# Pure annihilation type $B \to K_0^{*\pm}(1430)K^{(*)\mp}$ decays in the family non-universal $Z'$ model [*]

Ying Li(李营)[1,3;1)]    Dan-Dan Wang (王丹丹)[1]    Cai-Dian Lü (吕才典)[2,3;2)]

[1] Department of Physics, Yantai University, Yantai 264-005, China
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[3] State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics,
Chinese Academy of Sciences, Beijing 100190, China

**Abstract:** By assuming that the scalar meson $K_0^*(1430)$ belongs to the first excited states or the lowest lying ground states of $q\bar{q}'$, we study the pure annihilation-type decays $B \to K_0^{*\pm}(1430)K^{(*)\mp}$ in the QCD factorization approach. Within the Standard Model, the branching fractions are of the order of $10^{-8}$–$10^{-7}$, which is possible to measure in the ongoing LHCb experiment or forthcoming Belle-II experiment. We also study these decays in the family non-universal $Z'$ model. The results show that if $m_{Z'} \approx 600$ GeV ($\zeta = 0.02$), both the branching fractions and $CP$ asymmetries of $\overline{B}^0 \to K_0^{*+}(1430)K^-$ could be changed remarkably, which provides us with a place for probing the effect of new physics. These results could be used to constrain the parameters of the $Z'$ model.

**Keywords:** B decay, $CP$ asymmetry, $Z'$ model

**PACS:** 13.25.Hw, 12.38.Bx     **DOI:** 10.1088/1674-1137/40/1/013101

## 1   Introduction

Heavy flavor physics has been a hot topic for many years in particle physics, since it is important for the study of $CP$ violation and also a good place to search for new physics signals. With more and more data from the LHCb experiment, many hadronic B decay modes have been well studied experimentally, but this is not the case for the theoretical side. Of these decay modes, rare decays with flavor-changing neutral currents (FCNC) are the most interesting, since they have quite small branching ratios in the Standard Model (SM), and thus are more sensitive to any new physics contributions.

In this work, we shall study the impact of a family non-universal leptophobic $Z'$ boson on $B \to K_0^{*\pm}(1430)K^{(*)\mp}$ decays dominated by FCNCs. In the SM, the FCNC processes are suppressed since they are only induced by loop diagrams. The branching fractions of these decays are predicted at the order of $10^{-8}$–$10^{-7}$ [1], which it is possible to measure in the ongoing LHCb experiment or forthcoming Belle-II experiment, while the family non-universal $Z'$ boson leads to tree-level FCNCs, which may enhance the branching ratios of these decays.

Motivated by this, many FCNC processes induced by $Z'$ in flavor physics have been explored extensively in the literature [2–4]. Furthermore, as it is now unclear whether the scalar meson $K_0^{*\pm}(1430)$ belongs to the first excited states (Scenario 1) or the ground states (Scenario 2) [5] of $q\bar{q}'$, we have to discuss both cases in the current work.

Unlike the leptonic decays, the non-leptonic B decays are complicated because many degrees of freedom and scales are involved. Based on effective field theories, there are three major QCD-inspired approaches for dealing with them, namely, QCD factorization (QCDF) [6], perturbative QCD (PQCD) [7], and soft collinear effective theory [8]. In this work, we shall employ QCDF to evaluate the relevant hadronic matrix elements, as it is a systematic framework to calculate these matrix elements from QCD theory, which holds in the heavy quark limit $m_b \to \infty$.

## 2   The family non-universal $Z'$ model

The recent discovery at the LHC [9] of a light Higgs with mass around 125 GeV opened a new window to physics beyond the SM. In some new physics (NP)

models [10], when the initial group breaks down to $SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$ of the SM, an extra group $U(1)'$ will usually be produced, which leads to an additional massive neutral gauge boson called Z'. If such a gauge boson were observed, it would be concrete evidence of the existence of NP. Based on the assumption that the Z' shares similar characters with the SM Z boson, much effort has been made to search for the Z' directly by analyzing the dilepton data. Now, at the LHC, the lower mass limit is 2.86 TeV (1.90 TeV) at the 95% confidence level at 8 TeV colliding energy with an integrated luminosity of 19.5 fb$^{-1}$ by using $\mathrm{e^+e^-}$ and $\mu^+\mu^-$ [11] (or $\tau^+\tau^-$ [12]) events. However, such constraints from the LHC are invalid if the Z' boson does not couple or couples very weakly with the leptons, thus one has to resort to hadronic channels. Although the couplings between quarks and Z' are family universal in most models, the family non-universal Z' can also be realized in some models. For instance, such a family non-universal leptophobic Z' boson can be realized in the $E_6$ model [13]. Phenomenological studies of family non-universal Z' at possible colliders have been explored in detail recently [14].

On the gauge interaction basis, the interactions of the leptophobic Z' boson with SM quarks can be expressed as

$$\mathcal{L}^{\mathrm{Z}'} = -g_2 Z'^\mu \sum_{i,j} \overline{\psi}_i^\mathrm{I} \gamma_\mu [(\epsilon_{\psi_\mathrm{L}})_{ij} P_\mathrm{L} + (\epsilon_{\psi_\mathrm{R}})_{ij} P_\mathrm{R}] \psi_j^\mathrm{I}, \quad (1)$$

where the field $\psi_i$ is the ith family fermion and $P_\mathrm{L,R} = (1 \mp \gamma_5)/2$ are the chirality projection operators. $\epsilon_{\psi_\mathrm{L}}$ ($\epsilon_{\psi_\mathrm{R}}$) stands for the left-handed (right-handed) chiral couplings, and they are required to be hermitian because the Lagrangian is real. When the weak eigenstates are rotated to the physical basis, the mass eigenstates will be obtained by $\psi_\mathrm{L,R} = V_{\psi_\mathrm{L,R}} \psi_\mathrm{L,R}^\mathrm{I}$. Correspondingly, the coupling matrices of down-type quarks read

$$B_\mathrm{d}^\mathrm{L} \equiv V_{\mathrm{d}_\mathrm{L}} \epsilon_{\mathrm{d}_\mathrm{L}} V_{\mathrm{d}_\mathrm{L}}^\dagger, \qquad B_\mathrm{d}^\mathrm{R} \equiv V_{\mathrm{d}_\mathrm{R}} \epsilon_{\mathrm{d}_\mathrm{R}} V_{\mathrm{d}_\mathrm{R}}^\dagger. \quad (2)$$

