$B \to K\eta^{(\prime)}$ decays in the SM with fourth generation fermions *

CHENG Shan(程山) FAN Ying-Ying(樊莹莹) XIAO Zhen-Jun(肖振军)1)

Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210023, China

Abstract: By employing the perturbative QCD (pQCD) factorization approach, we calculate the new physics contributions to the four $B \to K\eta^{(\prime)}$ decays in the Standard Model (SM) with a fourth generation of fermions (SM4), induced by the loop diagrams involving t' quark. Within the considered parameter space of the SM4 we find that: (a) the next-to-leading order (NLO) pQCD predictions for the branching ratios and CP-violating asymmetries in both the SM and SM4 generally agree with the data within one standard deviation; (b) for $Br(B \to K\eta)$, the inclusion of the fourth generation contributions can improve the agreement between the theoretical predictions and the data effectively; (c) however, for $Br(B \to K\eta')$ the decrease due to t' loops is disfavored by the data; and, (d) the new physics corrections to the CP-violating asymmetries of the considered decays are only about 10%.

Key words: perturbative QCD factorization approach, B meson decays, standard model with fourth generation, CP violatoin

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1 Introduction

As a simple extension of the Standard Model(SM), the standard model with the fourth generation fermion (SM4) was rather popular in the 1980s [1–4]. However, unfortunately, the direct searches at the LHC experiments [5–7] have not yet found any sign of the heavy fourth generation t' and b' quarks. The phenomenological studies of the electroweak precision observables (EWPOs) [8–10] and some B meson rare decays [11–15] have also resulted in some constraints on the parameter space of the SM4. The observation of the SM Higgs boson at a mass of 126 GeV as reported by the CMS and ATLAS Collaboration [16, 17] leads to very strong limits on the SM4: it was claimed [18, 19] that the SM4 was ruled out at 5.3σ by the Higgs data. The loop diagrams (box or penguins) involving the fourth generation fermions t' and b', as is well-known, can provide new physics(NP) corrections to the branching ratios and CP violating asymmetries of B meson decays, such as the $B \to K\eta^{(\prime)}$ decays. At present, it is still interesting to study the possible NP effects to those well measured B meson rare decays and to draw additional constraints on the SM4 from the relevant phenomenological analysis. Such constraints are complimentary to those obtained from the EWPOs and/or the Higgs data.

The $B \to K\eta^{(\prime)}$ decays are penguin dominated decays and they have been studied intensively by many authors, for example in Refs. [20–24], in the framework of the SM or various new physical models. These four decays have been studied very recently [25] by employing the perturbative QCD (pQCD) factorization approach with the inclusion of all known next-to-leading order (NLO) contributions from different sources. The NLO pQCD predictions for both the branching ratios and the CP violating asymmetries agree well with the precision experimental measurements [26, 27].

In this paper, we will study the possible loop contributions induced by the heavy t' quark that appeared in the SM4. We will focus on the following points:

1) Besides all the known NLO contributions already considered in Ref. [25], we will here consider the effects of the t' contributions to the relevant Wilson coefficients, as presented in Refs. [11, 13, 14], on the $B \to K\eta^{(\prime)}$ decays in the conventional Feldmann-Kroll-Stech (FKS) η-η' mixing scheme [28].

2) We will check the SM4 parameter-dependence of the pQCD predictions for the branching ratios and CP-violating asymmetries, such as those $|\lambda_{t'}|, \phi_{t'}, m_{t'}$ with the definition of $V^*_{t'b}V_{t's} = |\lambda_{t'}|\exp[i\phi_{t'}]$.

The rest of this paper is organized as follows. In Section 2, we give a brief review for the pQCD factorization

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1) E-mail: xiaozhenjun@njnu.edu.cn

approach and the SM4 model. In Section 3, we will make numerical calculations and present the numerical results. A short summary will be given in the final section.

