\mu^+\nu_\mu$ decays. The numerical results for the branching ratios are listed in the last column of Table 3, and the constrained RPV effects of $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ in the exclusive $c \to d\mu^+\nu_\mu$ decays are shown in Fig. 4. We have the following remarks for the constrained RPV effects.

Table 4
Branching ratios of the exclusive $c \to se^+\nu_e$ decays (in units of 10^{-2}) except for $\mathcal{B}(D_s^+ \to e^+\nu_e)$ (in units of 10^{-7}).

Observable	Exp. data	SM predictions	SUSY w/$\lambda^*_{i11}\tilde{\lambda}'_{i22}$	
$\mathcal{B}(D_s^+ \to e^+\nu_e)$	$\cdots$	[1.23, 1.49]	[0.02, 1200]	*a*
	< 1200	[1.15, 1.58]	[0.02, 1200]	*b*
$\mathcal{B}(D_u^0 \to K^-e^+\nu_e)$	3.55 ± 0.05	[3.11, 4.67]	[3.51, 3.57]	*a*
	[3.47, 3.63]	[2.68, 5.25]	[3.48, 3.62]	*b*
$\mathcal{B}(D_d^+ \to K^0e^+\nu_e)$	8.83 ± 0.22	[7.93, 11.96]	[8.89, 9.05]	*a*
	[8.47, 9.19]	[6.81, 13.49]	[8.82, 9.19]	*b*
$\mathcal{B}(D_u^0 \to K^{*-}e^+\nu_e)$	2.16 ± 0.16	[1.84, 2.99]	[2.10, 2.25]	*a*
	[1.90, 2.42]	[1.52, 3.46]	[2.03, 2.30]	*b*
$\mathcal{B}(D_d^+ \to K^{*0}e^+\nu_e)$	5.52 ± 0.15	[4.68, 7.65]	[5.37, 5.67]	*a*
	[5.27, 5.77]	[3.85, 8.88]	[5.27, 5.76]	*b*
$\mathcal{B}(D_s^+ \to \phi e^+\nu_e)$	2.49 ± 0.14	[2.00, 3.26]	[2.35, 2.63]	*a*
	[2.26, 2.72]	[1.65, 3.78]	[2.26, 2.72]	*b*

For the slepton exchange coupling $\lambda^*_{i22}\tilde{\lambda}'_{i21}$, since all seven relevant branching ratios are not sensitive to both modulus and weak phase of the constrained $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ coupling, we do not show them in Fig. 4. From the forth column of Table 3 and Fig. 4(a–b), one can find that present accurate experimental measurements of $\mathcal{B}(D_u^0 \to \pi^-\mu^+\nu_\mu)$ and $\mathcal{B}(D_d^+ \to \rho^0\mu^+\nu_\mu)$ give very strong bounds on the branching ratios and the differential branching ratios of $D_u^0 \to \pi^-\mu^+\nu_\mu$, $D_d^+ \to \pi^0\mu^+\nu_\mu$ and $D_d^+ \to \rho^0\mu^+\nu_\mu$ decays, but it does not give obvious bound on other branching ratios and differential branching ratios. Considering the stronger bound on $|\lambda_{122}\lambda'_{121}| \leq 3.8 \times 10^{-5}$ in Ref. [57], $\lambda_{122}\lambda'_{121}$ coupling has no obvious effect on $\mathcal{A}_{FB}(D_u^0 \to \pi^-\mu^+\nu_\mu, D_d^+ \to \pi^0\mu^+\nu_\mu, D^0+_s \to K^0\mu^+\nu_\mu)$. As shown in Fig. 4(c), the constrained $\lambda^*_{322}\tilde{\lambda}'_{321}$ coupling still could have great effects on $\mathcal{A}_{FB}(D_u^0 \to \pi^-\mu^+\nu_\mu, D_d^+ \to \pi^0\mu^+\nu_\mu, D^0+_s \to K^0\mu^+\nu_\mu)$ at the middle and high s regions. Nevertheless, Fig. 4(d) shows us the constrained $\lambda^*_{i22}\tilde{\lambda}'_{i21}$ coupling has no obvious effect on $\mathcal{A}_{FB}(D_u^0 \to \rho^-\mu^+\nu_\mu, D_d^+ \to \rho^0\mu^+\nu_\mu, D_s^+ \to K^*\mu^+\nu_\mu)$.

