The double charm decays of B Mesons in the mSUGRA model

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Abstract

Based on the low energy effective Hamiltonian with naive factorization, we calculate the branching ratios (BRs) and CP asymmetries (CPAs) for the twenty three double charm decays $B/B_s \rightarrow D^{(*)}_{(s)} D^{(*)}_{(s)}$ in both the standard model (SM) and the minimal supergravity (mSUGRA) model. Within the considered parameter space, we find that (a) the theoretical predictions for the BRs, CPAs and the polarization fractions in the SM and the mSUGRA model are all consistent with the currently available data within $\pm 2\sigma$ errors; (b) For all the considered decays, the supersymmetric contributions in the mSUGRA model are very small, less than 7% numerically. It may be difficult to observe so small SUSY contributions even at LHC.

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I. INTRODUCTION

Within the standard model (SM), the double charm decays of $B_{u,d}$ and $B_s$ Mesons considered here are dominated by the color-favored “Tree” transition $b \rightarrow c\bar{c}d(s)$, while the color-suppressed “Penguin” transition is generally small. If the penguin contribution was absent, the mixing induced CP asymmetry (CPA), denoted as $S_f$, would be proportional to $\sin(2\beta)$, while the direct CPA, denoted as $C_f$, would be zero. In some new physics models beyond the SM, the penguin contributions can be large and may change the SM predictions for the branching ratios and the CP asymmetries (CPA) significantly. The study of these double charm $B/B_s$ meson decays therefore plays an important role in testing the SM as well as searching for the signals of the new physics (NP).

Experimentally, the BaBar and Belle Collaboration have reported the measurement of the direct CPA in $B^0 \rightarrow D^+D^-$ decay

$$C(B^0 \rightarrow D^+D^-) = \begin{cases} -0.91 \pm 0.23 \pm 0.06 \ (\text{Belle [1]}), \\ -0.07 \pm 0.23 \pm 0.03 \ (\text{BaBar [2]}) \end{cases} \quad (1)$$

It is easy to see that Belle found an evidence of CP violation in $B^0 \rightarrow D^+D^-$ at the 4.1$\sigma$ level [1], but BaBar did not [2]. On the other hand, such a large direct CPA in $B^0 \rightarrow D^+D^-$ decay has not been observed in the measurements for other similar decay modes: such as $\bar{B}^0 \rightarrow D^+(s)\bar{D}^-(s)$, $B^- \rightarrow D^{(*)0}\bar{D}^-(s)$ and $B^0 \rightarrow D^{(*)0}\bar{D}^-(s)$ [2–9], although they have the same flavor structures as $B^0 \rightarrow D^+D^-$ at the quark level. In the SM, the direct CPA’s should be naturally very small in size because the penguin contributions are small. If the large CP violation in $B^0 \rightarrow D^+D^-$ from Belle is true, it would establish the presence of new physics.

Up to now, by using the low-energy effective hamiltonian and various factorization hypothesis, many investigations on the decays of B to double-charm states have been carried out in the framework of the SM [10, 11] or some popular new physics models [12–15].

In this paper, we will present our systematic calculation of the branching ratios and CP violations for double charm decays $B/B_s \rightarrow D^{(*)}_{(s)}D^{(*)}_{(s)}$ in the minimal supergravity (mSUGRA) model [16]. In the framework of the mSUGRA model, the new physics contributions to the semileptonic, leptonic and radiative rare B decays and the charmless two-body B-meson decays have been investigated in previous works [17–21]. For the two-body $B \rightarrow M_1M_2$ decays, the new physics part of the Wilson coefficients $C_k(k = 3, \cdots, 6), C_{7\gamma}$ and $C_{8g}$ in the mSUGRA model can be found in Ref. [21].

The usual route to calculate the decay amplitude for non-leptonic two-body B decays is to start from the low energy effective Hamiltonian for $\Delta B = 1$ decays. With the operator product expansion method, the relevant $\Delta B = 1$ effective Hamiltonian can be factorized into the Wilson coefficients $C_i(\mu)$ times the four-quark operators $Q_i(\mu)$. As to $C_i(\mu)$, they have been evaluated to next-to-leading order with the perturbation theory and renormalization group method. The remanent and also intractable problem is to calculate the hadronic matrix elements of these four-quark operators. Up to now, many methods have been put forward to settle this problem, such as the naive or generalized factorization approach [22, 23], QCD factorization approach (QCDF) [24, 25] and the perturbative QCD (PQCD) approach [26]. For the strong phase, which is important for the CP violation prediction, is quite sensitive to these various approaches, and different
MSSM are assumed to obey a set of boundary conditions at the Grand Unification scale with the visible sector only through gravitational interactions. The free parameters in the assumption is that SUSY-breaking occurs in a hidden sector which communicates assumptions are added to the unconstrained MSSM in the mSUGRA model. One under-currents (FCNC), unacceptable amount of additional CP violation and so on, a set of gauge fermions.

\[ W = \varepsilon_{\alpha \beta} \left[ f_{Uij} Q_i^\alpha H_2^\beta U_j + f_{Dij} h_1^\alpha L_j^\beta D_j + f_{Eij} L_1^\alpha H_1^\beta E_j - \mu H_1^\alpha H_2^\beta \right], \]  

a set of terms which explicitly but softly break SUSY should be added to the supersymmetric Lagrangian. A general form of the soft SUSY-breaking terms is given as

\[-L_{soft} = (m_Q^2)_{ij} \tilde{q}_{Li}^* \tilde{q}_{Lj} + (m_U^2)_{ij} \tilde{u}_{Ri}^* \tilde{u}_{Rj} + (m_D^2)_{ij} \tilde{d}_{Ri}^* \tilde{d}_{Rj} + (m_L^2)_{ij} \tilde{l}_{Li}^* \tilde{l}_{Lj} + \varepsilon_{\alpha \beta} \left[ A_{Uij} \bar{q}_{Li}^\alpha h_2^\beta \tilde{u}_{Rj} + A_{Dij} \bar{h}_1^\alpha \tilde{q}_{Li}^\beta \tilde{d}_{Rj} + A_{Eij} \bar{h}_1^\alpha \tilde{E}_{Li}^\beta \tilde{e}_{Rj} + B \mu \bar{h}_1^\alpha h_2^\beta \right] \]

\[ + \frac{1}{2} m_B \tilde{B} \tilde{B} + \frac{1}{2} m_W^2 \tilde{W} \tilde{W} + \frac{1}{2} m_G \tilde{G} \tilde{G} + H.C. \]  

where \( \tilde{q}_{Li}, \tilde{u}_{Ri}, \tilde{d}_{Ri}, \tilde{l}_{Li}, \tilde{e}_{Ri}, h_1 \) and \( h_2 \) are scalar components of chiral superfields \( Q_i, U_i, D_i, L_i, E_i, H_1 \) and \( H_2 \) respectively, and \( \tilde{B}, \tilde{W} \) and \( \tilde{G} \) are \( U(1)_Y, SU(2)_L, \) and \( SU(3)_C \) gauge fermions.