Since we do not need the couplings for up-type quarks, we will not discuss them here. Obviously, if the matrixes $\epsilon_{\mathrm{d}_\mathrm{L,R}}$ are not proportional to the identity matrix, the nonzero off-diagonal elements in the $B_\mathrm{u,d}^\mathrm{L,R}$ appear, which will induce FCNC interactions at the tree level. For simplicity, the right-handed couplings are often supposed to be flavor-diagonal. Then, the effective Hamiltonian of the $\bar{\mathrm{b}} \to \bar{\mathrm{d}} q\bar{q}$ transitions mediated by the Z' is given by

$$\mathcal{H}_\mathrm{eff}^{\mathrm{Z}'} = \frac{2G_\mathrm{F}}{\sqrt{2}} \left(\frac{g_2 m_\mathrm{Z}}{g_1 m_{\mathrm{Z}'}}\right)^2 B_\mathrm{bd}^{\mathrm{L}*} (\bar{\mathrm{b}}\mathrm{d})_{V-A} \sum_q \left(B_\mathrm{qq}^\mathrm{L} (\bar{q}q)_{V-A}\right.$$

$$\left. + B_\mathrm{qq}^\mathrm{R} (\bar{q}q)_{V+A}\right) + \mathrm{h.c.}, \quad (3)$$

where $g_1 = e/(\sin\theta_\mathrm{W} \cos\theta_\mathrm{W})$ and $m_{\mathrm{Z}'}$ denotes the mass of the Z' boson. The diagonal elements $B_\mathrm{qq}^\mathrm{L,R}$ are real due to the hermiticity of the effective Hamiltonian. In con-

trast, the off-diagonal element $B_\mathrm{bd}^\mathrm{L}$ might be a complex number with a new weak phase $\phi_\mathrm{bd}$, and such a newly introduced phase can be used in explaining the large direct $CP$ asymmetries in $\mathrm{B} \to \mathrm{K}\pi$ [2, 3]. Compared with the effective SM Hamiltonian [15], the operators of the forms $(\bar{\mathrm{b}}\mathrm{d})_{V-A}(\bar{q}q)_{V-A}$ and $(\bar{\mathrm{b}}\mathrm{d})_{V-A}(\bar{q}q)_{V+A}$ in Eq. (3) already exist in the SM, so the Z' effect can be represented by modifying the Wilson coefficients of the corresponding operators. Thus, Eq. (3) can be rewritten as

$$\mathcal{H}_\mathrm{eff}^{\mathrm{Z}'} = -\frac{G_\mathrm{F}}{\sqrt{2}} V_\mathrm{tb} V_\mathrm{ts}^* \sum_q \left(\Delta C_3 O_3^{(q)} + \Delta C_5 O_5^{(q)}\right.$$

$$\left. + \Delta C_7 O_7^{(q)} + \Delta C_9 O_9^{(q)}\right) + \mathrm{h.c.}, \quad (4)$$

where $O_{3,5,7,9}^{(q)}$ are the four quark operators existing in the SM [15]. The additional contributions to the SM Wilson coefficients at the $M_\mathrm{W}$ scale in terms of Z' parameters are thus given as

$$\Delta C_{3(5)} = -\frac{2}{3 V_\mathrm{tb} V_\mathrm{td}^*} \left(\frac{g_2 m_\mathrm{Z}}{g_1 m_{\mathrm{Z}'}}\right)^2 B_\mathrm{bd}^\mathrm{L} \left(B_\mathrm{uu}^\mathrm{L(R)} + 2 B_\mathrm{ss}^\mathrm{L(R)}\right) (5)$$

$$\Delta C_{9(7)} = -\frac{4}{3 V_\mathrm{tb} V_\mathrm{td}^*} \left(\frac{g_2 m_\mathrm{Z}}{g_1 m_{\mathrm{Z}'}}\right)^2 B_\mathrm{bd}^\mathrm{L} \left(B_\mathrm{uu}^\mathrm{L(R)} - B_\mathrm{ss}^\mathrm{L(R)}\right). (6)$$

From the above equations, we find that both the electroweak penguins $\Delta C_{9(7)}$ and the QCD penguins $\Delta C_{3(5)}$ will be affected by the new gauge boson Z'. Since the scale of new physics is expected to be much higher than that of the electro-weak scale, in order to show that the new physics is primarily manifest in the electroweak penguins, we therefore follow Refs. [2–4] to assume $B_\mathrm{uu}^\mathrm{L(R)} \simeq -2 B_\mathrm{ss}^\mathrm{L(R)}$. In this case, the Z' contributions to the Wilson coefficients are

$$\Delta C_{3(5)} = 0, \Delta C_{9(7)} = 4 \frac{|V_\mathrm{tb} V_\mathrm{td}^*|}{V_\mathrm{tb} V_\mathrm{td}^*} \zeta^\mathrm{L(R)} \mathrm{e}^{i\phi_\mathrm{bd}}, \quad (7)$$

where

$$\zeta^\mathrm{X} = \left(\frac{g_2 m_\mathrm{Z}}{g_1 m_{\mathrm{Z}'}}\right)^2 \left|\frac{B_\mathrm{bd}^\mathrm{L} B_\mathrm{ss}^\mathrm{X}}{V_\mathrm{tb} V_\mathrm{td}^*}\right| \quad (\mathrm{X=L,R}), \quad (8)$$

$$\phi_\mathrm{bd} = \mathrm{Arg}[B_\mathrm{bd}^\mathrm{L}]. \quad (9)$$

Finally, we obtain the resulting effective Hamiltonian at the $M_\mathrm{W}$ scale

$$\mathcal{H}_\mathrm{eff}^{\mathrm{Z}'} = -\frac{4G_\mathrm{F}}{\sqrt{2}} \left(\frac{g_2 m_\mathrm{Z}}{g_1 m_{\mathrm{Z}'}}\right)^2 B_\mathrm{bd}^{\mathrm{L}*} \sum_q \left(B_\mathrm{ss}^\mathrm{L} O_9^{(q)} + B_\mathrm{ss}^\mathrm{R} O_7^{(q)}\right)$$

$$+ \mathrm{h.c.} \quad (10)$$

Because all heavy degrees of freedom (including the Z') above the scale of the W boson mass have already been integrated out and there are no new particles below $m_\mathrm{W}$, the renormalization group evolution of the above new Wilson coefficients down to low energies is exactly the same as in the SM [15].