3.3. The exclusive $c \to se^+\nu_e$ decays

RPV coupling product $\lambda^*_{i11}\tilde{\lambda}'_{i22}$ due to slepton exchange contributes to six exclusive $c \to se^+\nu_e$ decay modes, $D_s^+ \to e^+\nu_e$, $D_u^0 \to K^-e^+\nu_e$, $D_d^+ \to K^0e^+\nu_e$, $D_u^0 \to K^{*-}e^+\nu_e$, $D_d^+ \to K^{*0}e^+\nu_e$ and $D_s^+ \to \phi e^+\nu_e$. All relevant semileptonic branching ratios of the exclusive $c \to se^+\nu_e$ decays have been accurately measured and the pureleptonic branching ratios of $D_s^+ \to e^+\nu_e$ has been upperlimited by BESIII [2], CLEO-c [5,7,10–12], BABAR [15,16], BES [20,21], Belle [13] and MARK-III [23]. Their average values with 1σ error from PDG [47] and corresponding experimental bounds at 90% CL are given in the second column of Table 4. Moreover, the SM prediction values with 10% uncertainties for the form factors at $q^2 = 0$ as well as with 1σ and 1.64σ error ranges for the input parameters are listed in the third column of Table 4.

The weak phase of $\lambda^*_{i11}\tilde{\lambda}'_{i22}$ is not obviously constrained by present experimental data of the exclusive $c \to se^+\nu_e$ decays. The upper limits of $|\lambda^*_{i11}\tilde{\lambda}'_{i22}|$ from the 68% and 90% CL experimental data are listed in the forth line of Table 2. The direct quadric coupling $|\lambda^*_{i11}\tilde{\lambda}'_{i22}|$ is derived for the first time. Our bound on $|\lambda^*_{i11}\tilde{\lambda}'_{i22}|$ is stronger than previous one in [56].