2 Theoretical framework

For the charmless $B\to K\eta^{(\prime)}$ decays, the corresponding weak effective Hamiltonian can be written as [29]:

$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}}\left\{V_{\rm ub}V_{\rm uq}^*\left[C_1(\mu)O_1^{\rm u}(\mu)+C_2(\mu)O_2^{\rm u}(\mu)\right]\right.$$
$$\left. -V_{\rm tb}V_{\rm tq}^*\left[\sum_{i=3}^{10}C_i(\mu)O_i(\mu)\right]\right\}+{\rm H.c.}, \qquad (1)$$

where q=d, s, $G_{\rm F}=1.16639\times10^{-5}$ GeV^{-2} is the Fermi constant, O_i $(i=1,\cdots,10)$ are the local four-quark operators [29]. The Wilson coefficients C_i in Eq. (1) and the corresponding renormalization group evolution matrix are known currently at the LO and NLO levels [29].

In the B-rest frame, we assume that the light final state meson M_2 and M_3 (here M_i refers to K or $\eta^{(\prime)}$) is moving along the direction of $n=(1,\ 0,\ 0_{\rm T})$ and $v=(0,\ 1,\ 0_{\rm T})$, respectively. Using the light-cone coordinates, the B meson momentum $P_{\rm B}$ and the two final state mesons' momenta P_2 and P_3 (for M_2 and M_3 respectively) can be written as

$$P_{\rm B}=\frac{M_{\rm B}}{\sqrt{2}}(1,\ 1,\ 0_{\rm T}),\quad P_2=\frac{M_{\rm B}}{\sqrt{2}}(1-r_3^2,\ r_2^2,\ 0_{\rm T}),$$
$$P_3=\frac{M_{\rm B}}{\sqrt{2}}(r_3^2,\ 1-r_2^2,\ 0_{\rm T}), \qquad (2)$$

while the anti-quark momenta are chosen as

$$k_1=\frac{m_{\rm B}}{\sqrt{2}}(x_1,\ 0,\ \boldsymbol{k}_{1\rm T}),\quad k_2=\frac{m_{\rm B}}{\sqrt{2}}(x_2(1-r_3^2),\ x_2r_2^2,\ \boldsymbol{k}_{2\rm T}),$$
$$k_3=\frac{m_{\rm B}}{\sqrt{2}}(x_3r_3^2,\ x_3(1-r_2^2),\ \boldsymbol{k}_{3\rm T}), \qquad (3)$$

where $r_i=m_i/M_{\rm B}$ with m_i is the mass of meson M_i, and x_i refers to the momentum fraction of the anti-quark in each meson. After making the same integrations over the small components k_1^-, k_2^-, and k_3^+, as in Ref. [25], we conceptually obtain the decay amplitude

$$\mathcal{A}(B\to M_2M_3) \sim\int {\rm d}x_1{\rm d}x_2{\rm d}x_3b_1{\rm d}b_1b_2{\rm d}b_2b_3{\rm d}b_3$$
$$\times{\rm Tr}[C(t)\Phi_{\rm B}(x_1,b_1)\Phi_{\rm M_2}(x_2,b_2)$$
$$\times\Phi_{\rm M_3}(x_3,b_3)H(x_i,b_i,t)S_{\rm t}(x_i){\rm e}^{-S(t)}], \qquad (4)$$

where b_i is the conjugate space coordinate of $k_{i\rm T}$. In above equation, $C(t)$ is the Wilson coefficient evaluated at scale t, $H(x_i,\ b_i,\ t)$ is the hard kernel, and $\Phi_{\rm B}(x_1,\ b_1)$ and $\Phi_{\rm M_i}(x_i,\ b_i)$ are the wave function. The function $S_{\rm t}(x_i)$ and ${\rm e}^{-S(t)}$ are the threshold and $K_{\rm T}$ Sudakov factors, which effectively suppresses the soft dynamics [30].

