Abstract

The supersymmetric standard model contains a new CP-violating phase in the mass matrices for charginos and neutralinos, which could induce CP-odd anomalous couplings for the $WWZ$ and $WW\gamma$ vertices at the one-loop level. We study these couplings, paying attention to the model-parameter and $q^2$ dependencies. It is shown that the CP-odd form factors could have values of order $10^{-3} - 10^{-4}$, which are much larger than those predicted by the standard model. We also discuss the possibility of examining these form factors in experiments.

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1 Introduction

The study of trilinear gauge-boson vertices $WWZ$ and $WW\gamma$ is one of the main subjects for experiments at LEPII or near-future $e^+e^-$ colliders. Their precise measurements enable to examine the standard model (SM) in which the vertices are determined uniquely. Possible discrepancies between the experimental results and the SM predictions would imply the existence of physics beyond the SM [1, 2]. Various theoretical analyses therefore have been made on the vertices in the SM [3] and in its extensions, such as the two-Higgs-doublet model [4], the model with Majorana neutrinos [5], and the supersymmetric model [6], in particular for $CP$-conserving couplings.

In this paper we study the trilinear gauge-boson vertices focusing on $CP$ violation within the framework of the supersymmetric standard model (SSM) [7]. This model contains new sources of $CP$ violation as well as the standard Kobayashi-Maskawa mechanism. As a result, the $W$ and $Z$ bosons have $CP$-violating interactions with supersymmetric particles [8]. These interactions generate $CP$-violating couplings for $WWZ$ and $WW\gamma$ at the one-loop level [9, 10]. Since the SM does not predict $CP$ violation for the vertices at the tree level nor the one-loop level, observation of $CP$-violating phenomena arising from these vertices could immediately indicate the existence of physics other than the SM [11]. The SSM gives radiative corrections also to $CP$-even couplings for the vertices [12], although they are at most of the same order of magnitude as the SM predictions [6].

The new sources of $CP$ violation of the SSM can also give contributions to the electric dipole moments (EDMs) of the neutron and the electron through one-loop diagrams mediated by the charginos, neutralinos, or gluinos, together with the squarks or sleptons. For wide ranges of SSM parameters the magnitudes of the induced EDMs could be around or even larger than their present experimental upper bounds, thus providing non-trivial constraints on the SSM. We assume that $CP$-violating phases intrinsic in the SSM have a natural magnitude of order unity, since there is no convincing reason which suppresses them. Then, the masses of the squarks and sleptons are constrained from the EDMs to be larger than 1 TeV, while the charginos and neutralinos could have masses of order of 100 GeV [13].

The one-loop diagrams which induce the $CP$-violating couplings for $WWZ$ and $WW\gamma$ in the SSM could be mediated by various supersymmetric particles. However, if the new $CP$-violating phases are not suppressed, the squarks and sleptons have to be heavy and thus the diagrams with these particles can be neglected. Sizable
contributions to the couplings could only be generated through the diagrams mediated by the charginos and neutralinos shown in Fig. 1, on which our analyses are concentrated throughout this paper.

This paper is organized as follows. In sect. 2 the \( CP \)-violating interactions in the SSM are briefly summarized. In sect. 3 we obtain the \( CP \)-odd form factors for the \( WWZ \) and \( WW\gamma \) vertices and make numerical analyses in detail. The possibility of detecting the \( CP \)-odd couplings is discussed in sect. 4.

## 2 Model

The \( CP \)-odd couplings for the \( W \) bosons are induced by the interactions of charginos \( \omega_i \) and neutralinos \( \chi_j \), the charged and neutral mass eigenstates of higgsinos and \( SU(2) \times U(1) \) gauginos. Their mass matrices are given by

\[
M^- = \begin{pmatrix} \tilde{m}_2 & -g \nu_1^*/\sqrt{2} \\ -g \nu_2^*/\sqrt{2} & m_H \end{pmatrix},
\]

\[
M^0 = \begin{pmatrix} \tilde{m}_1 & 0 & g' \nu_1^*/2 & -g' \nu_2^*/2 \\ 0 & \tilde{m}_2 & -g \nu_1^*/2 & g \nu_2^*/2 \\ g' \nu_1^*/2 & -g \nu_1^*/2 & 0 & -m_H \\ -g' \nu_2^*/2 & g \nu_2^*/2 & -m_H & 0 \end{pmatrix},
\]