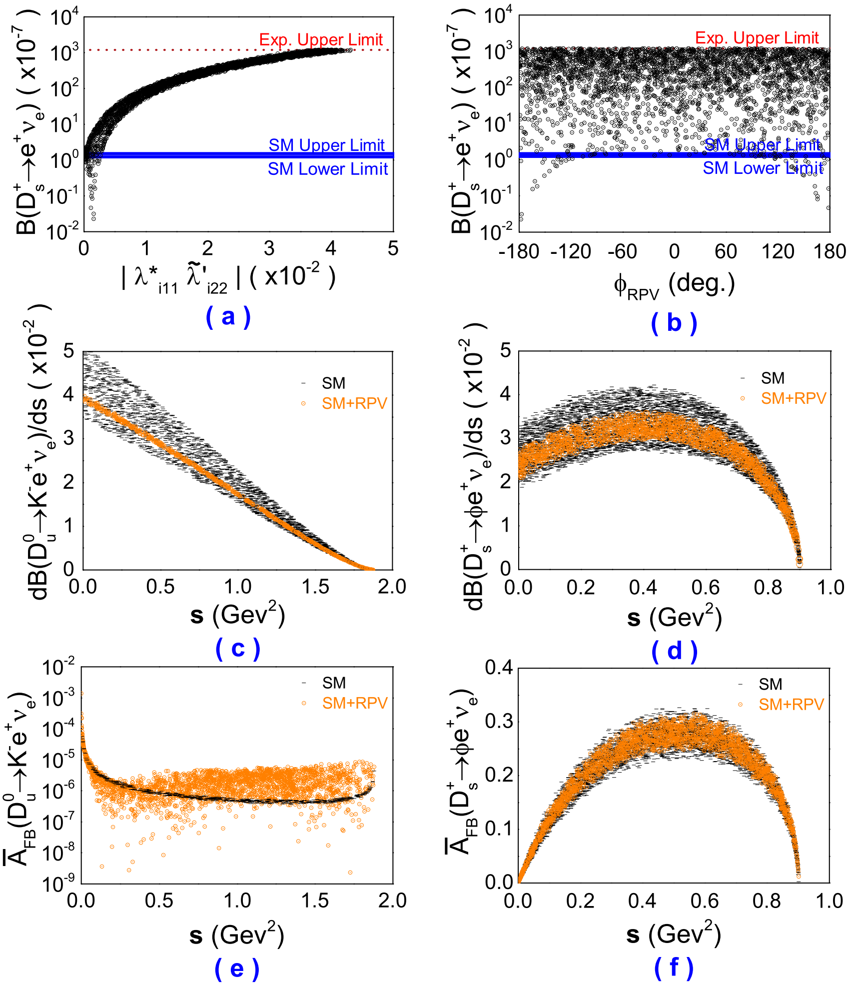

Fig. 5. The constrained effects of RPV coupling $\lambda^*_{i11}\tilde{\lambda}'_{i22}$ due to the slepton exchange at 90% CL in the exclusive $c \to s e^+ \nu_e$ decays.

We also predict the constrained RPV effects in the exclusive $c \to s e^+ \nu_e$ decays. The numerical results for the branching ratios are listed in the last column of Table 4. The branching ratios of the five semileptonic decays are significantly constrained by present experimental bounds, and they are not sensitive to constrained RPV couplings. The constrained RPV effects on other observables due to the slepton exchange are displayed in Fig. 5. One can see that the RPV effects on other observables in the exclusive $c \to s e^+ \nu_e$ decays are similar to ones in the exclusive $c \to d e^+ \nu_e$ decays. Just all differential branching ratios of the semileptonic D decays are stronger-constrained by relevant experimental measurements.

3.4. The exclusive $c \to s \mu^+ \nu_\mu$ decays

Slepton exchange coupling $\lambda^*_{i22}\tilde{\lambda}'_{i22}$ contributes to six exclusive $c \to s \mu^+ \nu_\mu$ decay modes, $D_s^+ \to \mu^+\nu_\mu$, $D_u^0 \to K^-\mu^+\nu_\mu$, $D_d^+ \to K^0\mu^+\nu_\mu$, $D_u^0 \to K^{*-}\mu^+\nu_\mu$, $D_d^+ \to K^{*0}\mu^+\nu_\mu$ and

Table 5
Branching ratios of the exclusive $c \to s\mu^+\nu_\mu$ decays (in units of 10^{-2}) except for $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$ (in units of 10^{-3}).

Observable	Exp. data	SM predictions	SUSY w/$\lambda^*_{i22}\tilde{\lambda}'_{i22}$	
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$	5.90 ± 0.33	$[5.22, 6.33]$	$[5.57, 6.23]$	*a*
	$[5.36, 6.44]$	$[4.89, 6.72]$	$[5.36, 6.44]$	*b*
$\mathcal{B}(D_u^0 \to K^-\mu^+\nu_\mu)$	3.31 ± 0.13	$[3.03, 4.53]$	$[3.33, 3.44]$	*a*
	$[3.10, 3.52]$	$[2.61, 5.09]$	$[3.17, 3.52]$	*b*
$\mathcal{B}(D_d^+ \to K^0\mu^+\nu_\mu)$	9.2 ± 0.6	$[7.72, 11.62]$	$[8.60, 8.87]$	*a*
	$[8.22, 10.18]$	$[6.64, 13.06]$	$[8.22, 9.03]$	*b*
$\mathcal{B}(D_u^0 \to K^{*-}\mu^+\nu_\mu)$	1.91 ± 0.24	$[1.76, 2.80]$	$[1.99, 2.15]$	*a*
	$[1.52, 2.30]$	$[1.47, 3.24]$	$[1.95, 2.20]$	*b*
$\mathcal{B}(D_d^+ \to K^{*0}\mu^+\nu_\mu)$	5.28 ± 0.15	$[4.51, 7.19]$	$[5.13, 5.43]$	*a*
	$[5.03, 5.53]$	$[3.74, 8.26]$	$[5.03, 5.53]$	*b*
$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu)$	$\cdots$	$[1.90, 3.06]$	$[1.93, 3.03]$	*a*
	$\cdots$	$[1.59, 3.49]$	$[1.60, 3.48]$	*b*