In the pQCD approach, the B meson is treated as a very good heavy-light system. Following Ref. [31], we can write the wave function of the B meson in the form of

$$\Phi_{\rm B}=\frac{\rm i}{\sqrt{2N_{\rm c}}}(\not{P}_{\rm B}+m_{\rm B})\gamma_5\phi_{\rm B}(\boldsymbol{k}_1). \qquad (5)$$

Here, we have adopted the widely used B-meson distribution amplitude

$$\phi_{\rm B}(x,b) = N_{\rm B}x^2(1-x)^2\exp\left[-\frac{M_{\rm B}^2\ x^2}{2\omega_{\rm b}^2}-\frac{1}{2}(\omega_{\rm b}b)^2\right], \qquad (6)$$

where the normalization factor $N_{\rm B}$ depends on the value of $\omega_{\rm b}$ and $f_{\rm B}$ and defined through the normalization relation $\int_0^1{\rm d}x\,\phi_{\rm B}(x,b=0)=f_{\rm B}/(2\sqrt{6})$. We also here take the shape parameter $\omega_{\rm b}=0.4\pm0.04$ GeV. For the final state kaon and $\eta^{(\prime)}$ mesons, we use the same wave functions and distribution functions as those used in Ref. [25].

In the SM4 model, the classic 3×3 Cabibbo-Kobayashi-Maskawa (CKM) matrix is extended into a 4×4 CKM-like mixing matrix [32]

$$U_{\rm SM4}=\begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} & V_{\rm ub'}\\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} & V_{\rm cb'}\\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} & V_{\rm tb'}\\ V_{\rm t'd} & V_{\rm t's} & V_{\rm t'b} & V_{\rm t'b'}\end{pmatrix}, \qquad (7)$$

where the t′ and b′ denote the fourth generation up- and down-type quark.

In the SM4, the t′ quark plays a similar role as the top quark in the loop diagrams and will provide NP terms, such as $B_0(x_{\rm t'})$, $C_0(x_{\rm t'})$, $D_0(x_{\rm t'})$ and $E_0(x_{\rm t'})$, to those relevant SM Inami-Lim functions $B_0(x_{\rm t})$, $C_0(x_{\rm t})$, $D_0(x_{\rm t})$ and $E_0(x_{\rm t})$ directly [33]. When the NP contributions are taken into account, the ordinary SM Wilson coefficients $C_i(M_{\rm W})$ will be changed accordingly. In the SM4, one can generally write the Wilson coefficients as the combination of the SM part and the additional fourth generation contribution [32]

$$C_i(m_{\rm W},m_{\rm t'})=C_i^{\rm SM}(m_{\rm W})+C_i^{4G}(m_{\rm W},m_{\rm t'}). \qquad (8)$$

As mentioned in previous sections, the three NP input parameters in the SM4 include $\lambda_{\rm t'}$, $\phi_{\rm t'}$ and $m_{\rm t'}$.

For the mixing scheme of η-η', we here use the conventional FKS scheme [28] in the quark-flavor basis: $\eta_{\rm q}=(u\bar{u}+d\bar{d})/\sqrt{2}$ and $\eta_{\rm s}=s\bar{s}$;

$$\begin{pmatrix}\eta\\ \eta'\end{pmatrix}=\begin{pmatrix}F_1(\phi)(u\bar{u}+d\bar{d})+F_2(\phi)s\bar{s}\\ F_1'(\phi)(u\bar{u}+d\bar{d})+F_2'(\phi)s\bar{s}\end{pmatrix}, \qquad (9)$$

where ϕ is the mixing angle and the mixing parameters are defined as

$$\sqrt{2}F_1(\phi)=F_2'(\phi)=\cos\phi,$$
$$F_2(\phi)=-\sqrt{2}F_1'(\phi)=-\sin\phi. \qquad (10)$$

The relation between the decay constants ($f^{\rm q}_{\eta}$, $f^{\rm s}_{\eta}$, $f^{\rm q}_{\eta'}$, $f^{\rm s}_{\eta'}$) and ($f_{\rm q}$, $f_{\rm s}$,) can be found in Ref. [24]. The chiral enhancement $m^{\rm q}_0$ and $m^{\rm s}_0$ have been defined in Ref. [34] by assuming the exact isospin symmetry $m_{\rm q}=m_{\rm u}=m_{\rm d}$. The three input parameters $f_{\rm q}$, $f_{\rm s}$ and ϕ in the FKS mixing scheme have been extracted from the data of the relevant exclusive processes [28]:

$$f_{\rm q}=(1.07\pm0.02)f_{\pi},\ f_{\rm s}=(1.34\pm0.06)f_{\pi},\ \phi=39.3^{\circ}\pm1.0^{\circ}, \tag{11}$$

with $f_{\pi}=0.13$ GeV.