where \( \nu_1 \) and \( \nu_2 \) are the vacuum expectation values of the Higgs bosons; \( m_H \) is the mass parameter in the bilinear term of the Higgs superfields in superpotential; and \( \tilde{m}_2 \) and \( \tilde{m}_1 \) are the masses of \( SU(2) \) and \( U(1) \) gauginos, respectively, appearing in the soft supersymmetry-breaking terms. In general, these parameters have complex values. Although there is some freedom of redefining the phases of the fields, all the complex phases cannot be rotated away. The mass matrices \( M^- \) and \( M^0 \) are diagonalized to give mass eigenstates:

\[
C_R^\dagger M^- C_L = \text{diag}(m_{\omega_1}, m_{\omega_2}) \quad (m_{\omega_1} < m_{\omega_2}),
\]

\[
N^\dagger M^0 N = \text{diag}(m_{\chi_1}, m_{\chi_2}, m_{\chi_3}, m_{\chi_4}) \quad (m_{\chi_1} < m_{\chi_2} < m_{\chi_3} < m_{\chi_4}),
\]

where \( C_R, C_L, \) and \( N \) are unitary matrices.

The complex mass matrices for the charginos and the neutralinos lead to \( CP \)-violating interactions. The interaction Lagrangian for the charginos, neutralinos, and \( W \) bosons are given by

\[
\mathcal{L} = \frac{1}{\sqrt{2}} g \tilde{\chi} \gamma^\mu \left( G_{L ji} \frac{1 - \gamma_5}{2} + G_{R ji} \frac{1 + \gamma_5}{2} \right) \omega_i W_{\mu}^\dagger + \text{h.c.},
\]

2
\[ G_{Lji} = \sqrt{2}N_{2j}^* C_{L1i} + N_{3j}^* C_{L2i}, \]
\[ G_{Rji} = \sqrt{2}N_{2j}^* C_{R1i} - N_{4j}^* C_{R2i}. \]

The interaction Lagrangian for the charginos and the neutralinos with the \( Z \) boson is given by
\[
\mathcal{L} = \frac{1}{\cos \theta_W} \frac{g}{2} \left\{ \omega_i \gamma^\mu \left( F_{Lij} \frac{1 - \gamma^5}{2} + F_{Rij} \frac{1 + \gamma^5}{2} \right) \omega_j - \frac{1}{4} \chi_i \gamma^\mu \left( F_{ij} \frac{1 - \gamma^5}{2} - F_{ij}^* \frac{1 + \gamma^5}{2} \right) \chi_j \right\} Z^\mu, \tag{6}
\]

\[ F_{L} = \left( \cos^2 \theta_W - \frac{1}{2} |C_{L21}|^2, -\frac{1}{2} C_{L21}^* C_{L22}, \cos^2 \theta_W - \frac{1}{2} |C_{L22}|^2 \right), \]
\[ F_{R} = \left( \cos^2 \theta_W - \frac{1}{2} |C_{R21}|^2, -\frac{1}{2} C_{R21}^* C_{R22}, \cos^2 \theta_W - \frac{1}{2} |C_{R22}|^2 \right), \]
\[ F_{ij} = N_{3i}^* N_{3j} - N_{4i}^* N_{4j}. \]

The SSM parameters which determine the interactions in Eqs. (5) and (6) are \( v_1, v_2, \tilde{m}_2, \tilde{m}_1, \) and \( m_H \) appearing in Eqs. (1) and (2). We assume the relation \( \tilde{m}_1 = (5/3) \tan^2 \theta_W \tilde{m}_2 \) suggested by grand unified theories. The redefinitions of the fields make it possible without loss of generality to take all these parameters except \( m_H \) real and positive. Then, the \( CP \)-violating phase is represented by the phase of \( m_H \), which we express as
\[ m_H = |m_H| \exp(i\theta). \tag{7} \]

Since \( v_1 \) and \( v_2 \) are related to the \( W \)-boson mass \( M_W \), independent parameters become \( \tan \beta, \tilde{m}_2, |m_H|, \) and \( \theta \), where the ratio of the vacuum expectation values \( v_2/v_1 \) is denoted by \( \tan \beta \).