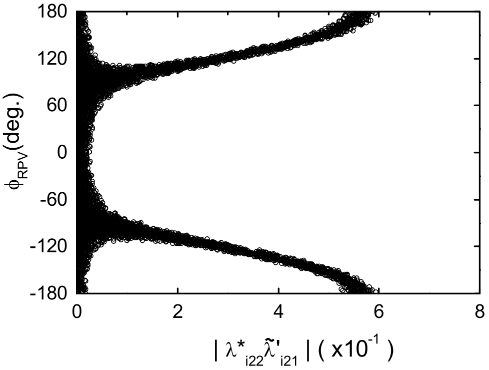

Fig. 6. The allowed RPV parameter spaces from the exclusive $c \to s\mu^+\nu_\mu$ decays at 90% CL with 500 GeV sfermion mass.

$D_s^+ \to \phi\mu^+\nu_\mu$. All branching ratios of the exclusive $c \to s\mu^+\nu_\mu$ decays except $\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu)$ have been accurately measured by CLEO-c [10,11], BESII [17], Belle [13,14], BABAR [15] and ALEPH [22]. And their experimental average values from PDG [47] and the SM prediction values are listed in the second and third columns of Table 5, respectively.

Our bounds for $\lambda^*_{i22}\tilde{\lambda}'_{i22}$ from the 90% CL experimental data are demonstrated in Fig. 6, and the upper limit of $|\lambda^*_{i22}\tilde{\lambda}'_{i22}|$ is listed in the last line of Table 2. In the case of $i = 1$, our bound on $|\lambda^*_{122}\tilde{\lambda}'_{122}|$ is weaker one order than previous one in [56], nevertheless, in the case of $i = 3$, our bound on $|\lambda^*_{322}\tilde{\lambda}'_{322}|$ is a little stronger than one in [56]. The constrained RPV effects in the exclusive $c \to s\mu^+\nu_\mu$ decays are also explored. The numerical results for the branching ratios are listed in the last column of Table 5, and we can see that all relevant experimental bounds except $\mathcal{B}(D_u^0 \to K^{*-}\mu^+\nu_\mu)$ give constraints on the RPV predictions. All RPV predictions of the branching ratios except $\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu)$ are significantly constrained by present experimental bounds, and they are not sensitive to the constrained RPV couplings. The constrained RPV effects on other observables due to the slepton exchange are displayed in Fig. 7. Noted

