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Direct CP violation in $K \to 3\pi$ decay: Addendum on CP-violating effects in charged-K decay

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Contrary to a recent claim that CP asymmetry in the slope parameter of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ is as large as of order 10^{-3}, our calculation shows that, within the framework of the $1/N_c$ approach, its magnitude is not likely to exceed the level of 10^{-5} even after including the effects of Z^0 penguin diagrams, isospin breaking, and higher-order weak chiral Lagrangians. Our result suggests that it is a formidable task to observe direct CP violation in charged $K \to 3\pi$ decay.

Aside from the CP-odd effects characterized by the parameters η_{+-0} and η_{000}, CP violation in $K \to 3\pi$ decay can also manifest itself in the following places: (1) charge asymmetry measured by the slope parameter j in the Dalitz plot distribution of $K_L \to \pi^+\pi^-\pi^0$,

$$|M|^2 \propto 1 + g(s_3 - s_0)/m_\pi^2 + j(s_2 - s_1)/m_\pi^2 + \cdots , \tag{1}$$

where $s_i = (k - p_i)^2$ with k and p_i being the four-momenta of the kaon and pion i (the subscript 3 is assigned to the "odd" pion), and $s_0 = (s_1 + s_2 + s_3)/3$; (2) partial-rate asymmetry in charged $K \to 3\pi$ decay,

$$\Delta\Gamma = \frac{\Gamma(K^+ \to 3\pi) - \Gamma(K^- \to 3\pi)}{\Gamma(K^+ \to 3\pi) + \Gamma(K^- \to 3\pi)} , \tag{2}$$

and (3) slope asymmetry of charged K's,

$$\Delta g = \frac{g(K^+ \to 3\pi) - g(K^- \to 3\pi)}{g(K^+ \to 3\pi) + g(K^- \to 3\pi)} . \tag{3}$$

Recently, CP asymmetries in $\tau^{\pm}(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})$ and $\tau'^{\pm}(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0})$ decays have been calculated in Ref. [1] to be

$$\begin{aligned} &\Delta\Gamma(\tau^{\pm}) \approx 3.8\times 10^{-5}, \quad \Delta g(\tau^{\pm}) \approx 1.4\times 10^{-3} , \\ &\Delta\Gamma(\tau'^{\pm}) \approx 1.2\times 10^{-4}, \quad \Delta g(\tau'^{\pm}) \approx 1.4\times 10^{-3} . \end{aligned} \tag{4}$$

This leads the authors of Ref. [1] to suggest that it is pertinent to search for CP asymmetry in the slope parameter g by modern high-statistics experiments (for example, ϕ-factory experiment). In Ref. [2] we have studied direct CP violation in neutral $K \to 3\pi$ decay. We wish to point out in this addendum that, within the framework of current algebra or chiral perturbation theory, the slope asymmetry is estimated to be at most of order 10^{-6}. Moreover, we present a calculation in the $1/N_c$ approach and find that its magnitude is not substantially enhanced by the effects of Z^0 penguins, isospin breaking, and higher-order weak chiral-Lagrangian terms. Our result suggests that CP asymmetry in the linear slope g is at least two orders of magnitude smaller than previously anticipated.

Since it is necessary to include final-state interactions in order to induce CP-violating asymmetry in the charged $K \to 3\pi$ decay, we write the τ and τ' amplitudes in terms of their isospin decomposition:

$$\begin{aligned} A(\tau^+) &= 2(a_1 + a_3)e^{i\delta_1} - (b_1 + b_3)Ye^{i\delta_2} + b_3' Ye^{i\delta_3} , \\ A(\tau^-) &= 2(a_1^* + a_3^*)e^{i\delta_1} - (b_1^* + b_3^*)Ye^{i\delta_2} + b_3'^* Ye^{i\delta_3} , \\ A(\tau'^+) &= (a_1 + a_3)e^{i\delta_1} + (b_1 + b_3)Ye^{i\delta_2} + b_3' Ye^{i\delta_3} , \\ A(\tau'^-) &= (a_1^* + a_3^*)e^{i\delta_1} + (b_1^* + b_3^*)Ye^{i\delta_2} + b_3'^* Ye^{i\delta_3} , \end{aligned} \tag{5}$$