Now, we will discuss the ranges of new parameters $\zeta^{L,R}$ and $\phi_{bd}$. Because both the gauge group $U(1)_Y$ and the new $U(1)'$ are expected to originate from the same large group, the relation $g_2/g_1 \sim 1$ is assumed. On the experimental side, if the leptophobic Z' boson is detected at the LHC, the mass of the Z' should be about a few TeV, which means $m_Z/m_{Z'}$ is of the order of $\mathcal{O}(10^{-1})$. In addition, the other parameters $|B_{bd}^L|$, $|B_{qq}^X|$ and new weak phases $\phi_{bd}$ could be constrained by the data induced by FCNCs. For instance, the mass difference $B_d^0$ and $\overline{B}_d^0$ requires $|B_{bd}^L| \sim |V_{tb}V_{td}^*|$. Then, with experimental data for $B_{d,s}$ nonleptonic charmless decays, $B_{qq}^{L,R} \sim 1$ could be extracted. As for the newly introduced phase $\phi_{bd}$, recent discussions indicate that $\phi_{bd} = -50°$ [3]. How to constrain these parameters globally is beyond the scope of this work; we will not discuss this topic explicitly here. So, to probe the new physics effect for maximum range, we assume $\zeta = \zeta^L = \zeta^R \in [0.001, 0.02]$, and $\phi_{bd} \in [-180°, 180°]$, and set $\zeta = 0.01$ and $\phi_{bd} = -50°$ for the center values.

# 3   QCD factorization calculation

In the $B \to K_0^{*\pm}(1430)K^{(*)\mp}$ decays, none of the quarks in the final states is the same as those of the initial B meson. Therefore they can occur only via annihilation type diagrams. However, in QCDF, the end-point singularity usually appears when calculating the annihilation type diagrams [6]. The most popular way is for the end-point divergent integral to be treated as an infrared sensitive contribution that is parameterized by

$$\int_0^1 \frac{dx}{1-x} \to X_A = \ln\left(\frac{m_B}{\Lambda}\right)(1+\rho_A e^{i\phi_A}), \qquad (11)$$

where the unknown parameters $\rho_A$ and $\phi_A$ could be fixed by the experimental data. This singularity can also be smeared by introducing an effective mass for the gluon [16]. We will adopt Eq. (11) in this work.

Within the framework of QCDF, the decay amplitudes of $B \to K_0^{*\pm}(1430)K^{(*)\mp}$ can be written as

$$A(\overline{B}^0 \to K_0^{*+}K^-) = \frac{G_F}{\sqrt{2}}\sum_{p=u,c}\lambda_p^{(d)}\left\{f_B f_{K_0^*} f_K\left[(b_1\delta_u^p + b_4 + b_{4,EW})_{K_0^{*+}K^-} + \left(b_4 - \frac{1}{2}b_{4,EW}\right)_{K^-K_0^{*+}}\right]\right\}, \qquad (12)$$

$$A(\overline{B}^0 \to K^+K_0^{*-}) = \frac{G_F}{\sqrt{2}}\sum_{p=u,c}\lambda_p^{(d)}\left\{f_B f_{K_0^*} f_K\left[(b_1\delta_u^p + b_4 + b_{4,EW})_{K^+K_0^{*-}} + \left(b_4 - \frac{1}{2}b_{4,EW}\right)_{K_0^{*-}K^+}\right]\right\}, \qquad (13)$$

$$A(\overline{B}^0 \to K_0^{*+}K^{*-}) = \frac{G_F}{\sqrt{2}}\sum_{p=u,c}\lambda_p^{(d)}\left\{-f_B f_{K_0^*} f_{K^*}\left[(b_1\delta_u^p + b_4 + b_{4,EW})_{K_0^{*+}K^{*-}} + \left(b_4 - \frac{1}{2}b_{4,EW}\right)_{K^{*-}K_0^{*+}}\right]\right\}, \qquad (14)$$

$$A(\overline{B}^0 \to K^{*+}K_0^{*-}) = \frac{G_F}{\sqrt{2}}\sum_{p=u,c}\lambda_p^{(d)}\left\{-f_B f_{K_0^*} f_{K^*}\left[(b_1\delta_u^p + b_4 + b_{4,EW})_{K^{*+}K_0^{*-}} + \left(b_4 - \frac{1}{2}b_{4,EW}\right)_{K_0^{*-}K^{*+}}\right]\right\}, \qquad (15)$$

where the building blocks $b_i$ and $b_{i,EW}$ read

$$b_1 = \frac{C_F}{N_c^2}C_1 A_1^i,$$

$$b_2 = \frac{C_F}{N_c^2}C_2 A_1^i,$$

$$b_3 = \frac{C_F}{N_c^2}\left[C_3' A_1^i + C_5'(A_3^i + A_3^f) + N_c C_6' A_3^f\right],$$

$$b_4 = \frac{C_F}{N_c^2}\left[C_4' A_1^i + C_6' A_2^f\right],$$

$$b_{3,EW} = \frac{C_F}{N_c^2}\left[C_9' A_1^i + C_7'(A_3^i + A_3^f) + N_c C_8' A_3^i\right],$$

$$b_{4,EW} = \frac{C_F}{N_c^2}\left[C_{10}' A_1^i + C_8' A_2^i\right]. \qquad (16)$$

The expressions of the functions $A_n^{i,f}$ can be found in Refs. [5, 17], and the subscripts 1, 2, 3 denote the annihilation amplitudes induced from the $(V-A)(V-A)$,

$(V-A)(V+A)$ and $(S-P)(S+P)$ operators, while the superscripts i and f refer to gluon emission from the initial and final-state quarks, respectively. When listing the two final state mesons $M_1 M_2$ in the formulas, we use the first meson $M_1$ to refer to one containing an anti-quark from the weak vertex, and $M_2$ to refer to one containing a quark from the weak vertex. As for the aforementioned endpoint singularity $X_A$, we adopt Eq. (11) with $\Lambda = 0.5$ GeV. Note that the recent global fit of $\rho_A$ and $\phi_A$ to $B \to SP$, SV implies $\rho_A = 0.15$ and $\phi_A = 82°$ with $\chi^2 = 8.3$ [18]. Therefore, we set $\rho_A \in [0.1, 0.2]$ and $\phi_A \in [60°, 120°]$ in estimating the uncertainties.