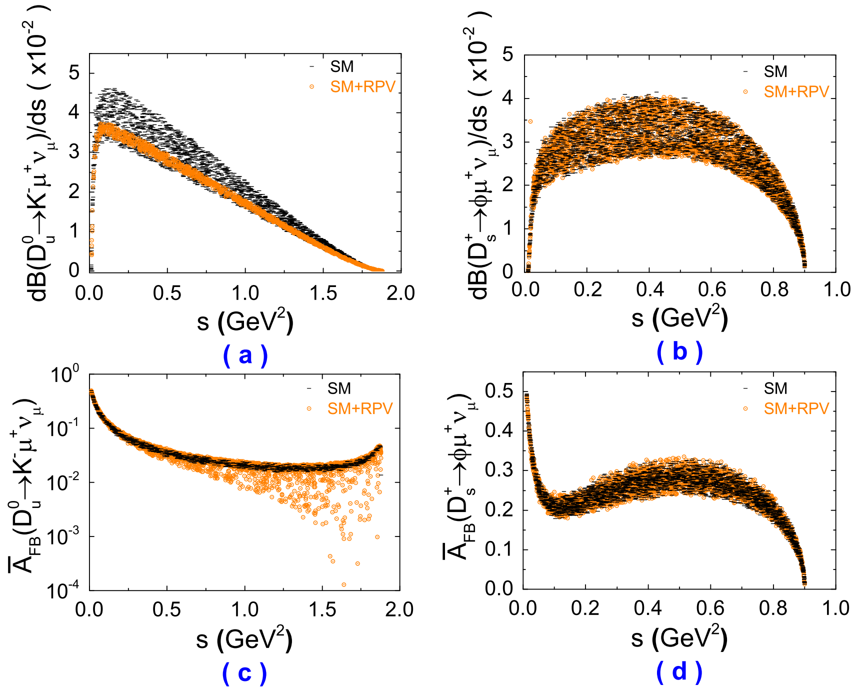

Fig. 7. The constrained effects of RPV coupling $\lambda^*_{i22}\tilde{\lambda}'_{i22}$ due to the slepton exchange at 90% CL in the exclusive $c \to s\mu^+\nu_\mu$ decays.

that the RPV effects on the differential branching ratios and the normalized FB asymmetries of relevant semileptonic decays in the exclusive $c \to s\mu^+\nu_\mu$ decays are similar to ones in the exclusive $c \to d\mu^+\nu_\mu$ decays. Just all differential branching ratios of the semileptonic D decays except $D_s^+ \to \phi\mu^+\nu_\mu$ are stronger-constrained by relevant experimental measurements. As for $\lambda_{122}\lambda'_{122}$ coupling, if considering the stronger bound, $|\lambda_{i22}\lambda'_{i22}| \leq 0.053$ [56], this coupling has no obvious effect on $\mathcal{A}_{FB}(D_u^0 \to \pi^-\mu^+\nu_\mu, D_d^+ \to \pi^0\mu^+\nu_\mu, D^0+_s \to K^0\mu^+\nu_\mu)$, too.

4. Conclusion

In this paper, we have studied RPV effects in the 26 semileptonic and leptonic D meson decays, $D^+ \to \ell^+\nu_\ell$, $D^0 \to \pi^-\ell^+\nu_\ell$, $D^+ \to \pi^0\ell^+\nu_\ell$, $D_s^+ \to K^0\ell^+\nu_\ell$, $D^0 \to \rho^-\ell^+\nu_\ell$, $D^+ \to \rho^0\ell^+\nu_\ell$, $D_s^+ \to K^{*0}\ell^+\nu_\ell$, $D_s^+ \to \ell^+\nu_\ell$, $D^0 \to K^-\ell^+\nu_\ell$, $D^+ \to K^0\ell^+\nu_\ell$, $D^0 \to K^{*-}\ell^+\nu_\ell$, $D^+ \to K^{*0}\ell^+\nu_\ell$ and $D_s^+ \to \phi\ell^+\nu_\ell$ with $\ell = e, \mu$. Considering the theoretical uncertainties and the experimental errors at 68% and 90% CL, we have constrained fairly parameter spaces of RPV coupling constants from the present experimental data, and many bounds are obtained for the first time. Furthermore, we have predicted the RPV effects on the branching ratios, the differential branching ratios and the normalized FB asymmetries of charged leptons, which have not been measured yet.

We have found that the constrained RPV effects due to squark exchange can be neglect, but the constrained RPV effects due to slepton exchange could be large on the branching ratios of pureleptonic $D_{d/s}^+ \to e^+\nu_e$ decays and the normalized FB asymmetries of semileptonic

$D_{u/d} \to \pi/K\ell^+\nu_\ell$ as well as $D_s^+ \to K^0\ell^+\nu_\ell$ decays. Such correlated signals would provide strong evidence for RPV interactions. The results in this paper could be useful for probing the RPV SUSY effects, and will correlate strongly with searches for the direct SUSY signals at future experiments.