## 3 Form factors

For the pair production of the \( W \) bosons in \( e^+e^- \) annihilation the trilinear gauge-boson vertex \( WWV \), \( V \) being \( Z \) or \( \gamma \), can generally be expressed in momentum space as \[\Gamma_V^{\mu \lambda \rho}(p, \bar{p}, q) = f_1^V (p - \bar{p})^\mu g^{\nu \lambda} - f_2^V (p - \bar{p})^\mu q^\nu q^\lambda / M_W^2 + f_3^V (q^\nu g^{\mu \lambda} - q^\lambda g^{\mu \nu}) + if_4^V (q^\nu g^{\mu \lambda} + q^\lambda g^{\mu \nu}) + if_5^V \varepsilon^{\mu \nu \lambda \rho} (p - \bar{p})_\rho - f_6^V \varepsilon^{\mu \nu \lambda \rho} q_\rho \]
\[ - f_7^V (p - \bar{p})^\mu \varepsilon^{\nu \lambda \rho \sigma} q_\rho (p - \bar{p})_\sigma / M_W^2, \tag{8} \]
where \( q, p \) and \( \bar{p} \) are the momenta of the vector bosons \( V_\mu, W^-_\mu \), and \( W^+_\mu \), respectively. Among the seven form factors, \( f_1^V, f_2^V, f_3^V \), and \( f_5^V \) are CP-even and \( f_4^V, f_6^V, \) and \( f_7^V \) are CP-odd. In the SM the form factors \( f_1^V \) and \( f_3^V \) alone do not vanish at the tree level, which holds also in the SSM.

The CP-odd form factors receive contributions from the one-loop diagrams in Fig. 1. The \( WWZ \) couplings are generated by Fig. 1(a) and Fig. 1(b), while the \( WW\gamma \) couplings by Fig. 1(a). We obtain the form factors as follows.

i) The \( WWZ \) vertex:

\[
f_4^Z = f_{4(a)}^Z + f_{4(b)}^Z, \tag{9}
\]

\[
f_{4(a)}^Z = \frac{-1}{(4\pi)^2 \cos^2 \theta_W} \frac{g^2}{2} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{4} \left\{ \text{Im} \left[ G_{Lki} G_{Lkj}^* F_{Lij} + G_{Rki} G_{Rkj}^* F_{Rij} \right] \left( -M_W^2 A_3 + (m_{w_j}^2 - m_{w_i}^2) S_3 \right) \right. \\
\left. + \text{Im} \left[ G_{Lki} G_{Lkj}^* F_{Rij} + G_{Rki} G_{Rkj}^* F_{Lij} \right] m_{w_i} m_{w_j} A_1 \right. \\
\left. + \text{Im} \left[ G_{Lki} G_{Rkj}^* F_{Lij} + G_{Rki} G_{Lkj}^* F_{Rij} \right] m_{w_j} m_{\chi_k} S_2 \right. \\
\left. + \text{Im} \left[ G_{Lki} G_{Rkj}^* F_{Rji} + G_{Rki} G_{Lkj}^* F_{Lij} \right] (-m_{w_i} m_{\chi_k} S_2) \right\},
\]

\[
f_{4(b)}^Z = \frac{-1}{(4\pi)^2 \cos^2 \theta_W} \frac{g^2}{4} \sum_{i=1}^{4} \sum_{j=1}^{4} \sum_{k=1}^{2} \left\{ \text{Im} \left[ G_{Lik} G_{Ljk}^* F_{j_{ji}} - G_{Rik} G_{Rjk}^* F_{j_{ji}}^* \right] \left( -M_W^2 A_3 + (m_{w_j}^2 - m_{w_i}^2) S_3 \right) \right. \\
\left. + \text{Im} \left[ G_{Lik} G_{Ljk}^* F_{j_{ji}}^* - G_{Rik} G_{Rjk}^* F_{j_{ji}} \right] \left( -m_{\chi_j} m_{\chi_i} A_1 \right) \right. \\
\left. + \text{Im} \left[ G_{Lik} G_{Rjk}^* F_{j_{ji}} - G_{Rik} G_{Ljk}^* F_{j_{ji}}^* \right] m_{\chi_j} m_{w_k} S_2 \right. \\
\left. + \text{Im} \left[ G_{Lik} G_{Rjk}^* F_{j_{ji}}^* - G_{Rik} G_{Ljk}^* F_{j_{ji}} \right] m_{\chi_j} m_{w_k} S_2 \right\},
\]