Because both $B^0$ and $\overline{B}^0$ could decay to $K_0^{*+}(1430)K^-$ and $K_0^{*-}(1430)K^+$, we then define four decay amplitudes, $A_f$, $A_{\bar{f}}$, $\bar{A}_f$ and $\bar{A}_{\bar{f}}$ as

$$A_f = \langle K_0^{*+}K^-|B^0\rangle, A_{\bar{f}} = \langle K_0^{*-}K^+|B^0\rangle;$$

$$\bar{A}_f = \langle K_0^{*+}K^-|\overline{B}^0\rangle, \bar{A}_{\bar{f}} = \langle K_0^{*-}K^+|\overline{B}^0\rangle. \qquad (17)$$

Table 1.　Branching fractions of B$\to$K$_0^*$(1430)K$^{(*)}$ under different scenarios ($10^{-7}$).

| scenario | decay modes | SM | Z′ |
|---|---|---|---|
| scenario 1 | $\overline{\text{B}}^0\to$K$_0^{*+}$(1430)K$^-$ | $0.97^{+0.43+0.23}_{-0.31-0.12}$ | $1.37^{+0.57+0.35+0.62}_{-0.43-0.19-1.05}$ |
| | $\overline{\text{B}}^0\to$K$_0^{*-}$(1430)K$^+$ | $8.33^{+3.31+2.65}_{-2.55-1.39}$ | $8.17^{+3.25+2.60+0.59}_{-2.50-1.36-0.18}$ |
| | $\overline{\text{B}}^0\to$K$_0^{*+}$(1430)K$^{*-}$ | $0.33^{+0.14+0.08}_{-0.10-0.04}$ | $0.40^{+0.16+0.10+0.10}_{-0.12-0.05-0.20}$ |
| | $\overline{\text{B}}^0\to$K$_0^{*-}$(1430)K$^{*+}$ | $14.54^{+5.75+4.54}_{-4.44-2.38}$ | $14.47^{+5.72+4.52+2.67}_{-4.42-2.37-0.08}$ |
| scenario 2 | $\overline{\text{B}}^0\to$K$_0^{*+}$(1430)K$^-$ | $0.58^{+0.45+0.04}_{-0.29-0.02}$ | $0.65^{+0.50+0.08+0.07}_{-0.32-0.03-0.18}$ |
| | $\overline{\text{B}}^0\to$K$_0^{*-}$(1430)K$^+$ | $1.07^{+0.72+0.79}_{-0.47-0.29}$ | $1.06^{+0.71+0.77+0.08}_{-0.47-0.28-0.06}$ |
| | $\overline{\text{B}}^0\to$K$_0^{*+}$(1430)K$^{*-}$ | $0.11^{+0.09+0.03}_{-0.06-0.02}$ | $0.12^{+0.09+0.04+0.01}_{-0.06-0.02-0.02}$ |
| | $\overline{\text{B}}^0\to$K$_0^{*-}$(1430)K$^{*+}$ | $1.84^{+1.26+1.38}_{-0.83-0.52}$ | $1.84^{+1.25+1.37+0.04}_{-0.82-0.51-0.04}$ |

Then, the direct $CP$ asymmetry is defined as

$$A_{CP}=\frac{|A_{\text{f}}|^2+|\bar{A}_{\text{f}}|^2-|A_{\bar{\text{f}}}|^2-|\bar{A}_{\bar{\text{f}}}|^2}{|A_{\text{f}}|^2+|\bar{A}_{\text{f}}|^2+|A_{\bar{\text{f}}}|^2+|\bar{A}_{\bar{\text{f}}}|^2}. \tag{18}$$

On the experimental side, the four time-dependent decay widths are given by (f=K$_0^{*+}$K$^-$ and $\bar{\text{f}}$=K$_0^{*-}$K$^+$)

$$\begin{aligned}\Gamma(\text{B}^0(\text{t})\to\text{f}) &= \text{e}^{-\Gamma\text{t}}\frac{1}{2}(|A_{\text{f}}|^2+|\bar{A}_{\text{f}}|^2)\\&\quad\times[1+C_{\text{f}}\cos\Delta mt-S_{\text{f}}\sin\Delta mt],\end{aligned}$$

$$\begin{aligned}\Gamma(\overline{\text{B}}^0(\text{t})\to\bar{\text{f}}) &= \text{e}^{-\Gamma\text{t}}\frac{1}{2}(|A_{\bar{\text{f}}}|^2+|\bar{A}_{\bar{\text{f}}}|^2)\\&\quad\times[1-C_{\bar{\text{f}}}\cos\Delta mt+S_{\bar{\text{f}}}\sin\Delta mt],\end{aligned}$$

$$\begin{aligned}\Gamma(\text{B}^0(\text{t})\to\bar{\text{f}}) &= \text{e}^{-\Gamma\text{t}}\frac{1}{2}(|A_{\bar{\text{f}}}|^2+|\bar{A}_{\bar{\text{f}}}|^2)\\&\quad\times[1+C_{\bar{\text{f}}}\cos\Delta mt-S_{\bar{\text{f}}}\sin\Delta mt],\end{aligned}$$

$$\begin{aligned}\Gamma(\overline{\text{B}}^0(\text{t})\to\text{f}) &= \text{e}^{-\Gamma\text{t}}\frac{1}{2}(|A_{\text{f}}|^2+|\bar{A}_{\text{f}}|^2)\\&\quad\times[1-C_{\text{f}}\cos\Delta mt+S_{\text{f}}\sin\Delta mt]. \quad(19)\end{aligned}$$

In the above functions, $\Delta m$ means the mass difference of the B$^0$/$\overline{\text{B}}^0$ meson, and $\Gamma$ is the average decay width of the B meson. The auxiliary parameters $C_{\text{f}}$ and $S_{\text{f}}$, which can be extracted from the data, are given by

$$C_{\text{f}} = \frac{|A_{\text{f}}|^2-|\bar{A}_{\text{f}}|^2}{|\bar{A}_{\text{f}}|^2+|A_{\text{f}}|^2}, \tag{20}$$

$$S_{\text{f}} = \frac{2\text{Im}(\lambda_{\text{f}})}{1+|\bar{A}_{\text{f}}/A_{\text{f}}|^2}, \tag{21}$$

$$\lambda_{\text{f}} = \frac{V_{\text{tb}}V_{\text{td}}^*}{V_{\text{tb}}^*V_{\text{td}}}\frac{\bar{A}_{\text{f}}}{A_{\text{f}}}. \tag{22}$$

The definitions of $C_{\bar{\text{f}}}$ and $S_{\bar{\text{f}}}$ can also be obtained by replacing f with $\bar{\text{f}}$. In order to show the implications of the

above four parameters, we usually use the following four new parameters:

$$C=\frac{1}{2}(C_{\text{f}}+C_{\bar{\text{f}}}),\quad\Delta C=\frac{1}{2}(C_{\text{f}}-C_{\bar{\text{f}}}), \tag{23}$$

$$S=\frac{1}{2}(S_{\text{f}}+S_{\bar{\text{f}}}),\quad\Delta S=\frac{1}{2}(S_{\text{f}}-S_{\bar{\text{f}}}). \tag{24}$$

Physically, $S$ and $C$ are related to the mixing-induced $CP$ asymmetry and the direct $CP$ asymmetry, respectively. Moreover, $\Delta C$ and $\Delta S$ are $CP$-even under $CP$ transformation $\lambda_{\text{f}}\to1/\lambda_{\bar{\text{f}}}$.