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References

[1] H. Ma, PoS Hadron 2013 (2014) 076.
[2] H.-B. Li, Nucl. Phys. B, Proc. Suppl. 233 (2012) 185, arXiv:1209.3059 [hep-ex].
[3] G. Huang, BESIII Collaboration, arXiv:1209.4813 [hep-ex].
[4] M. Ablikim, et al., BESIII Collaboration, Phys. Rev. D 89 (2014) 051104, arXiv:1312.0374 [hep-ex].
[5] D. Besson, et al., CLEO Collaboration, Phys. Rev. D 80 (2009) 032005, arXiv:0906.2983 [hep-ex].
[6] G.S. Huang, et al., CLEO Collaboration, Phys. Rev. Lett. 95 (2005) 181801, arXiv:hep-ex/0506053.
[7] T.E. Coan, et al., CLEO Collaboration, Phys. Rev. Lett. 95 (2005) 181802, arXiv:hep-ex/0506052.
[8] J. Yelton, et al., CLEO Collaboration, Phys. Rev. D 80 (2009) 052007, arXiv:0903.0601 [hep-ex].
[9] B.I. Eisenstein, et al., CLEO Collaboration, Phys. Rev. D 78 (2008) 052003, arXiv:0806.2112 [hep-ex].
[10] R.A. Briere, et al., CLEO Collaboration, Phys. Rev. D 81 (2010) 112001, arXiv:1004.1954 [hep-ex].
[11] J.P. Alexander, et al., CLEO Collaboration, Phys. Rev. D 79 (2009) 052001, arXiv:0901.1216 [hep-ex].
[12] K.M. Ecklund, et al., CLEO Collaboration, Phys. Rev. D 80 (2009) 052009, arXiv:0907.3201 [hep-ex].
[13] L. Widhalm, et al., Belle Collaboration, Phys. Rev. Lett. 97 (2006) 061804, arXiv:hep-ex/0604049.
[14] L. Widhalm, et al., Belle Collaboration, Phys. Rev. Lett. 100 (2008) 241801, arXiv:0709.1340 [hep-ex].
[15] P. del Amo Sanchez, et al., BaBar Collaboration, Phys. Rev. D 82 (2010) 091103, arXiv:1008.4080 [hep-ex].
[16] B. Aubert, et al., BaBar Collaboration, Phys. Rev. D 78 (2008) 051101, arXiv:0807.1599 [hep-ex].
[17] M. Ablikim, et al., BES Collaboration, Phys. Lett. B 644 (2007) 20, arXiv:hep-ex/0610020.
[18] M. Ablikim, et al., BES Collaboration, Phys. Lett. B 610 (2005) 183, arXiv:hep-ex/0410050.
[19] M. Ablikim, et al., BES Collaboration, Phys. Lett. B 608 (2005) 24, arXiv:hep-ex/0410030.
[20] M. Ablikim, et al., BES Collaboration, Eur. Phys. J. C 47 (2006) 31, arXiv:hep-ex/0605103.
[21] M. Ablikim, et al., BES Collaboration, Phys. Lett. B 597 (2004) 39, arXiv:hep-ex/0406028.
[22] A. Heister, et al., ALEPH Collaboration, Phys. Lett. B 528 (2002) 1, arXiv:hep-ex/0201024.
[23] J. Adler, et al., MARK-III Collaboration, Phys. Rev. Lett. 62 (1989) 1821.
[24] J. Barranco, D. Delepine, V. Gonzalez Macias, L. Lopez-Lozano, arXiv:1404.0454 [hep-ph].
[25] J. Barranco, D. Delepine, V. Gonzalez Macias, L. Lopez-Lozano, Phys. Lett. B 731 (2014) 36, arXiv:1303.3896 [hep-ph].
[26] A.G. Akeroyd, F. Mahmoudi, J. High Energy Phys. 0904 (2009) 121, arXiv:0902.2393 [hep-ph].
[27] B.A. Dobrescu, A.S. Kronfeld, Phys. Rev. Lett. 100 (2008) 241802, arXiv:0803.0512 [hep-ph].
[28] A.G. Akeroyd, C.H. Chen, Phys. Rev. D 75 (2007) 075004, arXiv:hep-ph/0701078.
[29] S. Fajfer, J.F. Kamenik, Phys. Rev. D 73 (2006) 057503, arXiv:hep-ph/0601028.
[30] S. Fajfer, J.F. Kamenik, Phys. Rev. D 72 (2005) 034029, arXiv:hep-ph/0506051.
[31] S. Fajfer, J.F. Kamenik, Phys. Rev. D 71 (2005) 014020, arXiv:hep-ph/0412140.
[32] A.G. Akeroyd, Prog. Theor. Phys. 111 (2004) 295, arXiv:hep-ph/0308260.
[33] A.G. Akeroyd, S. Recksiegel, Phys. Lett. B 554 (2003) 38, arXiv:hep-ph/0210376.
[34] S. Weinberg, Phys. Rev. D 26 (1982) 287.
[35] N. Sakai, T. Yanagida, Nucl. Phys. B 197 (1982) 533;
C.S. Aulakh, R.N. Mohapatra, Phys. Lett. B 119 (1982) 136.
[36] R. Barbier, et al., Phys. Rep. 420 (2005) 1, arXiv:hep-ph/0406039 and references therein.
[37] R. Barbier, et al., arXiv:hep-ph/9810232.
[38] M. Chemtob, Prog. Part. Nucl. Phys. 54 (2005) 71, arXiv:hep-ph/0406029.
[39] B. Allanach, et al., R parity Working Group Collaboration, arXiv:hep-ph/9906224, and references therein.