In order to avoid severe phenomenological problems, such as large flavor changing neutral currents (FCNC), unacceptable amount of additional CP violation and so on, a set of assumptions are added to the unconstrained MSSM in the mSUGRA model. One underlying assumption is that SUSY-breaking occurs in a hidden sector which communicates with the visible sector only through gravitational interactions. The free parameters in the MSSM are assumed to obey a set of boundary conditions at the Grand Unification scale \( M_X \) \[ 16, 27 \]

\[ \alpha_1 = \alpha_2 = \alpha_3 = \alpha_X, \]

\[ (m_Q^2)_{ij} = (m_U^2)_{ij} = (m_D^2)_{ij} = (m_L^2)_{ij} = (m_E^2)_{ij} = (m_0^2)\delta_{ij}, \]

\[ \Delta_1 = \Delta_2 = m_0, \]

\[ A_{Uij} = f_{Uij} A_0, \quad A_{Dij} = f_{Dij} A_0, \quad A_{Eij} = f_{Eij} A_0, \]

\[ m_B = m_W = m_G = m_\frac{1}{2} \]  

where \( \alpha_i = g_i^2/(4\pi) \), while \( g_i \) (i=1,2,3) denotes the coupling constant of the \( U(1)_Y, SU(2)_L, SU(3)_C \) gauge group, respectively. Besides the three parameters \( m_\frac{1}{2}, m_0 \) and...
TABLE I: Two typical sets of SUSY parameters to be used in the numerical calculation.

| CASE | $m_0$ | $m_{\tilde{t}}$ | $A_0$ | $\tan \beta$ | Sign$(\mu)$ | $R_7$ |
|------|-------|-----------------|-------|--------------|------------|------|
| A    | 300   | 300             | 0     | 2            | $-$        | 1.10 |
| B    | 369   | 150             | $-400$| 40           | $+$        | $-0.93$ |


$A_0$, the bilinear coupling $B$ and the supersymmetric Higgs(ino) mass parameter $\mu$ in the supersymmetric sector should also be determined. By requiring the radiative electroweak symmetry-breaking (EWSB) takes place at the low energy scale, both of them are obtained except for the sign of $\mu$. At this stage, only four continuous free parameters and an unknown sign are left in the mSUGRA model

$$\tan \beta, m_{\tilde{t}}, m_0, A_0, \text{sign}(\mu).$$

(5)

According to the previous studies about the constraints on the parameter space of the mSUGRA model \[21, 28–32\], we choose two sets of typical mSUGRA points as listed in Table I.

III. EFFECTIVE HAMILTONIAN AND OBSERVABLES

In this section, we will give a brief review of the theoretical framework of the low energy effective Hamiltonian and the factorized matrix elements as well as the decay amplitudes for $\Delta B = 1$ decays.

A. Effective Hamiltonian in the SM and mSUGRA model

In the SM, the low energy effective Hamiltonian for $\Delta B = 1$ transition at a scale $\mu$ is given by \[33\]

$$H_{\text{eff}}^{\text{SM}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left\{ C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} C_i Q_i + C_{\tilde{\gamma}\gamma} Q_{\tilde{\gamma}\gamma} + C_{8g} Q_{8g} \right\} + h.c.,$$

(6)

here $\lambda_p = V_{pb} V_{pq}^*$ for $b \to q$ transition ($p \in \{u, c\}, q \in \{d, s\}$). The detailed definition of the operators can be found in Ref. \[33\]. Within the SM and at the scale $M_W$, the Wilson coefficients $C_1(M_W), \ldots, C_{10}(M_W), C_{\tilde{\gamma}\gamma}(M_W)$ and $C_{8g}(M_W)$ have been given, for example, in Ref. \[33\]. By using QCD renormalization group equations, it is straightforward to run Wilson coefficients $C_i(M_W)$ from the scale $\mu \sim O(M_W)$ down to the lower scale $\mu \sim O(m_b)$.

In the mSUGRA model, there are four kinds of SUSY contributions to the $b \to d(s)$ transition at the one-loop level, depending on the virtual particles running in the penguin diagrams:

(i) the charged Higgs boson $H^\pm$ and up-type quarks $u, c, t$;
(ii) the charginos $\tilde{\chi}_{1,2}^\pm$ and the up-type squarks $\tilde{u}, \tilde{c}, \tilde{t}$;

(iii) the neutralinos $\tilde{\chi}_{1,2,3,4}^0$ and the down-type quarks $\tilde{d}, \tilde{s}, \tilde{b}$;

(iv) the gluinos $\tilde{g}$ and the down-type quarks $\tilde{d}, \tilde{s}, \tilde{b}$.

In general, the Wilson coefficients after the inclusion of various contributions can be expressed as

$$C_i(\mu_W) = C_{i,SM}^H + C_{i,H^-} + C_{i,\tilde{\chi}^0} + C_{i,\tilde{g}},$$

where $C_{i,H^-}, C_{i,\tilde{\chi}^0}$ and $C_{i,\tilde{g}}$ denote the Wilson coefficients induced by the penguin diagrams with the exchanges of the charged Higgs $H^\pm$, the chargino $\tilde{\chi}_{1,2}^\pm$, the neutralino $\tilde{\chi}_{1,2,3,4}^0$ and the gluino $\tilde{g}$, respectively. The detailed expressions of these Wilson coefficients can be found in Ref. [21].