## 4　Numerical results

Using the parameters of Refs. [5, 17, 18], with and without the Z′ boson, we present the predicted branching ratios of B$\to$K$_0^{*\pm}$(1430)K$^{(*)\mp}$ under different scenarios ($K_0^{*\pm}$(1430) as the first excited states or the ground states) in Table 1. The SM predictions are also listed for comparison. Within the PQCD approach based on the $k_{\text{T}}$ factorization, Liu Xin et al. have studied these decay modes [19]. Comparing their results with ours, we find that their results for branching ratios are larger than ours by $1\sim2$ orders of magnitude. Currently, we cannot determine which approach is better, but we hope that future experiments can test these two different approaches.

From Table 1, for decay modes $\overline{\text{B}}^0\to$K$_0^{*+}$(1430)K$^{(*)-}$, the differences between Scenario 1 and Scenario 2 are very small, so it is hard for us to discriminate the two different scenarios using these two decays. In contrast, the branching fractions of $\overline{\text{B}}^0\to$K$_0^{*-}$(1430)K$^{(*)+}$ under Scenario 1 and Scenario 2 have large differences, so if these two modes can be measured precisely they may be used to determine whether K$_0$(1430) belongs to the ground states or the first-excited states.

Table 2.   The CP-violating parameters $A_{CP}$, $C$, $\Delta C$, $S$ and $\Delta S$ of B→K$_0^*$(1430)K$^{(*)}$.

| parameters | K$_0^{*\pm}$K$^\mp$ | | K$_0^{*\pm}$K$^{*\mp}$ | |
| --- | --- | --- | --- | --- |
| | scenario-1 | scenario-2 | scenario-1 | scenario-2 |
| $A_{CP}$ | $0.79^{+0.01+0.01}_{-0.01-0.01}$ | $0.29^{+0.06+0.20}_{-0.09-0.14}$ | $0.96^{+0.00+0.00}_{-0.00-0.00}$ | $0.88^{+0.02+0.03}_{-0.01-0.02}$ |
| | $0.71^{+0.01+0.01+0.22}_{-0.01-0.01-0.11}$ | $0.24^{+0.07+0.18+0.14}_{-0.07-0.12-0.05}$ | $0.94^{+0.00+0.00+0.03}_{-0.00-0.00-0.01}$ | $0.87^{+0.02+0.03+0.02}_{-0.01-0.02-0.01}$ |
| $C$ | $-0.04^{+0.01+0.02}_{-0.01-0.01}$ | $-0.02^{+0.04+0.04}_{-0.02-0.05}$ | $-0.01^{+0.00+0.01}_{-0.00-0.00}$ | $0.01^{+0.01+0.02}_{-0.01-0.02}$ |
| | $-0.02^{+0.00+0.00+0.05}_{-0.00-0.01-0.11}$ | $0.02^{+0.03+0.04+0.08}_{-0.01-0.05-0.19}$ | $-0.01^{+0.00+0.01+0.04}_{-0.00-0.00-0.02}$ | $0.03^{+0.02+0.03+0.02}_{-0.01-0.02-0.06}$ |
| $\Delta C$ | $0.06^{+0.01+0.02}_{-0.02-0.03}$ | $0.25^{+0.04+0.09}_{-0.02-0.12}$ | $0.02^{+0.00+0.01}_{-0.00-0.00}$ | $0.11^{+0.03+0.06}_{-0.02-0.06}$ |
| | $0.01^{+0.01+0.02+0.22}_{-0.01-0.03-0.12}$ | $0.27^{+0.06+0.12+0.10}_{-0.05-0.15-0.16}$ | $0.01^{+0.00+0.01+0.07}_{-0.00-0.01-0.04}$ | $0.14^{+0.04+0.07+0.02}_{-0.03-0.07-0.08}$ |
| $S$ | $0.04^{+0.02+0.01}_{-0.02-0.01}$ | $-0.36^{+0.05+0.06}_{-0.05-0.04}$ | $0.01^{+0.00+0.00}_{-0.00-0.00}$ | $0.02^{+0.01+0.08}_{-0.01-0.04}$ |
| | $0.04^{+0.02+0.01+0.02}_{-0.02-0.01-0.07}$ | $-0.35^{+0.06+0.06+0.08}_{-0.06-0.04-0.21}$ | $0.01^{+0.00+0.00+0.01}_{-0.00-0.00-0.00}$ | $0.02^{+0.01+0.01+0.02}_{-0.02-0.01-0.02}$ |
| $\Delta S$ | $-0.84^{+0.03+0.02}_{-0.03-0.02}$ | $-0.20^{+0.12+0.10}_{-0.10-0.16}$ | $-0.98^{+0.00+0.02}_{-0.00-0.00}$ | $-0.91^{+0.02+0.02}_{-0.02-0.02}$ |
| | $-0.88^{+0.02+0.01+0.19}_{-0.02-0.02-0.03}$ | $-0.26^{+0.14+0.11+0.19}_{-0.11-0.18-0.05}$ | $-0.98^{+0.00+0.00+0.02}_{-0.00-0.00-0.01}$ | $-0.92^{+0.03+0.03+0.02}_{-0.02-0.03-0.02}$ |

In Table 2, we list our predictions for $A_{CP}$, $C$, $\Delta C$, $S$ and $\Delta S$ for the final states K$_0^{*+}$K$^-$ and K$_0^{*+}$K$^{*-}$, under the two different scenarios in both the SM (upper values) and Z' model (lower values). For all results, the first errors are from the uncertainties of the decay constants and the light-cone distribution amplitudes of final states, the second errors come from the $\rho_A$ and $\phi_A$, and the last errors in the Z' model are the results by scanning the possible ranges of $\zeta$ and $\phi_{bd}$. From the numerical results, we find that the largest uncertainties are from the $\rho_A$ and $\phi_A$. This is in contrast with other decay modes dominated by the spectator diagrams, whose uncertainties from the above two parameters are small. Unlike branching fractions, the $CP$ asymmetry parameters are not sensitive to non-perturbative hadronic parameters, where these uncertainties are canceled because they are ratios of different amplitudes. Therefore, these parameters are more sensitive to the effects of NP.