[40] A.A. Petrov, G.K. Yeghiyan, Phys. Rev. D 77 (2008) 034018, arXiv:0710.4939 [hep-ph].
[41] E. Golowich, S. Pakvasa, A.A. Petrov, Phys. Rev. Lett. 98 (2007) 181801, arXiv:hep-ph/0610039.
[42] S.-L. Chen, X.-G. He, A. Hovhannisyan, H.-C. Tsai, J. High Energy Phys. 0709 (2007) 044, arXiv:0706.1100 [hep-ph].
[43] S. Nandi, J.P. Saha, Phys. Rev. D 74 (2006) 095007, arXiv:hep-ph/0608341.
[44] G. Bhattacharyya, A. Raychaudhuri, Phys. Rev. D 57 (1998) 3837, arXiv:hep-ph/9712245.
[45] A. Kundu, J.P. Saha, Phys. Rev. D 70 (2004) 096002, arXiv:hep-ph/0403154.
[46] B. Grinstein, et al., Nucl. Phys. B 380 (1992) 369, arXiv:hep-ph/9204207.
[47] J. Beringer, et al., Particle Data Group, Phys. Rev. D 86 (2012) 010001, and 2013 partial update for the 2014 edition.
[48] D. Melikhov, B. Stech, Phys. Rev. D 62 (2000) 014006, arXiv:hep-ph/0001113.
[49] Y.-L. Wu, M. Zhong, Y.-B. Zuo, Int. J. Mod. Phys. A 21 (2006) 6125, arXiv:hep-ph/0604007.
[50] J. Koponen, C.T.H. Davies, G.C. Donald, E. Follana, G.P. Lepage, H. Na, J. Shigemitsu, arXiv:1305.1462 [hep-lat].
[51] H. Na, C.T.H. Davies, E. Follana, G.P. Lepage, J. Shigemitsu, Phys. Rev. D 82 (2010) 114506, arXiv:1008.4562 [hep-lat].
[52] C. Aubin, et al., Fermilab Lattice Collaboration, MILC Collaboration, HPQCD Collaboration, Phys. Rev. Lett. 94 (2005) 011601, arXiv:hep-ph/0408306.
[53] D. Scora, N. Isgur, Phys. Rev. D 52 (1995) 2783, arXiv:hep-ph/9503486.
[54] A. Bazavov, et al., Fermilab Lattice Collaboration, MILC Collaboration, Phys. Rev. D 85 (2012) 114506, arXiv:1112.3051 [hep-lat].
[55] Ru-Min Wang, et al., arXiv:1409.0181 [hep-ph].
[56] B.C. Allanach, A. Dedes, H.K. Dreiner, Phys. Rev. D 60 (1999) 075014, arXiv:hep-ph/9906209.
[57] D. Choudhury, P. Roy, Phys. Lett. B 378 (1996) 153, arXiv:hep-ph/9603363.