### B. Decay amplitudes in naive factorization

The decay amplitudes of $B \to D^{(*)}D_q^{(*)}$ in the SM within the naive factorization can be written as [22]

$$M^{SM}(B \to D^{(*)}D_q^{(*)}) = \frac{G_F}{\sqrt{2}} \left( \lambda_c a_c^i + \sum_{p=u,c} \lambda_p [a_p^p + a_p^{p0} + \xi (a_p^p + a_p^{p0})] \right) A_{[BD^{(*)},D_q^{(*)}]}.$$

where the coefficients $a_p^p = (C_i + \frac{C_{i}^{N_C}}{N_C}) + P_i^p$ with the upper (lower) sign applied when $i$ is odd (even), and $P_i^p$ account for penguin contributions. The factorization parameter $\xi$ in Eq. (8) arises from the transformation of $(V-A)(V+A)$ currents into $(V-A)(V-A)$ ones for the penguin operators. It depends on properties of the final-state mesons involved and is defined as

$$\xi = \begin{cases} 
+ \frac{2m_d^2}{(m_c+m_q)(m_b-m_c)} & (DD_q), \\
0 & (DD^*_q), \\
- \frac{2m_s^2}{(m_c+m_q)(m_b+m_c)} & (D^* D_q), \\
0 & (D^* D_q^*).
\end{cases}$$

The term $A_{[BD^{(*)},D_q^{(*)}]}$ in Eq. (8) is the factorized matrix element. For $B \to D^{(*)}D_q^{(*)}$ decay mode, it can be written as

$$A_{[BD^{(*)},D_q^{(*)}]} = \left< D_q^{(*)} | \bar{q} \gamma^\mu (1-\gamma_5)c | 0 \right> \left< D^{(*)} | \bar{c} \gamma_\mu (1-\gamma_5)b | B \right>. $$

The decay constants and form factors [22, 34] are usually defined as

$$\langle D_q(p_{D_q}) | \bar{q} \gamma^\mu \gamma_5 c | 0 \rangle = -i f_{D_q} p_{D_q}^\mu,$$

$$\langle D_q^*(p_{D_q^*}) | \bar{q} \gamma^\mu | 0 \rangle = f_{D_q^*} p_{D_q^*}^\mu,$$

$$\langle D(p_D) | \bar{c} \gamma_\mu b | B(p_B) \rangle = \frac{m_B^2 - m_D^2}{q^2} q_\mu F_0(q^2) + \left[ (p_B + p_D)_\mu - \frac{m_B^2 - m_D^2}{q^2} q_\mu \right] F_1(q^2),$$

$$\langle 0 | D(p_D) | B(p_B) \rangle = \frac{1}{16 \pi^2} \int \frac{d^4 p}{(2\pi)^4} \frac{1}{p^2 - m_D^2} \frac{1}{(p_B + p_D - p)^2 - m_B^2} G_0(p_B, p_D, q^2),$$

$$\langle 0 | D(p_D^*) | B(p_B) \rangle = \frac{1}{16 \pi^2} \int \frac{d^4 p}{(2\pi)^4} \frac{1}{p^2 - m_D^2} \frac{1}{(p_B + p_D^* - p)^2 - m_B^2} G_0(p_B, p_D^*, q^2).$$
\[ \langle D^*(p_{D^*}, \epsilon^*) | \bar{c} \gamma_{\mu} b | B(p_B) \rangle = \frac{2V(q^2)}{m_B + m_{D^*}} \epsilon_{\mu \nu \alpha \beta} \epsilon^{* \nu} p_B^\alpha p_{D^*}^\beta, \]

\[ \langle D^*(p_{D^*}, \epsilon^*) | \bar{c} \gamma_5 b | B(p_B) \rangle = i \left[ \epsilon_\mu (m_B + m_{D^*}) A_1(q^2) - (p_B + p_{D^*}) \mu (\epsilon^* \cdot p_B) \frac{A_2(q^2)}{m_B + m_{D^*}} \right] - i q_\mu (\epsilon^* \cdot p_B) \frac{2m_{D^*}}{q^2} [A_3(q^2) - A_0(q^2)], \]

where \( q = p_B - p_{D^*} \). In terms of decay constants and form factors, the matrix element \( A_{[BD^*(s),D_q^{(*)}]} \) can be written as follows

\[ A_{[BD^*(s),D_q^{(*)}]} = \begin{cases} if_{D_q} (m_B^2 - m_D^2) F_0(m_{D_q}^2), & (DD_q), \\
2f_{D_q} m_B p_c F_1(m_{D_q}^2), & (DD_q^*), \\
-2f_{D_q} m_B A_0(m_{D_q}^2), & (D^* D_q), \\
- \left( \epsilon^* \cdot p_D \right) \epsilon_\mu (m_B + m_{D^*}) A_1 \frac{2A_2(m_{D_q}^2)}{m_B + m_{D^*}}, \\
+ \epsilon_{\mu \nu \alpha \beta} \epsilon^{* \nu} p_B^\alpha p_{D^*}^\beta \frac{2V(m_{D_q}^2)}{m_B + m_{D^*}}, & (D^* D_q^*). \end{cases} \]

For the penguin contributions, we will consider not only QCD and electroweak penguin operator contributions but also the contributions from the electromagnetic and chromomagnetic dipole operators \( Q_{7\gamma} \) and \( Q_{8g} \), as defined by the factor \( P_i \) [22]:

\[ P_1^c = 0, \]

\[ P_4^c = \frac{\alpha_s}{9\pi} \left\{ C_1 \left[ \frac{10}{9} - G_{D_q^{(*)}}(m_p) \right] - 2F_1 C_{8g}^{eff} \right\}, \]

\[ P_6^c = \frac{\alpha_s}{9\pi} \left\{ C_1 \left[ \frac{10}{9} - G_{D_q^{(*)}}(m_p) \right] - 2F_2 C_{8g}^{eff} \right\}, \]

\[ P_8^c = \frac{\alpha_s}{9\pi N_c} \left\{ (C_1 + N_c C_2) \left[ \frac{10}{9} - G_{D_q^{(*)}}(m_p) \right] - 3F_2 C_{7\gamma}^{eff} \right\}, \]

\[ P_{10}^c = \frac{\alpha_s}{9\pi N_c} \left\{ (C_1 + N_c C_2) \left[ \frac{10}{9} - G_{D_q^{(*)}}(m_p) \right] - 3F_1 C_{7\gamma}^{eff} \right\}, \]

with the penguin loop-integral function \( G_{D_q^{(*)}}(m_p) \) defined as

\[ G_{D_q^{(*)}}(m_p) = \int_0^1 du G(m_p, k) \Phi_{D_q^{(*)}}(u), \]