In order to show the effects of Z' clearly, in Fig. 1 we plot the variations of the branching ratios as functions of the new weak phase $\phi_{bd}$ with different $\zeta=0.001$, 0.01, 0.02 under the different scenarios. Including the newly introduced Z' boson, one can see that if $\zeta < 0.01$ the effects of Z' are not large enough to be detected in these four decay modes, because the new physics contributions are buried by the large uncertainties of hadronic parameters. If $\zeta$ is around 0.2, the branching fraction of $\overline{\text{B}}^0 \to$K$_0^{*+}$(1430)K$^-$ under Scenario 1 changes remarkably to reach $2.0 \times 10^{-7}$, which could be measured in the forthcoming Belle-II experiment.

The relations of the direct $CP$ asymmetries $A_{CP}^{\text{dir}}$, $C$, $\Delta C$, $S$ and $\Delta S$ with $\phi_{bd}$ with different $\zeta$ are presented in Fig. 2 and Fig. 3, for B $\to$ K$_0^{*\pm}$(1430)K$^\mp$ and B $\to$ K$_0^{*\pm}$(1430)K$^{*\mp}$, respectively. From Fig. 2, the observables of $CP$ asymmetries are much more sensitive to the Z' than the branching fractions. For example, under Scenario 1, the direct asymmetry of $\overline{\text{B}}^0 \to$K$_0^{*\pm}$(1430)K$^\mp$ is 79% in the SM, while it would change to 49% with the Z' boson. In future, these observables could be used to probe the effects of new physics. If the Z' were detected in the colliders directly, these decays would also be useful to constrain the couplings.