\[
f_6^Z = f_{6(a)}^Z + f_{6(b)}^Z, \tag{10}
\]

\[
f_{6(a)}^Z = \frac{1}{(4\pi)^2 \cos^2 \theta_W} \frac{g^2}{2} \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{4} \left\{ \text{Im} \left[ G_{Lki} G_{Lkj}^* F_{Lij} - G_{Rki} G_{Rkj}^* F_{Rij} \right] \right. \\
\left. \left( -M_W^2 (A_3 - 2A_2) - 2q^2 A_4 + 3(m_{w_j}^2 - m_{w_i}^2) S_3 \right) \right. \\
\left. + \text{Im} \left[ G_{Lki} G_{Lkj}^* F_{Rij} - G_{Rki} G_{Rkj}^* F_{Lij} \right] m_{w_i} m_{w_j} A_1 \right. \\
\left. + \text{Im} \left[ G_{Lki} G_{Rkj}^* F_{Lij} - G_{Rki} G_{Lkj}^* F_{Rij} \right] m_{w_j} m_{\chi_k} (A_1 - S_1) \right. \\
\left. + \text{Im} \left[ G_{Lki} G_{Rkj}^* F_{Rji} - G_{Rki} G_{Lkj}^* F_{Lij} \right] m_{w_i} m_{\chi_k} (-A_1 - S_1) \right\},
\]
$$f_{6(b)}^Z = \frac{1}{(4\pi)^2} \frac{g^2}{\cos^2 \theta_W} \frac{1}{4} \sum_{i=1}^{4} \sum_{j=1}^{4} \sum_{k=1}^{2} \left\{ \text{Im} \left[ G_{L_i k} G_{R_j k}^* F_{ji} + G_{R_i k} G_{L_j k}^* F_{ji}^* \right] \right\} \times \left( M_W^2 (A_3 - 2A_2) + 2q^2 A_4 + 3(m_{\chi_i}^2 - m_{\chi_j}^2) S_i \right)$$

$$+ \text{Im} \left[ G_{L_i k} G_{R_j k}^* F_{ji} + G_{R_i k} G_{L_j k}^* F_{ji}^* \right] m_{\chi_i} m_{\chi_j} A_i$$

$$+ \text{Im} \left[ G_{L_i k} G_{R_j k}^* F_{ji} + G_{R_i k} G_{L_j k}^* F_{ji}^* \right] m_{\chi_j} m_{\omega_k} (-A_1 + S_i)$$

$$+ \text{Im} \left[ G_{L_i k} G_{R_j k}^* F_{ji} + G_{R_i k} G_{L_j k}^* F_{ji}^* \right] m_{\chi_i} m_{\omega_k} (-A_1 - S_i) \right\},$$

$$f_7^Z = 0,$$

(11)

where $S_i$ ($i = 1 - 3$) and $A_i$ ($i = 1 - 4$) stand for the functions defined by

$$[S_1, S_2, S_3] \equiv \int_0^1 dx \int_0^1 dy \int_0^1 dz \frac{\delta(1 - x - y - z)}{D(m_i, m_j, m_k)} [1, z, xy],$$

(12)

$$[A_1, A_2, A_3, A_4] \equiv \int_0^1 dx \int_0^1 dy \int_0^1 dz \frac{\delta(1 - x - y - z)}{D(m_i, m_j, m_k)} \left[ x - y, z(x - y), z^2(x - y), xy(x - y) \right],$$

$$D(m_i, m_j, m_k) \equiv - M_W^2 z(1 - z) - q^2 xy + m_i^2 x + m_j^2 y + m_k^2 z - i \varepsilon.$$

For $f_{6(a)}^Z$ and $f_{6(b)}^Z$ the arguments of these functions are given by $m_i = m_{\omega_i}, m_j = m_{\omega_j},$ and $m_k = m_{\chi_k},$ and for $f_{4(b)}^Z$ and $f_{6(b)}^Z$ given by $m_i = m_{\chi_i}, m_j = m_{\chi_j},$ and $m_k = m_{\omega_k}.$ The form factors $f_{i(a)}^Z$ and $f_{i(b)}^Z$ ($i = 4, 6$) arise from the diagrams in Fig. 1(a) and Fig. 1(b), respectively.