\[ G(m_p, k) = -4 \int_0^1 dx (1 - x) \ln \left[ \frac{m_p^2 - k^2 x (1 - x)}{m_b^2} \right] - i \epsilon, \]

where \( k^2 = m_c^2 + \bar{u}(m_b^2 - m_c^2 - m_{D_s}^2) + \bar{u}^2 m_{D_s}^2 \) is the penguin momentum transfer with \( \bar{u} = 1 - u \). In the function \( G_{D_q^{(*)}}(m_p) \), we have used a \( D_q^{(*)} \) meson-emitting distribution.
amplitude \( \Phi_{D_q^*}(u) = 6u(1-u)[1 + a_{D_q^*}(1-2u)] \), in stead of keeping \( k^2 \) as a free parameter as usual. The constants \( F_1 \) and \( F_2 \) in Eq. (17) are defined by \[22\]

\[
F_1 = \begin{cases} 
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b - m_c}{m_b - m_c} \left( \frac{m_b^2 - m_c^2}{m_b - m_c} \right)^2 - 2m^2 + m_b m_c & (DD_q), \\
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b + m_c}{m_b + m_c} \left( \frac{m_b^2 - m_c^2}{m_b + m_c} \right)^2 - 2m^2 + m_b m_c & (DD_q^*), \\
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b - m_c}{m_b - m_c} \left( \frac{m_b^2 - m_c^2}{m_b - m_c} \right)^2 - 2m^2 + m_b m_c & (D^* D_q), \\
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b + m_c}{m_b + m_c} \left( \frac{m_b^2 - m_c^2}{m_b + m_c} \right)^2 - 2m^2 + m_b m_c & (D^* D_q^*),
\end{cases}
\]

\[
F_2 = \begin{cases} 
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b - m_c}{m_b - m_c} \left( \frac{m_b^2 - m_c^2}{m_b - m_c} \right)^2 - 2m^2 + m_b m_c & (DD_q), \\
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b + m_c}{m_b + m_c} \left( \frac{m_b^2 - m_c^2}{m_b + m_c} \right)^2 - 2m^2 + m_b m_c & (DD_q^*), \\
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b - m_c}{m_b - m_c} \left( \frac{m_b^2 - m_c^2}{m_b - m_c} \right)^2 - 2m^2 + m_b m_c & (D^* D_q), \\
\int_0^1 du \Phi_{D_q^*}(u) \frac{m_b + m_c}{m_b + m_c} \left( \frac{m_b^2 - m_c^2}{m_b + m_c} \right)^2 - 2m^2 + m_b m_c & (D^* D_q^*),
\end{cases}
\]

where \( \epsilon_{2L} \cdot p_1 \approx (m_b^2 - m_{D_q^*}^2 - m_c^2)/2m_{D_q^*} \) and \( \epsilon_{2T} \cdot p_1 = 0 \) for \( B \rightarrow D^* D_q^* \) decays.

### C. Observables of \( B \rightarrow M_1 M_2 \) decays

In the \( B \) meson rest frame, the branching ratios of two-body \( B \) meson decays can be written as

\[
\mathcal{B}(B \rightarrow D^* D_q^*) = \frac{\tau_B |p_c|}{8\pi m_B^2} \left| \mathcal{M}(B \rightarrow D^* D_q^*) \right|^2 ,
\]

where \( \tau_B \) is the \( B \) meson lifetime, and \( |p_c| \) is the magnitude of momentum of particle \( M_1 \) and \( M_2 \) in the \( B \) rest frame and written as

\[
|p_c| = \sqrt{m_B^2 - (m_{D^*} + m_{D_q^*})^2(m_B^2 - (m_{D^*} - m_{D_q^*})^2} / 2m_B .
\]

In \( B \rightarrow D^* D_q^* \) decays, one generally should evaluate three amplitudes as \( \mathcal{M}_{0,\pm} \) in the helicity basis or as \( \mathcal{M}_{L,\perp,\perp} \) in the transversity basis, which are related by \( \mathcal{M}_L = \mathcal{M}_0 \) and \( \mathcal{M}_{\perp,\perp} = \frac{\mathcal{M}_{L,\perp}}{\sqrt{2}} \). Then we have

\[
\left| \mathcal{M}(B \rightarrow D^* D_q^*) \right|^2 = \left| \mathcal{M}_0 \right|^2 + \left| \mathcal{M}_+ \right|^2 + \left| \mathcal{M}_- \right|^2 = \left| \mathcal{M}_L \right|^2 + \left| \mathcal{M}_\parallel \right|^2 + \left| \mathcal{M}_\perp \right|^2 .
\]

The longitudinal polarization fraction \( f_L \) and transverse polarization fraction \( f_\perp \) are defined by

\[
f_{L,\perp}(B \rightarrow D^* D_q^*) = \frac{\Gamma_{L,\perp}}{\Gamma} = \frac{\left| \mathcal{M}_{L,\perp} \right|^2}{\left| \mathcal{M}_L \right|^2 + \left| \mathcal{M}_\parallel \right|^2 + \left| \mathcal{M}_\perp \right|^2} .
\]

In charged \( B \) meson decays, where mixing effects are absent, the only possible source of CPAs is

\[
\mathcal{A}_{CP}^{k,dir} = \frac{\left| \mathcal{M}_k(B^- \rightarrow f)/\mathcal{M}_k(B^+ \rightarrow f) \right|^2 - 1}{\left| \mathcal{M}_k(B^- \rightarrow f)/\mathcal{M}_k(B^+ \rightarrow f) \right|^2 + 1} ,
\]

\[
\text{(26)}
\]
and \( k = L, \|, \perp \) for \( B^- \to D^*D^*_q \) decays and \( k = L \) for \( B_u^- \to DD_q, DD^*_q, D^*D_q \) decays. Then for \( B_u^- \to D^*D^*_q \) decays, we have

\[
A^{+, \text{dir}}_{\text{CP}}(B \to D^*D^*_q) = \frac{A^{L, \text{dir}}_{\text{CP}} |M|_2 + A^{L, \text{dir}}_{\text{CP}} |M_L|^2}{|M|^2 + |M_L|^2}.
\] (27)

For neutral \( B_q \) meson decays, the situation becomes complicated because of \( B^0 - \bar{B}^0 \) mixing, and have been studied by many authors. We do not repeat the lengthy discussions here, one can see Refs. [35–38] for details.

