SUSY LOOP CONTRIBUTIONS TO THE W-PAIR PRODUCTION IN $e^+e^-$ COLLISIONS

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We discuss one-loop contributions of supersymmetry (SUSY) particles to the process $e^+e^- \rightarrow W^+W^-$ in the minimal supersymmetric standard model. The calculation is tested by using the sum rule among the form factors, which is based on the BRS invariance. The overall normalization factor of the amplitudes is tested by using the decoupling property of the SUSY particles in the large mass limit. The correction due to the one-loop effect of the sfermions can be of a few times $\pm 0.1\%$ level, whereas that of the charginos and neutralinos can be order 1%. We also study the CP-violating effects in the chargino and neutralino sector.

We present the results of our study on the one-loop super-partner particle contributions to the $e^+(k, \tau)e^-(\bar{k}, \bar{\tau}) \rightarrow W^+(p, \lambda)W^-(\bar{k}, \bar{\lambda})$ in the MSSM\(^1\), where $k$ and $p$ represent the momenta, and $\tau$ and $\lambda$ do the helicities. We here concentrate on the one-loop effects of sfermions\(^2\), charginos and neutralinos\(^3\).

The helicity amplitudes can be written by using 16 basis tensors $T_i^{\mu \alpha \beta}$ as

$$M_{\lambda \tau} = \sum_{i=1}^{16} F_{i, \tau}(s, t) j_{\mu}(k, \bar{k}, \tau) T_i^{\mu \alpha \beta} \epsilon_{\alpha}(p, \lambda)^* \epsilon_{\beta}(\bar{p}, \bar{\lambda})^* ,$$

where $j_{\mu}$ is the electron current, and $\epsilon_{\alpha}$ is the polarization vectors for the $W$ boson. The physical process is described by the first 9 of the 16 form factors $F_{i, \tau}(s, t)$ $(i = 1-16)$. In order to test the physical form factors $F_{i, \tau}(s, t)$ $(i = 1-9)$ by using the BRS sum rule\(^1\), we have to calculate unphysical form factors $F_{i, \tau}(s, t)$ $(i = 10-16)$ together with the form factors $H_{i, \tau}(s, t)$ $(i = 1-4)$ of helicity amplitudes for $e^+(k, \tau)e^-(\bar{k}, \bar{\tau}) \rightarrow \omega^+(p)W^-(\bar{k}, \bar{\lambda})$ ($\omega^+$: Nambu-Goldstone boson) by using basis tensors $S_i^{\mu \alpha}$ as

$$M_{\lambda \tau}^\omega(e^+e^- \rightarrow \omega^+W^-) = i \sum_{i=1}^{4} H_{i, \tau}(s, t) j_{\mu}(k, \bar{k}, \tau) S_i^{\mu \alpha} \epsilon_{\alpha}(p, \lambda)^* .$$

We employ the $\overline{\text{MS}}$ scheme for the one-loop calculation\(^2,3\).

One difficulty in loop-level calculations is to determine reliability of the results. This is especially so in our process in which a subtle gauge cancellation takes place among diagrams at each level of perturbation. In order to
obtain solid results, we test our calculation by using the sum rules among the form factor due to the BRS invariance. In addition, using the decoupling property of the SUSY particles in the large mass limit, we can test the overall normalization of the amplitudes.

Among the helicity amplitudes for $e^+e^- \rightarrow W^+W^-$, the SUSY loop contribution is the largest in the 00 helicity amplitude. In Fig. 1 (left), the squark one-loop effects on the 00 helicity amplitude are shown for parameter sets in Table 1. The corrections to the SM prediction are negative and the behavior is rather simple. It is found that the corrections to the SM prediction are at most a few times 0.1%. In Fig. 1(right), effects of the third generation squarks with large stop-mixing are shown. The parameters defined in Table 2 are chosen so as to be the maximal mixing with the mixing angle 45°. The corrections are positive. Larger effects appear for larger values of $A_f^{\text{eff}}$. However, it turns out that such enhancement due to the mixing is strongly constrained by the precision data. The cases for large corrections (case 2, case 3 in Table 2) stay outside the 99% contour of the allowed region. Consequently, only smaller corrections than a few times 0.1% are allowed.