## 5   Summary

Within the QCD factorization approach, we have studied the pure annihilation type decays B $\to$ K$_0^{*\pm}$(1430)K$^{(*)\mp}$ in the SM and the family non-universal leptophobic Z' model. Both the branching fractions and the $CP$ asymmetry observables have been calculated. The branching fractions we predict are 1–2 orders of magnitude smaller than the results from the PQCD approach. When the Z' is involved, if $m_{Z'} > 1$ TeV ($\zeta < 0.01$), its contributions will be buried by the large uncertainties of the SM. If $m_{Z'} \approx 600$ GeV ($\zeta = 0.02$), both the branching fractions and $CP$ asymmetries of $\overline{\text{B}}^0 \to$K$_0^{*+}$(1430)K$^-$ could change remarkably, which provides us with a place for probing the effects of new physics. We hope that these results can be tested in Belle-II, LHC-b or the future high-energy circular colliders.
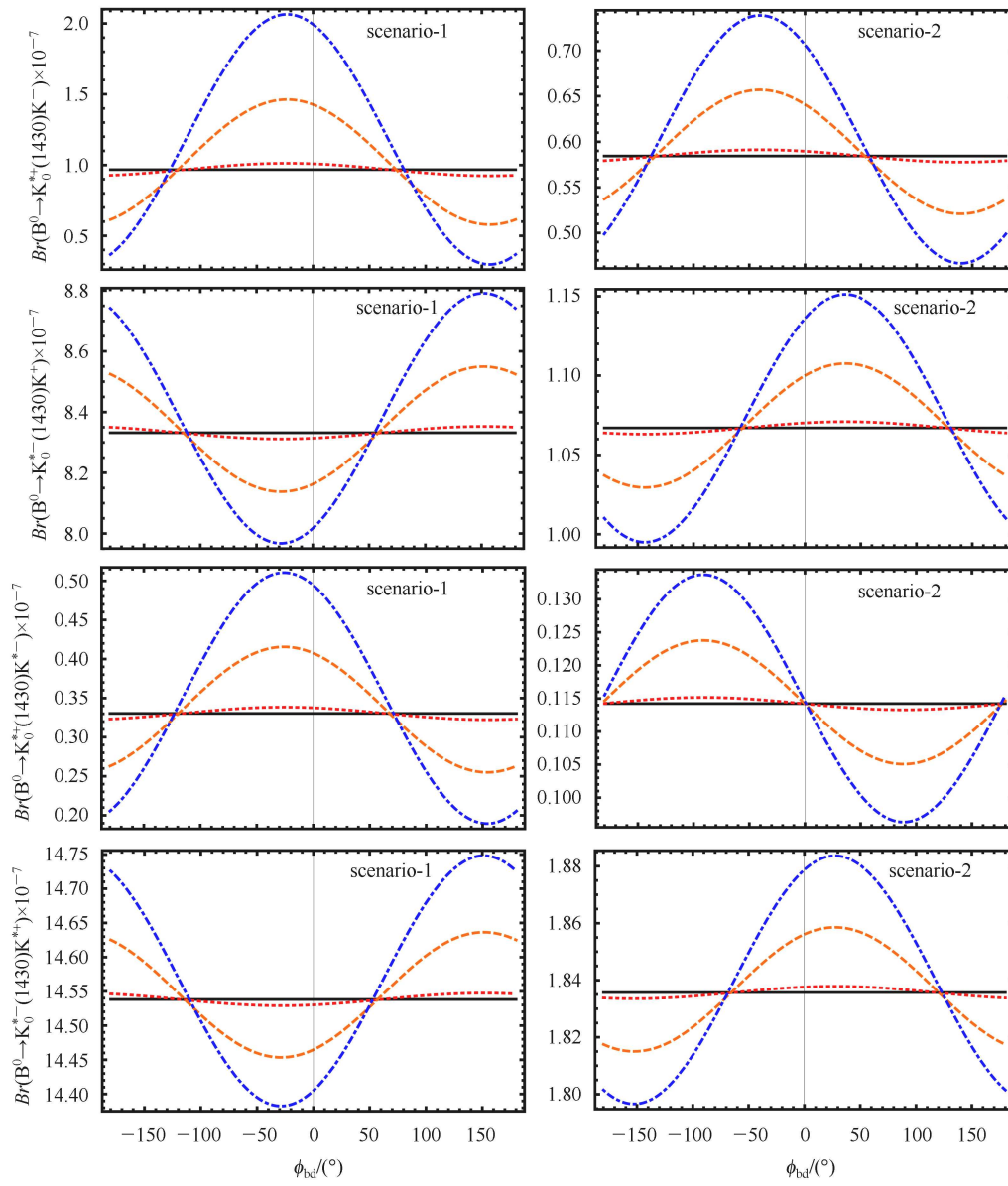
Fig. 1.    (color online) Branching ratios of $B \to K_0^{*\pm}(1430)K^{(*)\mp}$ as functions of the weak phase $\phi_{bd}$ under different scenarios. The dotted (red), dashed (orange) and dotted-dashed (blue) lines represent results from $\zeta = 0.001$, 0.01, 0.02, and the solid lines (black) are the SM predictions.
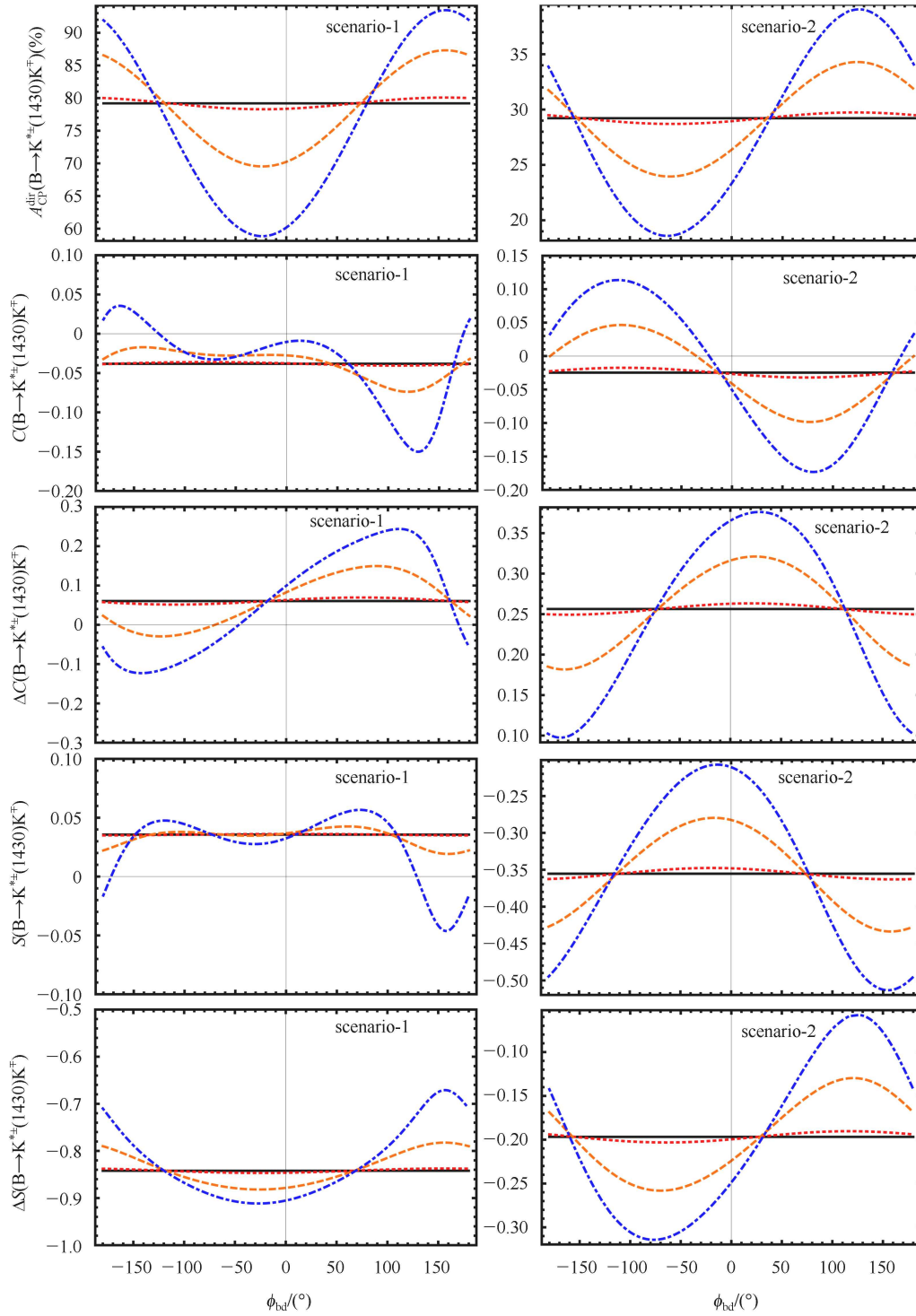
Fig. 2. (color online) $CP$-violating parameters $A_{CP}$, $C$, $\Delta C$, $S$ and $\Delta S$ (%) of $\mathrm{B} \to \mathrm{K}_0^*(1430)\mathrm{K}$ as functions of the weak phase $\phi_{\mathrm{bd}}$ under different scenarios. The dotted (red), dashed (orange) and dotted-dashed (blue) lines represent results from the $\zeta=0.001$, 0.01, 0.02, and the solid lines (black) are the SM predictions.
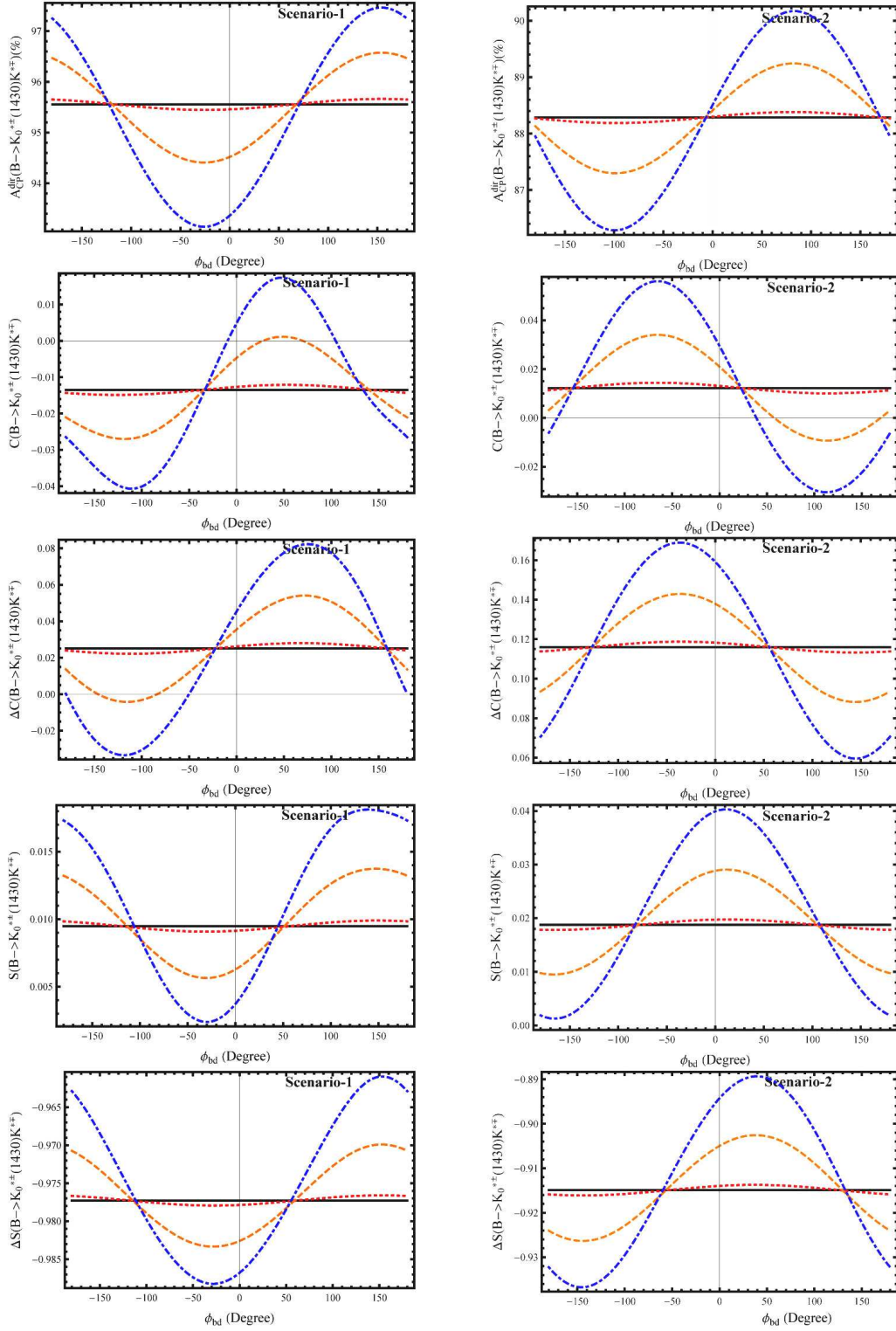
Fig. 3.   (color online) $CP$-violating parameters $A_{CP}$, $C$, $\Delta C$, $S$ and $\Delta S$ (%) of B $\rightarrow$ K$_0^*$(1430)K$^*$ as functions of the weak phase $\phi_{bd}$ under different scenarios. The dotted (red), dashed (orange) and dotted-dashed (blue) lines represent results from the $\zeta$=0.001, 0.01, 0.02, and the solid lines (black) are the SM predictions.