IV. NUMERICAL CALCULATIONS

A. Input parameters

- CKM matrix elements: In numerical calculation, we will use the following values which given as [39]

\[
|V_{ud}| = 0.9743, |V_{us}| = 0.2252, |V_{ub}| = 0.0035,
|V_{cd}| = 0.2251, |V_{cs}| = 0.9735, |V_{cb}| = 0.0412,
|V_{td}| = 0.0086, |V_{ts}| = 0.0404, |V_{tb}| = 0.9991,
\]

\[
\beta = (21.58^{+0.91}_{-0.81})^\circ, \quad \gamma = (67.8^{+4.2}_{-3.3})^\circ.
\] (28)

- Quark masses. When calculating the decay amplitudes, the pole and current quark masses will be used. For the former, we will use

\[
m_u = 4.2\text{MeV}, \quad m_c = 1.5\text{GeV}, \quad m_t = 175\text{GeV},
\]

\[
m_d = 7.6\text{MeV}, \quad m_s = 0.122\text{GeV}, \quad m_b = 4.62\text{GeV}.
\]

The current quark mass depends on the renormalization scale. In the \( \overline{\text{MS}} \) scheme and at a scale of 2\text{GeV}, we fix

\[
\overline{m}_u(2\text{GeV}) = 2.4\text{MeV}, \quad \overline{m}_d(2\text{GeV}) = 6\text{MeV},
\]

\[
\overline{m}_s(2\text{GeV}) = 105\text{MeV}, \quad \overline{m}_b(\overline{m}_b) = 4.26\text{GeV},
\]

and then employ the formulae in Ref. [33]

\[
\overline{m}(\mu) = \overline{m}(\mu_0) \left[ \frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right]^{\frac{\gamma_m^{(1)}}{2\beta_0}} \left[ 1 + \left( \frac{\gamma_m^{(1)}}{2\beta_0} - \frac{\beta_1 \gamma_m^{(0)}}{2\beta_0^2} \right) \frac{\alpha_s(\mu) - \alpha_s(\mu_0)}{4\pi} \right]
\] (29)

to obtain the current quark masses at any scale. The definitions of \( \alpha_s, \gamma_m^{(0)}, \gamma_m^{(1)}, \beta_0, \) and \( \beta_1 \) can be found in Ref. [33].

- Decay constants: The decay constants of \( D^*_q \) mesons have not been directly measured in experiments so far. In the heavy-quark limit \( (m_c \to \infty) \), spin symmetry predicts that \( f_{D^*_q} = f_{D_q} \), and most theoretical predictions indicate that symmetry-breaking corrections enhance the ratio \( f_{D^*_q}/f_{D_q} \) by 10% − 20% [40, 41]. In this paper, we will take \( f_D = 0.201 \pm 0.017\text{GeV}, \) \( f_{D_s} = 0.249 \pm 0.016\text{GeV} \) and \( f_{D^*_q} = f_{D_q} \) as our input values.
• Distribution amplitudes: The distribution amplitudes of $D_q^{(*)}$ mesons are less constrained, and we use the shape parameter $a_{D_q} = 0.7 \pm 0.2$ and $a_{D_q'} = 0.3 \pm 0.2$.

• Form factors: For the form factors involving $B \to D^{(*)}$ transitions, we take expressions which include perturbative QCD corrections induced by hard gluon vertex corrections of $b \to c$ transitions and power corrections in orders of $1/m_{b,c}$ [34, 42]. As for Isgur-Wise function $\xi(\omega)$, we use the fit result $\xi(\omega) = 1 - 1.22(\omega - 1) + 0.85(\omega - 1)^2$ from Ref. [43].

• Mass and lifetimes: For $B$ and $D$ meson masses, the lifetimes, we use the following as input parameters [44].

\[
\begin{align*}
    m_{B_u} &= 5.279\text{GeV}, \quad m_{B_d} = 5.280\text{GeV}, \quad m_{B_s} = 5.366\text{GeV}, \\
    M_{D^0} &= 1.865\text{GeV}, \quad M_{D^+} = 1.870\text{GeV}, \quad M_{D^+_s} = 1.969\text{GeV}, \\
    M_{D_s^{(*)}} &= 2.007\text{GeV}, \quad M_{D_s^{(*)}+} = 2.010\text{GeV}, \quad M_{D_s^{(*)}+} = 2.107\text{GeV} \\
    \tau_{B_u} &= (1.638)\text{ps}, \quad \tau_{B_d} = (1.530)\text{ps}, \\
    \tau_{B_s} &= (1.425^{+0.041}_{-0.041})\text{ps}. \quad (30)
\end{align*}
\]

Using the input parameters given above, we then present the numerical results and make some theoretical analysis for double charm $B_{u,d}$ and $B_s$ decay processes.

B. data and theoretical prediction

1. $b \to c\bar{c}d$ decays

In the SM, $\bar{B}_d^0 \to D^{(*)+} D^{(*)-}$, $B_u^- \to D^{(*)0} D^{(*)-}$ and $\bar{B}_s^0 \to D_s^{(*)+} D^{(*)-}$ decays are dominated by the tree $b \to c\bar{c}d$ transition, and receive additional $b \to c\bar{c}d$ penguin diagram contributions.

In Table III, we show the theoretical predictions for the $CP$-averaged branching ratios and the polarization fractions in SM and mSUGRA model. The weighted averages of the relevant experimental data [44] are given in the last column in both the Table III and Table III. The data with a star in the top right corner denote the BaBar measurement only, while that with two stars are the Belle measurements only. The central values of the theoretical predictions are obtained at the scale $\mu = m_b$, while the two errors are induced by the uncertainties of $f_D = 0.201 \pm 0.017\text{GeV}$ and $\gamma = 67.8^\circ \pm 20^\circ$.

From the numerical results and the data as given in Table III, we have the following remarks on the branching ratios and the polarization fractions of $b \to c\bar{c}d$ double charm decays:

(i) The SUSY contributions to the branching ratios of the considered decays are indeed very small, less than 5%, which is consistent with the general expectation since these decays are all "tree" dominated decay processes.