3 B→Kη(′) decays, the numerical results

3.1 NLO contributions in the pQCD approach

In Ref. [25], the authors studied the four $\mathrm{B}\to\mathrm{K}\eta^{(\prime)}$ decays with the inclusion of all of the known NLO contributions by using the pQCD factorization approach. For the SM part of the relevant decay amplitudes, we use the formulas as presented in Ref. [25], where the authors confirmed numerically that the still unknown NLO contributions from the relevant spectator and annihilation diagrams are indeed small in size and can be safely neglected.

In this paper, we will take all known NLO contributions as considered in Ref. [25] into account. For the sake of the reader, we list these NLO contributions as follows:

(1) The NLO Wilson coefficients $C_i(m_{\rm W})$ and the NLO renormalization group evolution matrix $U(t,\,m,\,\alpha)$ as defined in Ref. [29], and the strong coupling constant $\alpha_{\rm s}(t)$ at two-loop level.

(2) The Feynman diagrams contributing to the hard kernel $H^{(1)}(\alpha_{\rm s}^2)$ at the NLO level in the pQCD approach include: (a) the Vertex Correction (VC) [34]; (b) the Quark-Loop (QL) contributions [34, 35]; (c) the magnetic penguins (MG) contributions [34, 36]; and, (d) the NLO part of the form factors (FF) as given in Ref. [37].

For the explicit expressions of the decay amplitudes for the four $\mathrm{B}\to\mathrm{K}\eta^{(\prime)}$ decays and the relevant functions, one can see Ref. [25]. We here focus on the NP contributions from the heavy t′ quark.

3.2 Br(B→Kη(′)) in SM4

We use the following input parameters [26, 27] in the numerical calculations (all of the masses and decay constants are in units of GeV)

$$\begin{aligned}&f_{\rm B}=0.21\pm0.02,\ \ f_{\rm K}=0.16,\ \ m_{\eta}=0.548,\ \ m_{\eta'}=0.958,\\&m_{\rm K^0}=0.498,\ \ m_{\rm K^+}=0.494,\ \ m_{\rm 0K}=1.7,\ \ M_{\rm B}=5.28,\\&m_{\rm b}=4.8,\ \ m_{\rm c}=1.5, M_{\rm W}=80.41,\ \ \tau_{\rm B^0}=1.53\ {\rm ps},\\&\tau_{\rm B^+}=1.638\ {\rm ps}.\end{aligned} \tag{12}$$

For the CKM quark-mixing matrix in the SM, we adopt the Wolfenstein parametrization, as given in Ref. [26, 27], and take $A=0.832$, $\lambda=0.2246$, $\bar\rho=0.130\pm0.018$, $\bar\eta=0.350\pm0.013$. For the three NP parameters, we have chosen similar values as those used in Ref. [13]:

$$\begin{aligned}&|\lambda_{\rm t'}|=0.015\pm0.010,\ \ \phi_{\rm t'}=0^{\circ}\pm45^{\circ},\\&m_{\rm t'}=(600\pm400)\ {\rm GeV}.\end{aligned} \tag{13}$$

We here firstly calculate the branching ratios of the considered decay modes in both the SM and SM4 by employing the pQCD factorization approach. In the B-rest frame, the branching ratio of a general $\mathrm{B}\to\mathrm{M_2M_3}$ decay can be written as

$$Br(\mathrm{B}\to\mathrm{M_2M_3})=\tau_{\rm B}\frac{1}{16\pi m_{\rm B}}\chi\left|\mathcal{M}(\mathrm{B}\to\mathrm{M_2M_3})\right|^2, \tag{14}$$

where $\tau_{\rm B}$ is the lifetime of the B meson, $\chi\approx1$ is the phase space factor and equals to unit when the masses of final state light mesons are neglected.