ii) The $WW\gamma$ vertex:

$$f_6^\gamma = \frac{-1}{(4\pi)^2} g^2 \sum_{i=1}^{2} \sum_{k=1}^{4} \text{Im} \left[ G_{L_k i} G_{R_k i}^* - G_{L_k i}^* G_{R_k i} \right] m_{\omega_i} m_{\chi_k} S_1,$$

(13)

$$f_4^\gamma = 0,$$

(14)

$$f_7^\gamma = 0.$$  

(15)

The arguments of $S_1$ are given by $m_i = m_j = m_{\omega_i}$ and $m_k = m_{\chi_k}.$ The nonvanishing contribution to $f_6^\gamma$ only comes from Fig. 1(a) with the charginos being the same $i = j.$

We now make numerical analyses of the form factors. The numerical computations of one-loop integrals have been carried out following the method of [14]. For
the SM parameters we fix $\sin^2 \theta_W = 0.232$, $M_Z = M_W / \cos \theta_W = 91.2$ GeV, and $\alpha_{EM} = 1/128.9$. In Fig. 2 we show the absolute values of the real and imaginary parts of $f_4^Z$ and $f_6^Z$ as functions of the absolute value of the higgsino mass parameter $m_H$ for four sets of values of $\tilde{m}_2$ and $\tan \beta$ listed in Table 1. For the $CP$-violating phase we take $\theta = \pi/4$. The value of the momentum-squared for the $Z$ boson is set for $\sqrt{q^2} = 200$ GeV. In the ranges of smaller values for $|m_H|$ where curves are not drawn, the lighter chargino has a mass smaller than 45 GeV, which has been ruled out by LEP experiments \[\text{[E]}.\] If the masses of the particles which couple to the $Z$ boson in a loop diagram are near the threshold, $\sqrt{q^2} \approx m_i + m_j$, the contributions of this diagram to the form factors are enhanced. Below the threshold, the diagram does not generate the imaginary parts of the form factors. In the discussed parameter ranges, there exist several regions which are near the thresholds for pairs of charginos or neutralinos. This is the reason why the form factors complicatedly depend on the parameters. The values of $|\text{Re}(f_6^Z)|$ and $|\text{Im}(f_6^Z)|$ can become around $5 \times 10^{-4}$ for $\tan \beta = 2$, $\tilde{m}_2 = 100$ GeV, and $|m_H| \sim 100$ GeV. The magnitudes of $\text{Re}(f_4^Z)$ and $\text{Im}(f_4^Z)$ are smaller than those for $f_6^Z$ and at most around $1 \times 10^{-4}$. Larger values for $\tan \beta$ suppress the form factors.

In Fig. 3 the absolute values of the real and imaginary parts of $f_6^Z$ are shown for the same parameter values as in Fig. 2. The values of $|\text{Re}(f_6^Z)|$ and $|\text{Im}(f_6^Z)|$ can become around $5 \times 10^{-4}$ for $\tan \beta = 2$, $\tilde{m}_2 = 100$ GeV, and $|m_H| \sim 100$ GeV. As $\tan \beta$ increases, $|\text{Re}(f_6^Z)|$ and $|\text{Im}(f_6^Z)|$ decrease. Since the photon only couples to the pair of the same charginos, the parameter dependence of $f_6^Z$ is much simpler than $f_4^Z$ or $f_6^Z$.