(ii) The theoretical predictions of the Br’s in both the SM and the mSUGRA model are consistent with the experimental measurements within $\pm 2\sigma$ errors. The central value of the theoretical prediction for $Br(\bar{B}_d^0 \to D^+ D^-)$ ($Br(B_u^- \to D^{(*)0} D^-)$) is,
however, much larger (smaller) than that of the corresponding measurement. This point will be clarified by the forthcoming LHC experiments.

(iii) The SUSY contributions to the polarization fractions of these decays in mSUGRA model are very small, less than 2%, and can be neglected safely. Only the central values are presented here since they are not sensitive to the variations of the form factors and the weak phase \( \gamma \), which can be seen from the definition of the polarization fraction.

Table II: Theoretical predictions for CP-averaged branching ratios (in units of \( 10^{-4} \)), polarization (in percent) for \( b \to c c d \) decays in the SM and mSUGRA model. The last column shows currently available data [44].

| Observables | SM | mSUGRA | Data |
|-------------|----|--------|------|
| \( B(B^0 \to D^+D^-) \) | 3.26±0.57±0.10 | 3.27±0.58±0.10 | 3.15±0.55±0.08 | 2.1±0.3 |
| \( B(\bar{B}^0_d \to D^{*+}D^0) \) | 5.92±1.05±0.01 | 5.93±1.04±0.01 | 5.91±1.04±0.01 | 6.1±1.5 |
| \( B(\bar{B}^0_s \to D^{*+}D^0) \) | 7.24±1.28±0.06 | 7.25±1.28±0.06 | 7.19±1.26±0.06 | 8.2±0.9 |
| \( B(B_{u-}^- \to D^0D^-) \) | 3.48±0.61±0.11 | 3.50±0.62±0.10 | 3.37±0.69±0.11 | 3.8±0.4 |
| \( B(B_{s-}^- \to D^0D^-) \) | 3.43±0.60±0.03 | 3.42±0.60±0.02 | 3.44±0.61±0.03 | 6.3±1.4 ± 1.0* |
| \( B(B_{s-}^- \to D^0D^-) \) | 2.92±1.50±0.02 | 2.92±1.52±0.02 | 2.89±1.51±0.03 | 3.9±0.5 |
| \( B(B_{s-}^- \to D^0D^-) \) | 7.75±1.36±0.05 | 7.76±1.36±0.06 | 7.68±1.36±0.07 | 8.1±1.2 ± 1.2* |
| \( f_L(B^0_d \to D^{*+}D^-) \) | 53.86 | 53.87 | 53.79 | 57.0±8.0 ± 2.0** |
| \( f_L(B^-_u \to D^0D^-) \) | 53.88 | 53.89 | 53.81 | – |
| \( f_L(B^0_s \to D^{*+}D^-) \) | 53.88 | 53.89 | 53.81 | – |
| \( f_{L} (B^0_d \to D^{*+}D^-) \) | 5.51 | 5.50 | 5.51 | 15.0±2.5 |
| \( f_{L} (B^-_u \to D^0D^-) \) | 5.52 | 5.52 | 5.53 | – |
| \( f_{L} (B^0_s \to D^{*+}D^-) \) | 5.20 | 5.20 | 5.21 | – |

In Table III we present the theoretical predictions for the CPAs in the framework of the SM and the mSUGRA model. The currently available data are also listed in the last column. The uncertainties come from the scale \( m_b/2 \leq \mu \leq 2m_b \) and the weak angle \( \gamma = 67.8^\circ \pm 20^\circ \). From the numerical results and the data, we find that

(i) Just as generally expected based on the SM, the direct CPAs \( C_f \) are indeed quite small, while the mixing-induced CPAs of all considered decays are close to \(-0.7\) i.e. \( S_f \approx \sin(2\beta) \approx -0.7 \).
TABLE III: Theoretical predictions of CPAs (in percent) for the exclusive color-allowed $b \rightarrow c\bar{c}d$ decays. The last column shows the word averages [44].

| Observables                                      | SM       | mSUGRA   | Data |
|--------------------------------------------------|----------|----------|------|
| $S(B_{d}^{0}, B_{d}^{0} \rightarrow D^{+}D^{-})$ | -75.3$^{+1.4}_{-1.5}$ | -75.1$^{+1.3}_{-1.3}$ | -76.3$^{+1.3}_{-1.2}$ | -87 ± 26 |
| $S(B_{d}^{0}, B_{d}^{0} \rightarrow D^{*+}D^{-})$ | -68.4$^{+0.3}_{-0.4}$ | -68.4$^{+0.2}_{-0.3}$ | -68.5$^{+0.3}_{-0.2}$ | -61 ± 19 |
| $S(B_{d}^{0}, B_{d}^{0} \rightarrow D^{+}D^{*-})$ | -68.4$^{+0.1}_{-0.2}$ | -68.4$^{+0.1}_{-0.2}$ | -68.5$^{+0.2}_{-0.2}$ | -78 ± 21 |
| $S^{+}(B_{d}^{0}, B_{d}^{0} \rightarrow D^{*+}D^{*-})$ | -70.2$^{+0.4}_{-0.6}$ | -70.1$^{+0.5}_{-0.6}$ | -70.4$^{+0.4}_{-0.7}$ | -81 ± 14 |
| $C(B_{d}^{0}, B_{d}^{0} \rightarrow D^{+}D^{-})$     | -4.4$^{+0.3}_{-0.4}$  | -4.4$^{+0.3}_{-0.4}$  | -4.5$^{+0.3}_{-0.4}$  | -48 ± 42 |
| $C(B_{d}^{0}, B_{d}^{0} \rightarrow D^{*+}D^{-})$    | 7.8$^{+0.3}_{-0.6}$   | 7.7$^{+0.3}_{-0.6}$   | 8.3$^{+0.3}_{-0.6}$ | -9 ± 22 |
| $C(B_{d}^{0}, B_{d}^{0} \rightarrow D^{+}D^{*-})$    | -8.4$^{+1.1}_{-1.0}$  | -8.3$^{+1.0}_{-1.0}$  | -8.9$^{+1.0}_{-1.0}$ | 7 ± 14 |
| $C^{+}(B_{d}^{0}, B_{d}^{0} \rightarrow D^{*+}D^{*-})$ | -1.2$^{+0.2}_{-0.2}$  | -1.2$^{+0.2}_{-0.2}$  | -1.2$^{+0.2}_{-0.2}$ | -7 ± 9 |

(ii) The SUSY contributions to all considered decays are less than 7%. The new physics contributions is not sensitive to the variation of the scale $\mu$ and the weak angle $\gamma$.