where $Y = (s_3 - s_0)/m_\pi^2$, a_1, b_1 (a_3, b_3) arise from the transition into the $I=1$ state of three pions caused by the $\Delta I = \frac{1}{2}$ $(\frac{3}{2})$ weak interactions, and b_3' comes from the $I=2$ state of three pions. The phase is approximately determined by the isospin and the permutation symmetry of the 3π states [3]. In Eq. (5), the isospin phase δ_1 is for the amplitudes of the completely symmetric $I=1$ 3π state, δ_2 for $I=1$ 3π state with mixed symmetry, and δ_3 for the amplitudes of the $I=2$ state. For the purpose of the present paper, it suffices to neglect the quadratic terms in the Dalitz amplitude. It is then straightforward to obtain CP asymmetries

$$\Delta\Gamma(\tau) \cong N/\{4|a_1 + a_3|^2 + (|b_1 + b_3|^2 + |b_3'|^2 Y^2) - 4\,\mathrm{Re}[(a_1^* + a_3^*)(b_1 + b_3)]\cos(\delta_1 - \delta_2)Y\} \tag{6}$$

with

$$N = -4Y\{\mathrm{Im}[(a_1^* + a_3^*)(b_1 + b_3)]\sin(\delta_1 - \delta_2) - \mathrm{Im}[(a_1^* + a_3^*)b_3']\sin(\delta_1 - \delta_3) + \tfrac{1}{2}Y\,\mathrm{Im}[(b_1^* + b_3^*)b_3']\sin(\delta_2 - \delta_3)\} ,$$

and

$$\Delta g(\tau) \cong \frac{\mathrm{Im}[(a_1^* + a_3^*)(b_1 + b_3)]\sin(\delta_1 - \delta_2) - \mathrm{Im}[(a_1^* + a_3^*)b_3']\sin(\delta_1 - \delta_3)}{\mathrm{Re}[(a_1^* + a_3^*)(b_1 + b_3)]\cos(\delta_1 - \delta_2)} . \tag{7}$$

The isospin amplitudes a_i, b_i, and b'_3 can be calculated in chiral perturbation theory with the results [4]

$$a_1=A_0h,\quad a_3=\frac{1}{\sqrt{2}}A_2h,\quad b_1=3A_0hx\ ,$$
$$b_3=\frac{3}{4\sqrt{2}}(-5+9z)A_2hx,\quad b'_3=\frac{27}{4\sqrt{2}}(3+z)A_2hx\ , \tag{8}$$

where

$$x=\frac{m_\pi^2}{m_K^2},\quad z=\frac{m_\pi^2}{m_K^2-m_\pi^2},\quad h=\frac{1}{3\sqrt{3}}\frac{1}{f_\pi}\frac{m_K^2}{m_K^2-m_\pi^2}\ , \tag{9a}$$

and A_0 and A_2 are the $\Delta I=\frac{1}{2}$ and $\Delta I=\frac{3}{2}$ $K\to\pi\pi$ amplitudes, respectively:

$$A_0=-g_8 4\sqrt{3}\frac{m_K^2-m_\pi^2}{f_\pi^3},\quad A_2=-g_{27}4\sqrt{6}\frac{m_K^2-m_\pi^2}{f_\pi^3}\ , \tag{9b}$$

where g_8 and g_{27} are octet and 27-plet coupling constants, respectively, in the effective chiral Lagrangian for weak interactions. It should be stressed at this point that using current algebra one also obtains the same result of Eq. (8) except that h is replaced by $(1/3\sqrt{3}f_\pi)$ and $z=0$ [5]. Therefore, there is a small discrepancy between the effective-Lagrangian and current-algebra approaches for the isospin amplitudes a_i, b_i, and b'_i. This is ascribed to the fact that the Dalitz-amplitude parametrization given by Eq. (5) may contain a contribution p_π^2 which vanishes in the soft-pion limit but becomes m_π^2 when pions are on their mass shells [4].