In Figs. 4 and 5 we show the $\sqrt{q^2}$ dependencies of the form factors. Four curves (a), (b), (c), and (d) in Fig. 4 represent the absolute values of $\text{Re}(f_4^Z)$, $\text{Im}(f_4^Z)$, $\text{Re}(f_6^Z)$, and $\text{Im}(f_6^Z)$, respectively, and two curves (a) and (b) in Fig. 5 the absolute values of $\text{Re}(f_6^Z)$ and $\text{Im}(f_6^Z)$, respectively. The parameters are set for $\tilde{m}_2 = 200$ GeV, $|m_H| = 200$ GeV, $\tan \beta = 2$, and $\theta = \pi/4$. These parameter values lead to the masses of the charginos and the neutralinos shown in Table 2. By the same reason as for Figs. 2 and 3, the form factors $f_4^Z$ and $f_6^Z$ depend on $\sqrt{q^2}$ complicatedly, while $f_6^Z$ does simply. The magnitudes of $\text{Re}(f_6^Z)$, $\text{Im}(f_6^Z)$, $\text{Re}(f_6^Z)$, and $\text{Im}(f_6^Z)$ can become around $2 \times 10^{-4}$, though those of $\text{Re}(f_4^Z)$ and $\text{Im}(f_4^Z)$ are at most $2 \times 10^{-5}$. If $\tilde{m}_2$ and $|m_H|$ are of order 100 GeV and $\tan \beta$ is not much larger than unity, in general, there is a region of $\sqrt{q^2}$ where $|f_6^Z|$ or $|f_6^Z|$ becomes larger than $1 \times 10^{-4}$.
4 Discussions

We have shown that the SSM yields CP-odd anomalous couplings for the $WWZ$ and $WW\gamma$ vertices at the one-loop level. The CP-odd form factors could have magnitudes of $10^{-3} - 10^{-4}$, which are far larger than the SM predictions. If some CP-violating phenomena originating from the CP-odd couplings are observed, the SSM would become more promising as physics beyond the SM.

We now discuss the effects of the CP-odd form factors on observable quantities. The resultant CP-violating phenomena occur primarily in the pair production of polarized $W$ bosons in $e^+e^-$ annihilation, $e^+e^- \rightarrow W^+\bar{\lambda}W^-\lambda$, $\bar{\lambda}$ and $\lambda$ denoting respectively the helicities of $W^+$ and $W^-$. Among various combinations for the helicities $(\bar{\lambda}, \lambda)$, the pairs $(+, 0)$, $(-, 0)$, and $(+, +)$ are CP-conjugate to the pairs $(0, -)$, $(0, +)$, and $(-, -)$, respectively. If CP invariance is conserved, these CP-conjugate processes have the same cross sections. Thus, nonvanishing values for the differences of the cross sections $\sigma_{+0} - \sigma_{0-}$, $\sigma_{-0} - \sigma_{0+}$, and $\sigma_{++} - \sigma_{--}$ exhibit CP violation. These differences are indeed generated by the imaginary parts of the CP-odd form factors. For instance, CP violation can be evaluated by an asymmetry

$$A_{CP} = \frac{\sigma_{+0} - \sigma_{0-}}{\sigma_{+0} + \sigma_{0-}},$$

which is given by

$$A_{CP} = \left( -1 + \frac{s}{s - M_Z^2} \right)^{-1} \left\{ 2I^\gamma + \frac{s}{s - M_Z^2} (I^\gamma + I^Z) + \left( \frac{s}{s - M_Z^2} \right)^2 2I^Z \right\},$$

$$I^V = \text{Im}(f_4^V) - \frac{\text{Im}(f_6^V)}{\beta},$$

where $\beta = \sqrt{1 - 4M_W^2/q^2}$. We can see that the magnitude of $A_{CP}$ becomes of order of the CP-odd form factors. In the SSM such CP asymmetries could thus be of order of $10^{-3} - 10^{-4}$ in a maximal case. On the other hand, the real parts of the CP-odd form factors induce $T$ violation in the angular distribution of the polarization vector $\epsilon$ for the $W^+$ or $W^-$ boson, leading to a $T$-odd asymmetry

$$A_T = \frac{\sigma((p_\perp \times p) \cdot \epsilon > 0) - \sigma((p_\perp \times p) \cdot \epsilon < 0)}{\sigma((p_\perp \times p) \cdot \epsilon > 0) + \sigma((p_\perp \times p) \cdot \epsilon < 0)},$$

where $p_\perp$ and $p$ denote the momenta of the electron and the $W$ boson, respectively. The value of $A_T$ becomes also the same order of magnitude as the CP-odd form factors.
The helicity of the $W$ boson affects the energy distribution of the particle produced by the $W$-boson decay. Consequently the $CP$ asymmetry $A_{CP}$ for the $W$-boson pair production could be observed as an asymmetry between the energy distributions of the particles produced from $W^+$ and $W^-$. Unless the contributions of different $CP$-conjugate pairs are canceled, this resultant asymmetry would be of the same order of magnitude as $A_{CP}$. The $T$-odd asymmetry $A_T$ leads to some $T$-odd asymmetry among the particle momenta in the final state [11] with the same order of magnitude. Assuming maximal $CP$ violation, a total of $10^6 - 10^8$ pairs of $W$ bosons would make it possible to examine these asymmetries. However, in near-future $e^+e^-$ experiments it seems to be difficult to achieve such a number of events [17].

