CP-odd WWZ couplings induced by vector-like quarks

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Abstract. A minimal extension of the standard model includes extra quarks with charges 2/3 and/or $-1/3$, whose left-handed and right-handed components are both SU(2) singlets. This model predicts new interactions of the flavor-changing neutral current at the tree level, which also violate CP invariance. We study CP-odd anomalous couplings for the W, W, and Z gauge bosons induced by the new interactions at the one-loop level. These couplings become non-negligible only if both up-type and down-type extra quarks are incorporated. Their form factors are estimated to be maximally of order 10^{-5}. Such magnitudes are larger than those predicted in the standard model, though smaller than those in certain other models.

1 Introduction

Experiments at LEP2 and planned e^+e^- linear colliders can directly probe gauge-boson self-interactions, an aspect of the standard model (SM) characteristic of its non-Abelian nature. Their precise measurements serve a detailed examination of the SM, whose predictions have been well studied including quantum corrections. If some deviations from the SM predictions are found, the SM will have to be extended. For this task, studying peculiar features of various models is indispensable. Theoretical analyses therefore have been made on the gauge-boson self-interactions in the extensions of the SM [1,2]. In particular, CP-even couplings for the W, W, and Z gauge bosons have been studied in the two-Higgs-doublet model [3], the model with Majorana neutrinos [4], the supersymmetric model [5], and so on. The CP-odd WWZ couplings have also recently been discussed in the supersymmetric model [6].

One of the minimal extensions of the SM is the vector-like quark model (VQM). This model includes extra quarks with charges 2/3 and/or $-1/3$, whose left-handed components, as well as right-handed ones, are singlets under SU(2). Although many features of the SM are not significantly modified, new sources of CP violation and flavor-changing neutral current (FCNC) are incorporated. Therefore, their effects on the K-meson and B-meson systems have been studied extensively [7]. It has been also argued [8] that baryon asymmetry of the universe could be attributed to these new sources of CP violation.

In this paper, we study the effects of the VQM on CP-odd couplings for the WWZ vertex. This model predicts

that the Z boson couples to quarks of different generations, causing interactions of FCNC at the tree level. For a pair of light ordinary quarks, these interactions should be suppressed in view of the experimental results. However, the t quark and the extra up-type quark U could have a sizable coupling with the Z boson. Since these interactions of FCNC also violate CP invariance, non-negligible CP-odd couplings for the WWZ vertex may be induced at the one-loop level. On the other hand, the SM does not contain the CP-odd WWZ couplings at the tree level nor at the one-loop level. The supersymmetric model predicts them at the one-loop level [6]. The CP-odd WWZ couplings at the one-loop level could become a window for physics beyond the SM. It will be shown that form factors for the couplings in the VQM can be evaluated without making many assumptions on mixings among the quarks. The form factors are non-negligible at the one-loop level, though the possible maximal magnitudes are smaller than those in the supersymmetric model.

This paper is organized as follows. In Sect. 2 we briefly summarize the model. In Sect. 3 the CP-odd form factors are obtained and numerical analyses are performed. Our summary is contained in Sect. 4.

2 Model

The quark sector is enlarged to have extra quarks whose transformation properties are given by $(3, 1, 2/3)$ or $(3, 1, -1/3)$ for the SU(3)×SU(2)×U(1) gauge symmetry. The left-handed and right-handed components have the same properties. For definiteness, we assume the particle contents to have one up-type and one down-type extra quarks. The quark masses are generated by Yukawa couplings and

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bare mass terms. The mass matrices are given by 4×4 matrices, which are denoted by M^u and M^d respectively for up-type and down-type quarks. The mass eigenstates are obtained by diagonalizing the mass matrices as follows:

$$A_L^{u\dagger} M^u A_R^u = \text{diag}(m_{u1}, m_{u2}, m_{u3}, m_{u4}), \qquad (1)$$

$$A_L^{d\dagger} M^d A_R^d = \text{diag}(m_{d1}, m_{d2}, m_{d3}, m_{d4}), \qquad (2)$$

where A_L^u, A_R^u, A_L^d, and A_R^d are unitary matrices. We express the mass eigenstates by u^a and d^a ($a = 1$–4), a being the generation index, which may be also called (u, c, t, U) and (d, s, b, D).