Substituting Eq. (8) into Eq. (6) gives

$$\begin{aligned}\Delta\Gamma(\tau)=&\ 27xY(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}})[4+9x^2Y^2-12xY\cos(\delta_1-\delta_2)]^{-1}\\&\times[(1-z)\sin(\delta_1-\delta_2)+(3+z)\sin(\delta_1-\delta_3)-\tfrac{3}{2}(3+z)xY\sin(\delta_2-\delta_3)]\end{aligned} \tag{10}$$

where ϵ'_{NL} is the CP-violating parameter given by (ϕ_i being the isospin phase of A_i)

$$\epsilon'_{\mathrm{NL}}=-\frac{1}{\sqrt{2}}\left[\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}e^{i(\pi/2+\phi_2-\phi_0)} \tag{11}$$

and use of the experimental fact of $\phi_2-\phi_0\approx-\pi/4$ has been made. The subscript "NL" is utilized to emphasize that the effect of direct CP violation in $\mathrm{Im}A_2$ has not been included. When $z\to0$ and $x\to m_\pi^2/(m_K^2-m_\pi^2)$ are taken, the expression of the CP asymmetry in partial-rate differences given by Eq. (10) is in agreement with Ref. [6] except for the sign of the last term in the numerator (see also Ref. [7]). Likewise, we find, for τ' decay,

$$\begin{aligned}\Delta\Gamma(\tau')=&\ \tfrac{27}{2}xY(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}})[1+9x^2Y^2+6xY\cos(\delta_1-\delta_2)]^{-1}\\&\times[-(1-z)\sin(\delta_1-\delta_2)+(3+z)\sin(\delta_1-\delta_3)+3(3+z)xY\sin(\delta_2-\delta_3)]\ ,\end{aligned} \tag{12}$$

and slope asymmetries to be

$$\begin{aligned}\Delta g(\tau)&=-\frac{9}{4}\frac{(1-z)\sin(\delta_1-\delta_2)+(3+z)\sin(\delta_1-\delta_3)}{\cos(\delta_1-\delta_2)}(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}})\ ,\\ \Delta g(\tau')&=-\frac{9}{4}\frac{(1-z)\sin(\delta_1-\delta_2)-(3+z)\sin(\delta_1-\delta_3)}{\cos(\delta_1-\delta_2)}(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}})\ ,\end{aligned} \tag{13}$$

in agreement with the current-algebra predictions [8] in the limit of $z=0$.

Equations (10), (12), and (13) are obtained within the framework of lowest-order chiral perturbation theory and hence are model-independent predictions for direct CP-violating effects in charged $K\to3\pi$ decay. The numerical results of CP asymmetry in partial-rate differences depend on the details of energy dependence of phase shifts. Using the isospin phases derived by Zeldovich [3], Avilez [6] obtained $\Delta\Gamma(\tau)=0.094|\epsilon'|$ after integrating over the whole Dalitz plot, while Grinstein, Rey and Wise [7] found the partial-rate asymmetry to be $-0.04(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}})$ by applying the phase shifts calculated from the absorptive part of chiral loops. As to the slope asymmetry, we see that, aside from the phase-shift terms, it is of order ϵ'_{NL} (which may be viewed as the upper bound of Δg). From Eq. (2.24) of Ref. [2], we get $|\epsilon'_{\mathrm{NL}}|\approx1.6\times10^{-2}\times0.057|\epsilon|\approx2\times10^{-6}$ in the Kobayashi-Maskawa model. (Note that ϵ'_{NL} is rather insensitive to the variation of the top-quark mass.) Therefore, Δg and $\Delta\Gamma$ are naively expected to be of order 10^{-6} and 10^{-7}, respectively.

Before proceeding, we notice that the term $\mathrm{Im}(a_1^*b_1)$ is naively expected to be the dominant contribution to CP asymmetries $\Delta\Gamma$ and Δg since it is not subject to the $\Delta I=\frac{3}{2}$ suppression. However, to the lowest order in chiral expansion,

$$\frac{\mathrm{Im}a_1}{\mathrm{Re}a_1}=\frac{\mathrm{Im}b_1}{\mathrm{Re}b_1}=\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} \tag{14}$$

and hence $\mathrm{Im}(a_1^*b_1)=0$. As we shall see, the presence of Z^0 penguins and higher-order chiral corrections will contribute to $\mathrm{Im}(a_1^* b_1)$. However, it is very difficult to imagine at this stage that the aforementioned corrections will be able to enhance the slope asymmetry by three orders of magnitude to the level of 10^{-3}. Nevertheless, in the following we will study the effect of the electroweak penguins and higher-derivative weak chiral Lagrangians in some detail. For simplicity, we will limit ourselves to the decay $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ since it does not receive isospin-breaking corrections.