# References

1  Y. Li, H. Y. Zhang, Y. Xing, Z. H. Li, and C. D. Lu, Phys. Rev. D, **91**: 074022 (2015)

2  V. Barger, C.W. Chiang, P. Langacker, and H.S. Lee, Phys. Lett. B, **598**: 218 (2004)

3  Q. Chang, X. Q. Li, and Y. D. Yang, JHEP, **0905**: 056 (2009); Q. Chang, X. Q. Li, and Y. D. Yang, JHEP, **1002**: 082 (2010); Q. Chang, X. Q. Li, and Y. D. Yang, JHEP, **1004**: 052 (2010); Q. Chang, X. Q. Li, and Y. D. Yang, J. Phys. G, **41**: 105002 (2014); Q. Chang, and Y.H. Gao, Nucl. Phys. B, **845**: 179 (2011)

4  J. Hua, C. S. Kim, and Y. Li, Phys. Lett. B, **690**: 508–513 (2010); J. Hua, C. S. Kim, and Y. Li, Eur. Phys. J. C, **69**: 139–146 (2010); Y. Li, J. Hua, and K.C. Yang, Eur. Phys. J. C, **71**: 1775 (2011); Y. Li, X. J. Fan, J. Hua, and E. L. Wang, Phys. Rev. D, **85**: 074010 (2012); C. W. Chiang, R. H. Li, and C. D. LU, Chinese Physics C, **36**: 14–24 (2012); Y. Li, E. L. Wang, and H. Y. Zhang, Advances in High Energy Physics, 2175287 (2013); Y. Li, Phys. Rev. D, **89**: 014003 (2014)

5  H. Y. Cheng, C. K. Chua, and K. C. Yang, Phys. Rev. D, **73**: 014017 (2006)

6  M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, Phys. Rev. Lett., **83**: 1914 (1999); M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, Nucl. Phys. B, **591**: 313 (2000); M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, Nucl. Phys. B, **606**: 245 (2001)

7  Y. Y. Keum, H. N. Li, and A. I. Sanda, Phys. Rev. D, **63**: 054008 (2001)

8  C. W. Bauer, D. Pirjol, I. Z. Rothstein, and I. W. Stewart, Phys. Rev. D, **70**: 054015 (2004)

9  G. Aadet et al (ATLAS Collaboration), Phys. Lett. B, **716**: 1 (2012); S. Chatrchyan et al (CMS Collaboration), Phys. Lett. B, **716**: 30 (2012)

10  P. Langacker, and M. Plumacher, Phys. Rev. D, **62**: 013006 (2000); P. Langacker, Rev. Mod. Phys., **81**: 1199 (2009)

11  The ATLAS Collaboration (ATLAS Collaboration), ATLAS-CONF-2013-017, ATLAS-COM-CONF-2013-010

12  The ATLAS Collaboration (ATLAS Collaboration), ATLAS-CONF-2013-066, ATLAS-COM-CONF-2013-083

13  K. S. Babu, C. F. Kolda, and J. March-Russell, Phys. Rev. D, **54**: 4635 (1996); K. S. Babu, C. F. Kolda, and J. March-Russell, Phys. Rev. D, **57**: 6788 (1998)

14  C. W. Chiang, T. Nomura, and K. Yagyu, JHEP, **1405**: 106 (2014); C. W. Chiang, T. Nomura, and K. Yagyu, JHEP, **1505**: 127 (2015)

15  G. Buchalla, A. J. Buras, and M. E. Lautenbacher, Rev. Mod. Phys., **68**: 1125 (1996)

16  Q. Chang, X. Q. Li, and Y.D. Yang, JHEP, **0809**: 038 (2008)

17  H. Y. Cheng, C. K. Chua, and K. C. Yang, Phys. Rev. D, 2008, **77**: 014034 [arXiv:0705.3079 [hep-ph]]

18  H. Y. Cheng, C. K. Chua, K. C. Yang, and Z. Q, Zhang, Phys. Rev. D, **87**: 114001 (2013)

19  X. Liu, Z. J. Xiao, and Z. T. Zou, J. Phys. G, **40**: 025002 (2013); X. Liu, Z. J. Xiao, and Z. T. Zou, Phys. Rev. D, **88**: 094003 (2013)