The interaction Lagrangian for the quarks with the W boson is given by

$$\mathcal{L} = \frac{g}{\sqrt{2}} \overline{u^a} V_{ab} \gamma^\mu \frac{1 - \gamma_5}{2} d^b W_\mu^\dagger + \text{h.c.} \quad . \qquad (3)$$

Here the 4×4 matrix V stands for an extended Cabibbo–Kobayashi–Maskawa matrix, which is defined by

$$V_{ab} = \sum_{i=1}^{3} (A_L^{u\dagger})_{ai} (A_L^d)_{ib}. \qquad (4)$$

Note that V is not unitary. The interaction Lagrangian for the quarks with the Z boson is given by
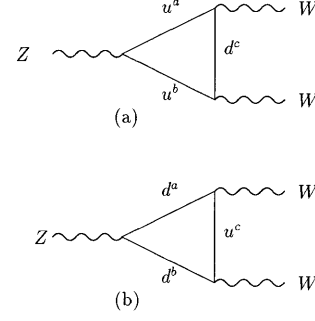
$$\mathcal{L} = -\frac{g}{\cos\theta_W} \overline{u^a} \gamma^\mu \left(F_{Lab}^u \frac{1 - \gamma_5}{2} + F_{Rab}^u \frac{1 + \gamma_5}{2} \right) u^b Z_\mu$$

$$-\frac{g}{\cos\theta_W} \overline{d^a} \gamma^\mu$$

$$\times \left(F_{Lab}^d \frac{1 - \gamma_5}{2} + F_{Rab}^d \frac{1 + \gamma_5}{2} \right) d^b Z_\mu, \qquad (5)$$

$$F_L^u = \frac{1}{2} V V^\dagger - \frac{2}{3} \sin^2\theta_W, \quad F_R^u = -\frac{2}{3} \sin^2\theta_W,$$

$$F_L^d = -\frac{1}{2} V^\dagger V + \frac{1}{3} \sin^2\theta_W, \quad F_R^d = \frac{1}{3} \sin^2\theta_W.$$

Since V is not a unitary matrix, off-diagonal elements of F_L^u and F_L^d become non-vanishing, leading to FCNC at the tree level. The Lagrangian in (5), as well as that in (3), can induce CP violation.

3 Form factors

For the pair production of W bosons in e^+e^- annihilation, the trilinear gauge-boson interaction for W^+, W^-, and Z is generally expressed as [1]

$$\mathcal{L}_{\text{eff}} = g \cos\theta_W \Gamma^{\mu\nu\lambda} W_\mu^\dagger W_\nu Z_\lambda, \qquad (6)$$

$$\Gamma^{\mu\nu\lambda} = f_1 (p - \bar{p})^\lambda g^{\mu\nu} + f_2 \frac{1}{M_W^2} (p - \bar{p})^\lambda q^\mu q^\nu$$

$$+ f_3 (q^\mu g^{\lambda\nu} - q^\nu g^{\lambda\mu}) + \mathrm{i} f_4 (q^\mu g^{\lambda\nu} + q^\nu g^{\lambda\mu})$$

$$+ \mathrm{i} f_5 \varepsilon^{\mu\nu\lambda\rho} (p - \bar{p})_\rho + f_6 \varepsilon^{\mu\nu\lambda\rho} q_\rho$$

$$+ f_7 \frac{1}{M_W^2} (p - \bar{p})^\lambda \varepsilon^{\mu\nu\rho\sigma} q_\rho (p - \bar{p})_\sigma,$$

Fig. 1a,b. Possible one-loop diagrams which induce CP-odd couplings for the WWZ vertex

where p and $\bar{p}$ denote the outward momenta of the gauge bosons W^- and W^+, respectively, and q the inward momentum of Z. The couplings with the form factors f_1, f_2, f_3, and f_5 are CP-even, while those with f_4, f_6, and f_7 are CP-odd. Both in the SM and in the VQM, only the form factors f_1 and f_3 have non-vanishing values at the tree level.