We first compute the weak transitions $K^{+}\to\pi^{+}\pi^{+}\pi^{-}$ and $\pi^{+}\pi^{0}\pi^{0}$ induced by the electroweak-penguin operator Q_8 (see Fig. 1)

$$Q_8=-12\sum_q e_q(\bar{s}_L q_R)(\bar{q}_R d_L)\ . \tag{15}$$

Following Ref. [2] we find after some manipulation that

$$\begin{aligned}&\langle\pi^{+}\pi^{+}\pi^{-}|Q_8|K^{+}\rangle=6v^2\ ,\\&\langle\pi^{+}\pi^{0}\pi^{0}|Q_8|K^{+}\rangle=3v^2+\tfrac{9}{2}v^2 zY\ ,\end{aligned}\tag{16}$$

where

$$\begin{aligned}v(\mu)&=\frac{m_\pi^2}{m_u(\mu)+m_d(\mu)}=\frac{m_{K^+}^2}{m_u(\mu)+m_s(\mu)}\\&=\frac{m_{K^0}^2}{m_d(\mu)+m_s(\mu)}\end{aligned}\tag{17}$$

characterizes the quark order parameter $\langle\bar{q}q\rangle$. Combining Eq. (16) with the Q_8-induced $K^0\to 3\pi$ transitions [2],

$$\begin{aligned}&\langle\pi^{+}\pi^{-}\pi^{0}|Q_8|K^{0}\rangle=\frac{9}{2\sqrt{2}}v^2 z\left[Y-\tfrac{1}{3}X\right]\ ,\\&\langle\pi^{0}\pi^{0}\pi^{0}|Q_8|K^{0}\rangle=0\ ,\end{aligned}\tag{18}$$

and noting that the $K^0\to 3\pi$ decay amplitudes are parametrized as [4]

$$\begin{aligned}A(K^0\to\pi^+\pi^-\pi^0)=&-\frac{1}{\sqrt{2}}(a_1-2a_3)e^{i\delta_1}\\&-\frac{1}{\sqrt{2}}(b_1-2b_3)Ye^{i\delta_2}-\frac{\sqrt{2}}{3}b_3' Xe^{i\delta_3},\\A(K^0\to\pi^0\pi^0\pi^0)=&-\frac{3}{\sqrt{2}}(a_1-2a_3)e^{i\delta_1}\ ,\end{aligned}\tag{19}$$

we obtain [9]

$$\begin{aligned}&\mathrm{Im}a_1^{\mathrm{EWP}}=2v^2\lambda,\quad \mathrm{Im}a_3^{\mathrm{EWP}}=v^2\lambda\ ,\\&\mathrm{Im}b_1^{\mathrm{EWP}}=0,\quad \mathrm{Im}b_3^{\mathrm{EWP}}=\mathrm{Im}b_3'^{\mathrm{EWP}}=\tfrac{9}{4}v^2 z\lambda\ ,\end{aligned}\tag{20}$$

where $\lambda=(G_F/\sqrt{2})V_{ud}V_{us}^*(\frac{1}{3}y_7+y_8)$ (see Ref. [2] for notation), and the contribution due to the penguin operator Q_7 has also been included.

We next turn to the consideration of higher-order chiral effects. Following Sec. III D of Ref. [2], we get

$$\frac{\mathrm{Im}a_1}{\mathrm{Re}a_1}=\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\left[1-\frac{(4/\beta-1)\langle Q_6\rangle^{\mathrm{HO}}}{\langle Q_6\rangle^{\mathrm{LO}}+(4/\beta)\langle Q_6\rangle^{\mathrm{HO}}}\right]_{X=Y=0}\tag{21}$$

and a similar expression for $\mathrm{Im}b_1/\mathrm{Re}b_1$, where $\langle Q_6\rangle\equiv\langle\pi^+\pi^+\pi^-|Q_6|K^+\rangle$, β is a parameter defined in Ref. [2] as the ratio of $\langle Q_6\rangle^{\mathrm{HO}}$ to $\langle Q_2-Q_1\rangle^{\mathrm{HO}}$, and Q_6 is the usual QCD penguin operator given by $-8\sum_q(\bar{s}_L q_R)(\bar{q}_R d_L)$. Applying the results of Ref. [2] we find