Next, we discuss the chargino and neutralino loop effects. We here assume the GUT relation $M_1 = 5M_2s^2/3c^2$, the light chargino mass $m_{\tilde{\chi}_1^+} = 110\text{GeV}$, and the scattering angle $\theta = 90^\circ$. In Fig. 2(a), we show $\mu$ parameter dependences for $\tan \beta = 3$ and 50. The corrections are about 0.7% at $|\mu| = 1000$ GeV for $\tau = -1$, whereas they remain to be small for $\tau = +1$ as around 0.1%

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| First 2 generations | Case 1 | Case 2 | Case 3 |
|---------------------|--------|--------|--------|
| Input parameters    |        |        |        |
| $m_{\tilde{q}} = m_{\tilde{d}} = m_{\tilde{d}}$ | 300    | 500    | 1000   |
| $A_f^{\text{eff}}$ | 0      | 0      | 0      |

Table 1: Cases without squark mixing for Fig. 1(left).

| $t\cdot b$ sector: | Case 1 | Case 2 | Case 3 |
|---------------------|--------|--------|--------|
| Input parameters    |        |        |        |
| $m_{\tilde{t}} = m_{\tilde{b}} = m_{\tilde{b}}$ | 300    | 400    | 500    |
| $A_f^{\text{eff}}$ | 625    | 1025   | 1539   |

| Output parameters   |        |        |        |
|---------------------|--------|--------|--------|
| $m_{\tilde{t}_1}$   | 100    | 100    | 100    |
| $m_{\tilde{t}_2}$   | 478    | 607    | 741    |
| $\cos \theta_t$     | 0.708  | 0.708  | 0.707  |

Table 2: Maximal stop-mixing cases for Fig. 1(right).
Figure 1: Squark contributions for non-LR-mixing (left) and for maximal LR-mixing (right).

| Parameter | A | B | C | D | E |
|-----------|---|---|---|---|---|
| $\mu$ (GeV) | +120 | +145 | +400 | +1000 | +130 |
| $M_2$ (GeV) | 541 | 242 | 125 | 115 | 158 |
| $\phi_1$ | 0 | 0 | 0 | 0 | $\frac{2}{3}\pi$ |
| $\phi_\mu$ | 0 | 0 | 0 | 0 | $\frac{3}{2}\pi$ |

Table 3: Parameter sets for Figs. 2 and 3.

level. In Fig. 2(b), $\sqrt{s}$ dependences for four sets of parameter (sets A to D of Table 3) are shown. The lightest chargino mass is fixed to be $m_{\tilde{\chi}^0_1} = 110$ GeV, and $\tan \beta = 3$ is assumed for all cases. A sharp peak can be seen at $\sqrt{s} = 220$ GeV for each curve, which corresponds to the threshold for the pair production of the lightest chargino. The corrections are negative for $\tau = +1$.

There are new sources for the CP-violating phases in the MSSM. In the chargino and neutralino sector, it arises from the $\mu$-term, $\mu e^{i\phi_\mu}$, and from the gaugino mass parameters $M_1 e^{i\phi_1}$ when we take the phase of $M_2$ to be zero by rephasing. We find that large CP-violating phases in chargino and neutralino sectors are possible without contradicting the EDM constraints. In Figs. 3(a) and 3(b), the real part (solid curve) and the imaginary part (dotted curve) of $f_4^Z$, $f_6^Z$, and $f_6^\gamma$ are shown as a function of $\sqrt{s}$ for the parameters of set E in Table 3. These form factors take their maximum or minimum at around $\phi_\mu = \phi_1 = 2/3\pi$ or $4/3\pi$. The CP-violating effects of $f_4$ and $f_6$ may be measured through the difference of the helicity amplitudes $M^{\pm 0}$ and $M^{\mp 0}$. The CP-violating effects in the helicity amplitudes can be of the order 0.1%.

In conclusion, the sfermion one-loop contributions to the 00 helicity amplitude are at most a few times 0.1%, while the effects due to charginos and
neutralinos can be of the order of 1%. We also found that the CP-violating effects on the helicity amplitudes $M^{0}$ and $M^{-0}$ can be of the order of 0.1%.

References

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