When all currently known NLO contributions are included, we find the pQCD predictions for $Br(\mathrm{B}\to\mathrm{K}\eta^{(\prime)})$ in the SM4 (in unit of 10^{-6}):

$$\begin{aligned}Br(\mathrm{B^0}\to\mathrm{K^0}\eta)&=1.46^{+0.30}_{-0.17}(\omega_{\rm b})^{+1.33}_{-0.57}(m_{\rm s})^{+0.28}_{-0.22}(f_{\rm B})^{+0.53}_{-0.45}(a_2^{\eta})^{+0.03}_{-0.09}(|\lambda_{\rm t'}|)^{+0.14}_{-0.14}(\phi_{\rm t'})^{+0.04}_{-0.11}(m_{\rm t'}),\\Br(\mathrm{B^0}\to\mathrm{K^0}\eta')&=44.1^{+15.8}_{-10.3}(\omega_{\rm b})^{+11.6}_{-9.7}(m_{\rm s})^{+8.3}_{-8.3}(f_{\rm B})^{+1.2}_{-0.6}(a_2^{\eta})^{+3.1}_{-1.1}(|\lambda_{\rm t'}|)^{+3.5}_{-3.5}(\phi_{\rm t'})^{+4.0}_{-2.1}(m_{\rm t'}),\\Br(\mathrm{B^+}\to\mathrm{K^+}\eta)&=3.59^{+1.32}_{-1.02}(\omega_{\rm b})^{+2.37}_{-1.57}(m_{\rm s})^{+0.67}_{-0.68}(f_{\rm B})^{+0.88}_{-0.77}(a_2^{\eta})^{+0.23}_{-0.08}(|\lambda_{\rm t'}|)^{+0.34}_{-0.33}(\phi_{\rm t'})^{+0.38}_{-0.10}(m_{\rm t'}),\\Br(\mathrm{B^+}\to\mathrm{K^+}\eta')&=51.7^{+13.0}_{-9.8}(\omega_{\rm b})^{+12.6}_{-6.8}(m_{\rm s})^{+9.9}_{-9.7}(f_{\rm B})^{+2.2}_{-1.3}(a_2^{\eta})^{+1.5}_{-4.1}(|\lambda_{\rm t'}|)^{+4.3}_{-4.7}(\phi_{\rm t'})^{+1.9}_{-5.1}(m_{\rm t'}),\end{aligned} \tag{15}$$

where the major theoretical errors are induced by the uncertainties of two sets of input parameters:

1) The ordinary "SM" input parameters: $\omega_{\rm b}=0.4\pm0.04$ GeV, $m_{\rm s}=0.13\pm0.03$ GeV, $f_{\rm B}=0.21\pm0.02$ GeV and Gegenbauer moment $a_2^{\eta}=0.44\pm0.22$ (here a_2^{η} denotes $a_2^{\eta_{\rm q}}$ or $a_2^{\eta_{\rm s}}$), respectively;

2) The NP input parameters with the uncertainties as defined in Eq. (13).

In Table 1, we list the NLO pQCD predictions in the framework of the SM (column two) or the SM4 (column three). In column four we show the NLO SM predictions based on the QCD factorization (QCDF) approach, as given in Ref. [35]. And finally, the world averaged values of experimental measurements [26] are given in the last column. The SM predictions in the column two of Table 1 agree perfectly with those as given in Ref. [25], where the ordinary FKS η-η′ mixing scheme was employed. The theoretical errors labeled with "SM" or

"NP" denote the quadrature combination of the theoretical errors from the uncertainties of two sets of input parameters (ω_b, m_s, f_B, a_2^η) and ($|\lambda_{t'}|$, $\phi_{t'}$, $m_{t'}$), respectively. From the numerical results as shown in Eq. (15) and Table 1, we find the following points:

1) The pQCD predictions for $Br(B\to K\eta^{(\prime)})$ become smaller than the SM ones after the inclusion of the NP contributions due to the destructive interference between the SM and NP contributions, but they still agree with the measure values within one standard deviation since the theoretical errors are still large.