(iii) The theoretical predictions in the SM and mSUGRA model are all consistent with the experimental measurements within ±1σ error. Of course, the errors of currently available data are very large now.

2. $b \rightarrow c\bar{c}s$ decays

The twelve decay modes $B_{d}^{0} \rightarrow D^{(*)+}D_{s}^{(*)-}$, $B_{d}^{0} \rightarrow D^{(*)0}D_{s}^{(*)-}$ and $B_{s}^{0} \rightarrow D_{s}^{(*)+}D_{s}^{(*)-}$ are the tree-dominated processes, and also receive the additional $b \rightarrow c\bar{c}s$ penguin contributions.

In Table IV we present the theoretical predictions for the CP-averaged branching ratios and the polarization fractions in the framework of the SM and the mSUGRA model. The last column in table IV correspond to the world averages [44]. The theoretical predictions for CP asymmetries of considered decays are given in Table IV although they have not been measured yet. The central values of the theoretical predictions are obtained at the scale $\mu = m_{b}$, while the two errors are induced by the uncertainties of $f_{D}$ = 0.201 ± 0.017GeV and $\gamma = 67.8^\circ ± 20^\circ$. 

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TABLE IV: Theoretical predictions for CP-averaged $B\nabla$ (in units of $10^{-3}$) and polarization fractions (in units of $10^{-2}$) of exclusive color-allowed $b \to c\bar{c}s$ decays in the SM and the mSUGRA model. The last column corresponds to the world averages [44].

| Observables | SM | mSUGRA | Data |
|-------------|----|--------|------|
| $B(B_d^0 \to D^+ D_s^-)$ | 8.77$_{-1.09}^{+1.16}$ | 8.83$_{-1.10}^{+1.17}$ | 8.39$_{-1.36}^{+1.11}$ | 7.4 ± 0.7 |
| $B(B_d^0 \to D^{*+} D_s^-)$ | 8.78$_{-1.10}^{+1.16}$ | 8.77$_{-1.09}^{+1.17}$ | 8.78$_{-1.09}^{+1.17}$ | 8.2 ± 1.1 |
| $B(B_d^0 \to D^+ D_s^{*-})$ | 7.30$_{-0.91}^{+0.97}$ | 7.31$_{-0.91}^{+0.97}$ | 7.22$_{-0.90}^{+0.96}$ | 7.5 ± 1.6 |
| $B(B_d^0 \to D^{*+} D_s^{*-})$ | 21.2$_{-2.6}^{+2.8}$ | 21.2$_{-2.6}^{+2.8}$ | 20.9$_{-2.6}^{+2.8}$ | 17.8 ± 1.4 |
| $B(B_u^0 \to D^0 D_s^-)$ | 9.38$_{-1.17}^{+1.24}$ | 9.44$_{-1.18}^{+1.25}$ | 9.77$_{-1.12}^{+1.19}$ | 10.2 ± 1.7 |
| $B(B_u^0 \to D^{0*} D_s^-)$ | 9.40$_{-1.17}^{+1.25}$ | 9.39$_{-1.17}^{+1.25}$ | 9.40$_{-1.17}^{+1.25}$ | 8.4 ± 1.7 |
| $B(B_u^0 \to D^0 D_s^{*-})$ | 7.82$_{-0.97}^{+1.04}$ | 7.83$_{-0.97}^{+1.04}$ | 7.73$_{-0.96}^{+1.03}$ | 7.8 ± 1.6 |
| $B(B_u^0 \to D^{0*} D_s^{*-})$ | 22.6$_{-2.8}^{+3.0}$ | 22.7$_{-2.8}^{+3.0}$ | 22.4$_{-2.8}^{+3.0}$ | 17.4 ± 2.3 |
| $B(B_s^0 \to D^+_s D_s^-)$ | 8.68$_{-1.08}^{+1.15}$ | 8.73$_{-1.08}^{+1.16}$ | 8.30$_{-1.03}^{+1.10}$ | 11 ± 4 |
| $B(B_s^0 \to D^{+_s} D_s^-)$ | 8.74$_{-1.09}^{+1.16}$ | 8.73$_{-1.08}^{+1.16}$ | 8.75$_{-1.09}^{+1.16}$ | – |
| $B(B_s^0 \to D^{+_s} D_s^{*-})$ | 7.16$_{-0.89}^{+0.95}$ | 7.17$_{-0.88}^{+0.98}$ | 7.08$_{-0.88}^{+0.94}$ | – |
| $B(B_s^0 \to D^{*_s} D_s^{*-})$ | 20.8$_{-2.6}^{+2.8}$ | 20.8$_{-2.6}^{+2.8}$ | 20.6$_{-2.6}^{+2.7}$ | <257 |
| $f_L(B_d^0 \to D^{**} D_s^{*-})$ | 51.68 | 51.70 | 51.58 | 52 ± 5 |
| $f_L(B_u^0 \to D^{**} D_s^{*-})$ | 51.70 | 51.72 | 51.61 | – |
| $f_L(B_s^0 \to D^{**} D_s^{*-})$ | 51.70 | 51.71 | 51.60 | – |
| $f_L(B_d^0 \to D^{**} D_s^{*-})$ | 5.50 | 5.50 | 5.51 | – |
| $f_L(B_u^0 \to D^{**} D_s^{*-})$ | 5.51 | 5.51 | 5.52 | – |
| $f_L(B_s^0 \to D^{**} D_s^{*-})$ | 5.19 | 5.18 | 5.20 | – |

From the numerical results and currently available data, one can see that

(i) For the Br’s and CPAs, the SUSY contributions again are very small for all considered decays, less than 3% numerically. The theoretical predictions in both the SM and the mSUGRA model are all consistent with currently available data within one or two standard deviations.

(ii) The direct CP violations $C(B_d^0 \to D_s^+ D_s^{-})$ and $C(B_s^0 \to D_s^+ D_s^{*-})$ are at the ±10% level and to be tested by the LHC experiments. And the CP asymmetries for the remaining ten decays are very small, about $10^{-3}$ or $10^{-4}$ numerically, since the penguin effects are doubly Cabibbo-suppressed for the color-allowed $b \to c\bar{c}s$ decays.