The CP-odd form factors receive contributions from the one-loop diagrams in which up-type quarks or down-type quarks couple to the Z boson as shown in Fig. 1. We obtain the form factors arising from the diagram in Fig. 1a as

$$f_4 = \frac{-g^2}{64\pi^2 \cos^2\theta_W} \sum_{a=1}^{4} \sum_{b=1}^{4} \sum_{c=1}^{4} \text{Im} \left[V_{ac} V_{bc}^* (VV^\dagger)_{ba} \right]$$

$$\times I_4(m_{ua}, m_{ub}, m_{dc}), \qquad (7)$$

$$f_6 = \frac{-g^2}{64\pi^2 \cos^2\theta_W} \sum_{a=1}^{4} \sum_{b=1}^{4} \sum_{c=1}^{4} \text{Im} \left[V_{ac} V_{bc}^* (VV^\dagger)_{ba} \right]$$

$$\times I_6(m_{ua}, m_{ub}, m_{dc}), \qquad (8)$$

$$f_7 = 0, \qquad (9)$$

where the functions I_4 and I_6 are defined by

$$I_4(m_{ua}, m_{ub}, m_{dc})$$

$$= \int\int_D \mathrm{d}x \mathrm{d}y \left\{ M_W^2 (1 - x - y)^2 (x - y) \right.$$

$$\left. + (m_{ua}^2 - m_{ub}^2) xy \right\} \Big/ \left\{ -M_W^2 (1 - x - y)(x + y) \right.$$

$$\left. - q^2 xy + m_{ua}^2 x + m_{ub}^2 y + m_{dc}^2 (1 - x - y) - \mathrm{i}\varepsilon \right\}, (10)$$

$$I_6(m_{ua}, m_{ub}, m_{dc})$$

$$= \int\int_D \mathrm{d}x \mathrm{d}y \left\{ M_W^2 (1 - x - y)(1 + x + y)(x - y) \right.$$

$$\left. - 2q^2 xy(x - y) - 3(m_{ua}^2 - m_{ub}^2) xy \right\}$$

$$\Big/ \left\{ -M_W^2 (1 - x - y)(x + y) - q^2 xy + m_{ua}^2 x + m_{ub}^2 y \right.$$

$$\left. + m_{dc}^2 (1 - x - y) - \mathrm{i}\varepsilon \right\}. \qquad (11)$$

The domain D for integration is given by

$$x \geq 0, \quad y \geq 0, \quad x + y \leq 1. \tag{12}$$

The contributions of the diagram in Fig. 1b can similarly be obtained. However, these contributions are negligible compared to those from Fig. 1a as shown later.

The form factors f_4 and f_6 in (7) and (8) are expressed more simply by taking approximations for the quark masses. Since the quarks of the first two generations and the b quark are much lighter than the W boson, the integrands of I_4 and I_6 in (10) and (11) are determined almost only by the W-boson mass M_W, the heavy quark masses m_t, m_U, m_D, and the momentum-squared q^2 of the Z boson. We can safely neglect mass differences among the light quarks. Then, taking $m_u = m_c$ and $m_d = m_s = m_b$, the form factors are written as

$$f_i = \frac{g^2}{32\pi^2 \cos^2 \theta_{\mathrm{W}}} C S_i \quad (i = 4, 6), \tag{13}$$

$$C = \mathrm{Im}\left[V_{34} V_{44}^* (VV^\dagger)_{43}\right],$$

$$\begin{aligned} S_i = &\, I_i(m_u, m_t, m_d) - I_i(m_u, m_U, m_d) \\ &+ I_i(m_t, m_U, m_d) - I_i(m_u, m_t, m_D) \\ &+ I_i(m_u, m_U, m_D) - I_i(m_t, m_U, m_D). \end{aligned}$$

Here, C depends on the mixing parameters for the quarks, while S_4 and S_6 depend on the mass parameters m_U, m_D and an experimental parameter q^2. It is seen that S_4 and S_6 vanish if the equality $m_u = m_t$ is assumed. Correspondingly, the contributions to f_4 and f_6 from the diagram in Fig. 1b become negligible, since the equality $m_d = m_b$ holds to a good approximation.