2) For $Br(B^0\to K^0\eta)$ ($Br(B^+\to K^+\eta)$), the NP decrease of the central value of the pQCD prediction is about 40% (10%). The agreement between the theoretical predictions for $Br(B\to K\eta)$ is improved effectively after the inclusion of NP contributions.

3) However, for $Br(B^0\to K^0\eta')$ ($Br(B^+\to K^+\eta')$) the NP decrease is about 23% (12%), but such changes are disfavored by the data.

Although the four $B\to K\eta^{(\prime)}$ decays are generally penguin-dominated decays, the relative strength of the penguin part against the tree and/or other parts can be rather different for different decay modes. The explicit numerical calculations tell us that the penguin contribution plays a more important rule in $B^0\to K^0\eta$ decay than in other three decay modes in consideration, the t'-penguins consequently provide a much larger modification to $Br(B^0\to K^0\eta)$ (a decrease about 40%) than to other decays (a decrease from 10% to 23% in magnitude).

3.3 *CP*-violating asymmetries in SM4

Now we turn to the CP-violating asymmetries of $B\to K\eta^{(\prime)}$ decays in the pQCD approach. For $B^\pm\to K^\pm\eta$ decays, there is a large direct CP asymmetry ($\mathcal{A}_{CP}^{\rm dir}$) due to the destructive interference between the penguin amplitude and the tree amplitude. The NLO pQCD predictions for the direct CP asymmetries (in units of 10^{-2}) $\mathcal{A}_{CP}^{\rm dir}(B^\pm\to K^\pm\eta)$ and $\mathcal{A}_{CP}^{\rm dir}(B^\pm\to K^\pm\eta')$ in the SM (column two) and the SM4 (column three) are listed in Table 2. As a comparison, the QCDF predictions and the data as given in Refs. [26, 35] are also given in the last two columns.

As to the CP-violating asymmetries for the neutral decays $B^0\to K^0\eta^{(\prime)}$, the effects of B^0–$\bar{B}^0$ mixing should be considered. The explicit formulae for the CP-violating asymmetries of $B^0(\bar{B}^0)\to K^0\eta^{(\prime)}$ decays can be easily found (for example, in Ref. [25]), we here make the numerical calculations and then show the NLO pQCD predictions for the direct and mixing-induced CP asymmetries in Table 3. The theoretical errors labeled with "SM" or "NP" have been specified previously.

Table 1. The NLO pQCD predictions for the branching ratios (in unit of 10^{-6}) in the framework of the SM (column two) and SM4 (column three). As a comparison, the QCDF predictions [35] and the measured values [26] are also listed in the last two columns.

channel	NLO$^{\rm SM}$	NLO$^{\rm SM4}$	QCDF [35]	data [26]
$Br(B^0\to K^0\eta)$	$2.53^{+3.6}_{-1.7}$	$1.46^{+1.49}_{-0.78}({\rm SM})^{+0.15}_{-0.20}({\rm NP})$	$1.1^{+2.4}_{-1.5}$	$1.23^{+0.27}_{-0.24}$
$Br(B^0\to K^0\eta')$	$57.1^{+23.7}_{-17.0}$	$44.1^{+21.3}_{-16.4}({\rm SM})^{+6.2}_{-4.2}({\rm NP})$	$46.5^{+41.9}_{-22.0}$	66.1 ± 3.1
$Br(B^+\to K^+\eta)$	$3.94^{+3.8}_{-2.2}$	$3.59^{+2.93}_{-2.14}({\rm SM})^{+0.56}_{-0.36}({\rm NP})$	$1.9^{+3.0}_{-1.9}$	$2.4^{+0.22}_{-0.21}$
$Br(B^+\to K^+\eta')$	$58.6^{+24.0}_{-17.2}$	$51.7^{+20.8}_{-15.4}({\rm SM})^{+4.9}_{-8.1}({\rm NP})$	$49.1^{+45.2}_{-23.6}$	71.1 ± 2.6