$$\frac{\mathrm{Im}(a_1^* b_1)^{\mathrm{HO}}}{\mathrm{Re}a_1\mathrm{Re}b_1}=\frac{1}{2}\frac{m_K^2}{\Lambda_\chi^2}(1-9x)\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\ ,\tag{22}$$

and

$$\begin{aligned}\mathrm{Re}a_1^{\mathrm{HO}}&=\frac{2}{3}\frac{m_K^2}{\Lambda_\chi^2}(1-3x)a_1\ ,\\\mathrm{Re}a_3^{\mathrm{HO}}&=\frac{2}{3}\frac{m_K^2}{\Lambda_\chi^2}(1-3x)a_3\ ,\\\mathrm{Re}b_1^{\mathrm{HO}}&=\frac{4}{3}\frac{m_K^2}{\Lambda_\chi^2}(1+3x)b_1\ ,\\\mathrm{Re}b_3^{\mathrm{HO}}&=\frac{11-9z}{15-27z}\frac{m_K^2}{\Lambda_\chi^2}(1+3x)b_3\ ,\\\mathrm{Re}b_3'^{\mathrm{HO}}&=\frac{5+z}{9+3z}\frac{m_K^2}{\Lambda_\chi^2}(1+3x)b_3'\ ,\end{aligned}\tag{23}$$

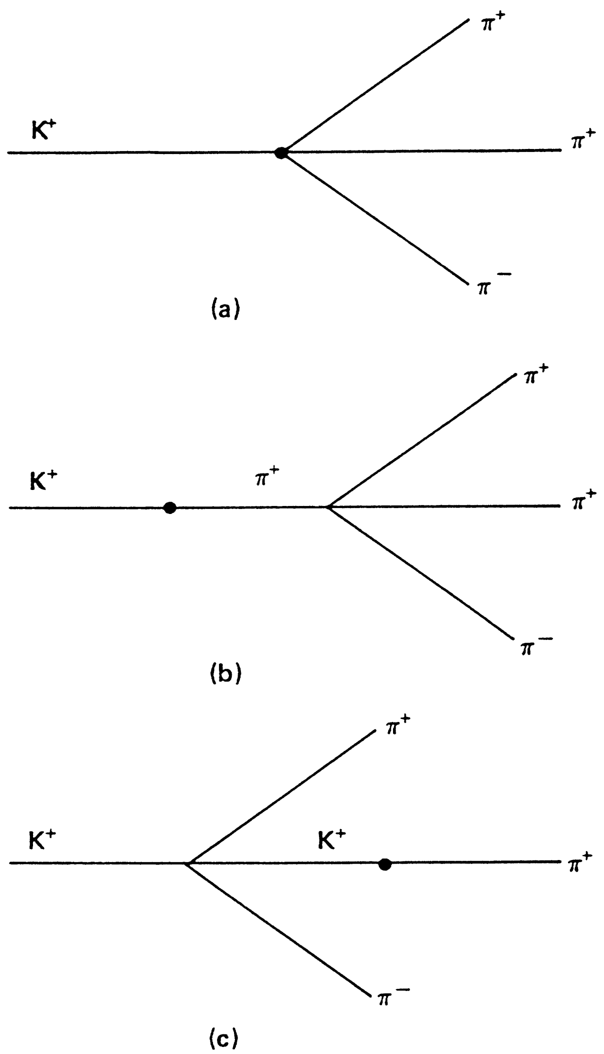

FIG. 1. Diagrams contributing to $K^{+}\to\pi^{+}\pi^{+}\pi^{-}$ via the electroweak penguin interactions Q_7 and Q_8 denoted by a black dot.

with $\Lambda_\chi \sim 1$ GeV being the chiral-symmetry-breaking scale.