Numerical analyses for the form factors are now in order. We first consider S_4 and S_6. The integrals in (10) and (11) are precisely evaluated by a numerical method [9]. In Figs. 2a and b the absolute values for the real and imaginary parts of S_4 and S_6 are shown as functions of m_U for $m_U \geq 200\,\mathrm{GeV}$, taking $(q^2)^{1/2} = 200\,\mathrm{GeV}$ and $m_D = 200\,\mathrm{GeV}$ (Fig. 2a), $500\,\mathrm{GeV}$ (Fig. 2b). Curves (i), (ii), (iii), and (iv) represent $\mathrm{Re}(S_4)$, $\mathrm{Im}(S_4)$, $\mathrm{Re}(S_6)$, and $\mathrm{Im}(S_6)$, respectively. In wide ranges the imaginary parts do not vary much with m_U and m_D, being $\mathrm{Im}(S_4) \approx -0.3$ and $\mathrm{Im}(S_6) \approx 0.9$. The real parts are in the ranges $|\mathrm{Re}(S_4)| \lesssim 0.2$ and $|\mathrm{Re}(S_6)| \lesssim 0.4$. The values of S_4 and S_6 are not much dependent on m_D for $m_D \gtrsim 400\,\mathrm{GeV}$. In Fig. 3 the $(q^2)^{1/2}$-dependencies of S_4 and S_6 are shown for $(q^2)^{1/2} \geq 180\,\mathrm{GeV}$, taking $m_U = 300\,\mathrm{GeV}$ and $m_D = 300\,\mathrm{GeV}$. Curves (i), (ii), (iii), and (iv) stand for the same objects as in Fig. 2. The absolute values decrease, as $(q^2)^{1/2}$ increases.

Next we consider the magnitude of C. It is seen from (3) and (5) that V_{34}, V_{44}^*, and $(VV^\dagger)_{43}$ are related to the couplings of tDW, UDW, and UtZ, respectively. Experimental results available at present have not yet given much information on their values. However, C is expressed in terms of the unitary matrices A_{L}^u and A_{L}^d as

$$C = -\mathrm{Im}\bigg[(A_{\mathrm{L}}^u)_{43}(A_{\mathrm{L}}^{u\dagger} A_{\mathrm{L}}^d)_{34}(A_{\mathrm{L}}^{d\dagger} A_{\mathrm{L}}^u)_{44}(A_{\mathrm{L}}^{u\dagger})_{44}$$
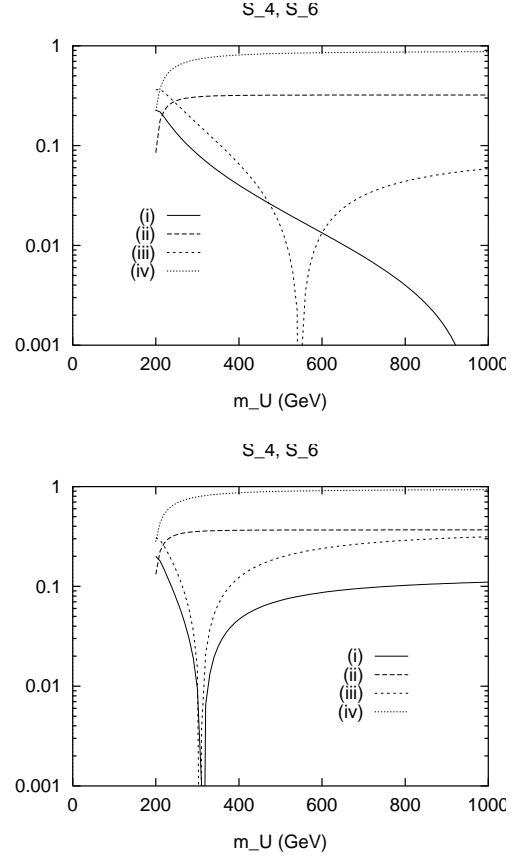
Fig. 2a,b. The absolute values of the real and imaginary parts of S_4 and S_6 as functions of m_U at $(q^2)^{1/2} = 200\,\mathrm{GeV}$. Four curves (i)–(iv) correspond to $\mathrm{Re}(S_4)$, $\mathrm{Im}(S_4)$, $\mathrm{Re}(S_6)$, $\mathrm{Im}(S_6)$. **a** $m_D = 200\,\mathrm{GeV}$, **b** $m_D = 500\,\mathrm{GeV}$
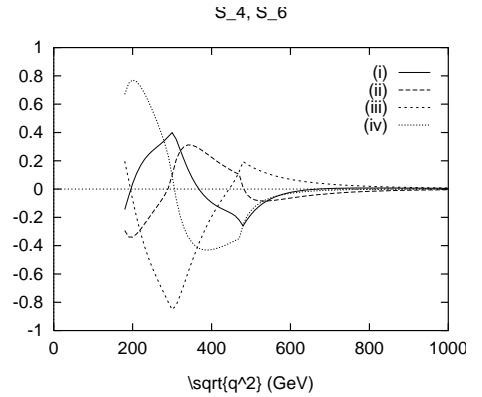
Fig. 3. The values of the real and imaginary parts of S_4 and S_6 as functions of $(q^2)^{1/2}$ for $m_U = 300\,\mathrm{GeV}$ and $m_D = 300\,\mathrm{GeV}$. (i) $\mathrm{Re}(S_4)$, (ii) $\mathrm{Im}(S_4)$, (iii) $\mathrm{Re}(S_6)$, (iv) $\mathrm{Im}(S_6)$