The form factor $f_6^\gamma$ for the $WW\gamma$ vertex could be measured indirectly by the EDMs of the neutron and the electron. If this form factor has a nonvanishing value, these EDMs receive contributions from one-loop diagrams generated by SM interactions [18]. For $f_6^\gamma \sim 10^{-4}$, the neutron EDM is predicted to be of order $10^{-26}$ cm [10], which is smaller than the present experimental upper bound by only one order of magnitude. The improvement for precision of the experiments is expected [19], so that the EDMs may be able to disclose the $CP$-odd form factor. Another possibility of indirect measurements is in neutron-nucleus collisions at very low energy, where enormous resonance enhancement for $P$-violating effects has been observed [20]. The same enhancement for $T$-violating effects is expected, by which $CP$-odd couplings of the neutron and the $Z$ boson could be probed very precisely [21]. Such couplings can be generated at the one-loop level by SM interactions, if $CP$-odd couplings for $WWZ$ are nonvanishing. If the $CP$-odd couplings of the neutron and the $Z$ boson can be explored to the same order of magnitude as the neutron EDM, the form factor $f_6^Z$ for $WWZ$ may become detectable.

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|            | (i.a) | (i.b) | (ii.a) | (ii.b) |
|------------|-------|-------|--------|--------|
| $\tilde{m}_2$ (GeV) | 100   | 100   | 200    | 200    |
| $\tan \beta$    | 2     | 10    | 2      | 10     |

Table 1: The values of $\tilde{m}_2$ and $\tan \beta$ for curves (i.a)–(ii.b) in Figs. 2 and 3.

| $m_{\omega_i}$ (GeV) | 133  | 274  |
| $m_{\chi_j}$ (GeV)   | 85   | 146  | 203   | 278   |

Table 2: The mass spectra of the charginos and neutralinos in Figs. 4 and 5.

Figure 1: One-loop diagrams mediated by charginos and neutralinos which induce $CP$-odd couplings for $WWZ$ and $WW\gamma$. 
Fig. 2(a)

Fig. 2(b)
Figure 2: The absolute values of the real and imaginary parts of $f^Z_4$ and $f^Z_6$ as functions of $|m_H|$ for $\theta = \pi/4$ at $\sqrt{q^2} = 200$ GeV. Four curves (i.a)–(ii.b) correspond to the four sets of parameter values given in Table 1. (a) $\text{Re}(f^Z_4)$, (b) $\text{Im}(f^Z_4)$, (c) $\text{Re}(f^Z_6)$, (d) $\text{Im}(f^Z_6)$. 
Figure 3: The absolute values of the real and imaginary parts of $f_6^\gamma$ as functions of $|m_H|$ for $\theta = \pi/4$ at $\sqrt{q^2} = 200$ GeV. Four curves (i.a)–(ii.b) correspond to the four sets of parameter values given in Table 1. (a) Re($f_6^\gamma$), (b) Im($f_6^\gamma$).
Figure 4: The absolute values of the real and imaginary parts of $f^Z_4$ and $f^Z_6$ as functions of $\sqrt{q^2}$ for $\tan \beta = 2$, $\tilde{m}_2 = 200$ GeV, $|m_H| = 200$ GeV, and $\theta = \pi/4$. (a) $\text{Re}(f^Z_4)$, (b) $\text{Im}(f^Z_4)$, (c) $\text{Re}(f^Z_6)$, (d) $\text{Im}(f^Z_6)$. 
Figure 5: The absolute values of the real and imaginary parts of $f_6^\gamma$ as functions of $\sqrt{q^2}$ for $\tan \beta = 2$, $\tilde{m}_2 = 200$ GeV, $|m_H| = 200$ GeV, and $\theta = \pi/4$. (a) $\text{Re}(f_6^\gamma)$, (b) $\text{Im}(f_6^\gamma)$. 