It is instructive at this point to compare the relative magnitude of $\mathrm{Im}(a_1^* b_1)^{\mathrm{EWP}}$ and $\mathrm{Im}(a_1^* b_1)^{\mathrm{HO}}$. It follows from Eq. (20) that

$$\frac{\mathrm{Im}(a_1^* b_1)^{\mathrm{EWP}}}{\mathrm{Re}a_1 \mathrm{Re}b_1} = -\frac{\mathrm{Im}a_1^{\mathrm{EWP}}}{\mathrm{Im}A_0}\frac{\mathrm{Re}A_0}{\mathrm{Re}a_1}\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} ,$$
$$= -\frac{3}{2}\left[\frac{y_7+3y_8}{3y_6}\right]\frac{\Lambda_\chi^2}{m_K^2}\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} , \quad (24)$$

where use has been made of Eq. (8) and $\mathrm{Im}A_0$ has been approximated by the penguin operator Q_6:

$$\mathrm{Im}A_0 \approx 4\left[\frac{3}{2}\right]^{1/2} G_F V_{ud} V_{us}^* y_6 f_\pi v^2 \frac{m_K^2 - m_\pi^2}{\Lambda_\chi^2} . \quad (25)$$

The imaginary Wilson coefficients y_i, which depend on the top quark mass, have been evaluated in Ref. [10] with the values (at $\mu = 1$ GeV and $\Lambda_{\mathrm{QCD}} = 100$ MeV)

$$\eta = 0.49, \; 0.16, \; -0.30, \; -0.88, \; -2.26, \; -3.97$$

for (26)

$$m_t = 75, \; 100, \; 125, \; 150, \; 200, \; 250 \text{ GeV} ,$$

where $\eta \equiv (y_7 + 3y_8)/(3y_6\alpha)$, and α is the fine-structure constant. From Eqs. (22), (24), and (26) it is clear that the higher-order chiral effect dominates when $m_t < 150$ GeV, but it is then overcome by the electroweak-penguin contribution for $m_t > 150$ GeV. Therefore, the effect of higher-order weak chiral Lagrangians in the 3π decay of the charged K is not as dramatic as in the case of $K^0 \to 3\pi$ (see Ref. [2]). This is attributed to the fact that contributions due to higher chiral terms are not only subject to the chiral suppression of order m_K^2/Λ_χ^2, but also suppressed by the small phase difference of a_1 and b_1 characterized by the factor of $(1-9x)$ in Eq. (22).

We are ready to consider the Z^0-penguin and higher chiral effects on the CP asymmetries $\Delta\Gamma$ and Δg. Substituting (20), (22), and (23) into (6) and (7) yields

$$\Delta\Gamma(\tau) = xY(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}})[4 + 9x^2Y^2 - 12xY\cos(\delta_1-\delta_2)]^{-1}$$
$$\times[(47-24\eta)(1+z)\sin(\delta_1-\delta_2) + (25-0.2\eta)(3+z)\sin(\delta_1-\delta_3) - (52-3.1\eta)(3+z)xY\sin(\delta_2-\delta_3)] \quad (27)$$

and

$$\Delta g(\tau) = -\frac{(3.2-1.6\eta)(1+z)\sin(\delta_1-\delta_2) + (1.7-0.02\eta)(3+z)\sin(\delta_1-\delta_3)}{\cos(\delta_1-\delta_2)}(\sqrt{2}\mathrm{Re}\epsilon'_{\mathrm{NL}}) . \quad (28)$$

Comparing (28) and (27) with the previous uncorrected results (13) and (10), we see that the enhancement due to the higher-derivative weak chiral Lagrangian and electroweak penguins is most significant for the coefficient of the $\sin(\delta_1-\delta_2)$ term, but it is at most of order 5 even when the top-quark mass is as large as 250 GeV. We thus conclude that the CP-violating asymmetry in the slope parameter of $K^\pm \to \pi^\pm\pi^+\pi^-$ does not likely exceed the level of 10^{-5}. This makes the experimental observation of direct CP violation in charged $K \to 3\pi$ decay practically impossible.

Since our result for the slope asymmetry Δg is about 2 orders of magnitude smaller than that given by Ref. [1], it is of great importance to pin down the sources of discrepancy between our calculation and Ref. [1]. However, because isospin breaking and higher derivative chiral corrections to current-algebra predictions are not explicitly displayed by authors of Ref. [1] (effects of the Z^0-penguin diagram on the imaginary Wilson coefficients were also not taken into account by them), it is very difficult to identify the underlying reasons for disagreement. At any rate, given the fact that the current-algebra expectation of the slope asymmetry is of order 10^{-6}, it seems to us that an enhancement of Δg from 10^{-6} to the level of 10^{-3} by aforementioned corrections is very unlikely.

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