$$-(A_{\mathrm{L}}^u)_{43}(A_{\mathrm{L}}^{u\dagger} A_{\mathrm{L}}^d)_{34}(A_{\mathrm{L}}^d)_{44}|(A_{\mathrm{L}}^u)_{44}|^2$$

$$-|(A_{\mathrm{L}}^u)_{43}|^2(A_{\mathrm{L}}^d)_{44}(A_{\mathrm{L}}^{d\dagger} A_{\mathrm{L}}^u)_{44}(A_{\mathrm{L}}^{u\dagger})_{44}\bigg]. \tag{14}$$

Since the mass of the D quark is considered to be significantly larger than those of the d and s quarks, we may neglect mixings between the D quark and these light quarks,

taking $(A_\mathrm{L}^d)_{i4} = (A_\mathrm{L}^d)_{4i} = 0$ $(i = 1, 2)$. Then, C is given by

$$C = -|(A_\mathrm{L}^d)_{34}|^2 \mathrm{Im}\left[(A_\mathrm{L}^u)_{43}(A_\mathrm{L}^{u\dagger})_{33}(A_\mathrm{L}^u)_{34}(A_\mathrm{L}^{u\dagger})_{44}\right]. \quad (15)$$

We can see that C is proportional to $(A_\mathrm{L}^d)_{34}$. If there is no mixing between the D quark and the ordinary down-type quarks, the form factors f_4 and f_6 vanish. In order to have non-negligible CP-odd couplings, the extra down-type quark D, as well as U, should exist and be mixed with other down-type quarks. The magnitude of C is estimated to be at most of order 0.1, since C contains the product of four different elements of a unitary matrix in addition to $|(A_\mathrm{L}^d)_{34}|^2$. If the mixings of the quarks for the third and fourth generations are not suppressed, $|C|$ becomes maximal. However, the mixing for the down-type quarks would be suppressed, since the mass difference between the b quark and the D quark is still large. Therefore, we take the allowed range of C for $|C| < 0.01$ as a conservative constraint. Some new source of CP violation yields the electric dipole moment (EDM) of the neutron at the one-loop level, leading to its large magnitude. Then nontrivial constraints could be imposed on the new source of CP violation. In the present model, however, the neutron EDM is not induced at the one-loop level, so that the magnitude of C is not constrained from the available experimental upper bounds.

The form factors are written by (13) as

$$f_i = 1.7 \times 10^{-3} C S_i \quad (i = 4, 6). \quad (16)$$

Taking into account the constraints on C and S_i, we make an estimate

$$|f_4|, |f_6| < 1 \times 10^{-5}. \quad (17)$$

Possible maximal values of this result are larger than the predictions in the SM, though smaller by two orders of magnitude than those in the supersymmetric model [6], where the CP-odd form factors are also induced at the one-loop level. Experimentally, the real and imaginary parts of these form factors could be measured respectively by e.g. asymmetries in the angular distributions and in the energy distributions for the particles produced by W^+ and W^- decays. (For a detailed discussion, see [6].) These asymmetries are of the same order of magnitude as the form factors. Assuming a maximal value, a total of more than 10^{10} pairs of W bosons would be necessary to detect the form factors. It seems to be difficult to achieve such a number of events in near-future experiments.

4 Summary

We have discussed CP-odd couplings for the WWZ vertex within the framework of the VQM. These couplings could be sizably induced through the one-loop diagram in which the Z boson couples to the up-type quarks. Both up-type and down-type extra quarks are necessary to have non-negligible form factors. Their possible maximal magnitudes have been estimated without assuming a detailed structure for the quark mixings, giving at most a magnitude of the order of 10^{-5}. These magnitudes are larger than the predictions by the SM but smaller than those by the supersymmetric model. The VQM does not yield CP-odd WWZ couplings which can be detected experimentally in the near future.

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