V. SUMMARY

In this paper, we have investigated the new contributions to the branching ratios, polarization fractions and CP asymmetries of the twenty three double charm decays
TABLE V: Theoretical predictions for CPAs (in percent) of exclusive color-allowed $b \to c\bar{c}s$ decays in the SM and the mSUGRA model.

| Observables | SM | mSUGRA | Data |
|-------------|----|--------|------|
| $A_{\text{CP}}^{\text{dir}}(B^0_d \to D^+ D^-_s)$ | $-0.26^{+0.02+0.05}_{-0.03-0.02}$ | $-0.26^{+0.02+0.05}_{-0.01-0.02}$ | $-0.27^{+0.02+0.06}_{-0.02-0.02}$ | – |
| $A_{\text{CP}}(B^+_d \to D^{*+} D^-_s)$ | $0.30^{+0.02+0.01}_{-0.02-0.01}$ | $0.30^{+0.02+0.01}_{-0.02-0.01}$ | $0.30^{+0.02+0.01}_{-0.02-0.01}$ | – |
| $A_{\text{CP}}^{\text{dir}}(B^0_s \to D_s^0 D^-_s)$ | $-0.07^{+0.02+0.02}_{-0.02-0.01}$ | $-0.07^{+0.02+0.02}_{-0.01-0.01}$ | $-0.07^{+0.02+0.02}_{-0.02-0.02}$ | – |
| $A_{\text{CP}}^{+, \text{dir}}(B^0_d \to D^{*+} D^-_s)$ | $0.38^{+0.02+0.02}_{-0.02-0.01}$ | $0.38^{+0.02+0.02}_{-0.01-0.01}$ | $0.38^{+0.02+0.02}_{-0.02-0.02}$ | – |
| $A_{\text{CP}}^{\text{dir}}(B^-_s \to D^0 D^-_s)$ | $-0.26^{+0.02+0.05}_{-0.03-0.02}$ | $-0.26^{+0.02+0.05}_{-0.01-0.02}$ | $-0.27^{+0.02+0.06}_{-0.02-0.02}$ | – |
| $A_{\text{CP}}^{\text{dir}}(B^-_u \to D^0 D^-_s)$ | $0.30^{+0.02+0.01}_{-0.02-0.01}$ | $0.30^{+0.02+0.01}_{-0.02-0.01}$ | $0.30^{+0.02+0.01}_{-0.02-0.01}$ | – |
| $A_{\text{CP}}^{\text{dir}}(B^-_u \to D^0 D^-_s)$ | $-0.07^{+0.02+0.02}_{-0.02-0.01}$ | $-0.07^{+0.02+0.02}_{-0.01-0.01}$ | $-0.07^{+0.02+0.02}_{-0.02-0.02}$ | – |
| $A_{\text{CP}}^{+, \text{dir}}(B^-_u \to D^0 D^-_s)$ | $0.38^{+0.02+0.02}_{-0.02-0.01}$ | $0.38^{+0.02+0.02}_{-0.01-0.01}$ | $0.38^{+0.02+0.02}_{-0.02-0.02}$ | – |
| $S(B^0_s, B^0_s \to D^+_s D^-_s)$ | $0.55^{+0.11+0.04}_{-0.12-0.04}$ | $0.55^{+0.06+0.04}_{-0.11-0.04}$ | $0.62^{+0.14+0.06}_{-0.11-0.04}$ | – |
| $S(B^0_s, B^0_s \to D^+_s D^-_s)$ | $0.93^{+0.02+0.02}_{-0.01-0.02}$ | $0.93^{+0.01+0.02}_{-0.06-0.02}$ | $0.94^{+0.02+0.02}_{-0.01-0.02}$ | – |
| $S(B^0_s, B^0_s \to D^+_s D^+ D^-_s)$ | $-0.94^{+0.03+0.02}_{-0.01-0.01}$ | $-0.94^{+0.10+0.02}_{-0.01-0.02}$ | $-0.93^{+0.02+0.02}_{-0.03-0.02}$ | – |
| $S^+(B^0_s, B^0_s \to D^+_s D^+ D^-_s)$ | $0.13^{+0.04+0.01}_{-0.03-0.02}$ | $0.12^{+0.03+0.01}_{-0.03-0.02}$ | $0.14^{+0.05+0.02}_{-0.03-0.02}$ | – |
| $C(B^0_s, B^0_s \to D^+_s D^-_s)$ | $0.26^{+0.05+0.05}_{-0.02-0.02}$ | $0.26^{+0.01+0.02}_{-0.02-0.02}$ | $0.27^{+0.02+0.06}_{-0.02-0.02}$ | – |
| $C(B^0_s, B^0_s \to D^+_s D^-_s)$ | $9.91^{+0.91+0.05}_{-1.14-0.04}$ | $9.82^{+0.21+0.04}_{-1.15-0.05}$ | $10.52^{+0.89+0.05}_{-1.12-0.04}$ | – |
| $C(B^0_s, B^0_s \to D^+_s D^-_s)$ | $-9.93^{+1.16+0.01}_{-0.95-0.04}$ | $-9.84^{+1.18+0.05}_{-0.25-0.03}$ | $-10.54^{+1.14+0.05}_{-0.93-0.05}$ | – |
| $C^+(B^0_s, B^0_s \to D^+_s D^-_s)$ | $0.07^{+0.01+0.01}_{-0.02-0.02}$ | $0.07^{+0.02+0.01}_{-0.01-0.02}$ | $0.07^{+0.01+0.01}_{-0.02-0.02}$ | – |

$B/s \to D^{(*)}_s D^{(*)}_s$ in the SM and the mSUGRA model by employing the effective hamiltonian for $\Delta B = 1$ transition and the naive factorization approach.

From the numerical results and the phenomenological analysis, the following conclusions can be reached:

(i) For the exclusive double charm decays $B/s \to D^{(*)}_s D^{(*)}_s$ studied in this paper, the SUSY contributions in the mSUGRA model are very small, less than 7% numerically. It may be difficult to observe so small SUSY contributions even at LHC.

(ii) All the theoretical predictions in the SM and mSUGRA model are consistent with the experimental measurements within ±2σ errors.

(iii) The theoretical predictions in both the SM and mSUGRA model still have large theoretical uncertainties. The dominant errors are induced by the uncertainties of the form factors $f_D$ or $f_{D_s}$.

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