Table 2. The pQCD predictions for the direct CP asymmetries (in units of 10^{-2}) of charged $B^\pm\to K^\pm\eta^{(\prime)}$ decays in the SM and SM4.

mode	NLO$^{\rm SM}$	NLO$^{\rm SM4}$	QCDF [35]	data [26]
$\mathcal{A}_{CP}^{\rm dir}(K^\pm\eta)$	$-25.9^{+13.8}_{-17.4}$	$-27.9^{+12.4}_{-10.5}({\rm SM})^{+8.6}_{-6.7}({\rm NP})$	-19^{+29}_{-30}	-37 ± 8
$\mathcal{A}_{CP}^{\rm dir}(K^\pm\eta')$	$-4.3^{+2.0}_{-1.6}$	$-4.6^{+2.0}_{-2.0}({\rm SM})^{+1.3}_{-0.4}({\rm NP})$	$-9.0^{+10.6}_{-16.2}$	$1.3^{+1.6}_{-1.7}$

Table 3. The pQCD predictions for the CP asymmetries (in units of 10^{-2}) for neutral $B^0\to K^0\eta^{(\prime)}$ decays in the SM and SM4, and the measured values as given by HFAG [26].

mode	NLO$^{\rm SM}$	NLO$^{\rm SM4}$	data [26]
$\mathcal{A}_{CP}^{\rm dir}(B^0\to K_S^0\eta)$	$-11.0^{+4.0}_{-3.9}$	$-14.8^{+5.0}_{-5.1}({\rm SM})^{+1.3}_{-0.6}({\rm NP})$	—
$\mathcal{A}_{CP}^{\rm mix}(B^0\to K_S^0\eta)$	$65.9^{+3.3}_{-5.1}$	$71.4^{+3.2}_{-1.6}({\rm SM})\pm0.03({\rm NP})$	—
$\mathcal{A}_{CP}^{\rm dir}(B^0\to K_S^0\eta')$	3.5 ± 0.3	$4.1^{+0.2}_{-0.3}({\rm SM})^{+0.6}_{-0.3}({\rm NP})$	1 ± 9
$\mathcal{A}_{CP}^{\rm mix}(B^0\to K_S^0\eta')$	69.8 ± 0.3	$70.5^{+0.1}_{-0.2}({\rm SM})\pm0.2({\rm NP})$	64 ± 11

From the numerical results, as listed in Tables 2 and 3, one can see that the NP effects on the pQCD predictions for the CP-violating asymmetries of the considered four decays are generally much smaller than the theoretical errors.

4 Summary

In this paper, we calculated the NP contributions to the four $\mathrm{B}\to\mathrm{K}\eta^{(\prime)}$ decays in the SM4. From our numerical calculations and phenomenological analysis, we find the following points:

1) In both the SM and SM4, the pQCD predictions for the branching ratios and CP-violating asymmetries agree with the data within one standard deviation, which, of course, is partially due to the still large theoretical errors.

2) For $Br(\mathrm{B}^0\to\mathrm{K}^0\eta)$ and $Br(\mathrm{B}^+\to\mathrm{K}^+\eta)$, the NP decrease is about 40% and 10%, respectively. The agreement between the theoretical predictions and the data is improved effectively after the inclusion of NP contributions.

3) However, for $Br(\mathrm{B}^0\to\mathrm{K}^0\eta')$ and $Br(\mathrm{B}^+\to\mathrm{K}^+\eta')$ the NP decrease is about 23% and 12%, respectively, but such changes are disfavored by the data.

4) The NP corrections on the CP-violating asymmetries of the considered decays are only about 10%.

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