1-loop effects of MSSM particles in Higgs productions at the ILC

Yusaku Kouda¹, Tadashi Kon¹, Masato Jimbo², Yoshimasa Kurihara³, Tadashi Ishikawa³, Kiyoshi Kato⁴, Masaaki Kuroda⁵
¹ Seikei University, Musashino, Tokyo 180-8633, Japan
² Chiba University of Commerce, Ichikawa, Chiba 272-0827, Japan
³ KEK, Tsukuba, Ibaraki 305-0801, Japan
⁴ Kogakuin University, Shinjuku, Tokyo 163-8677, Japan
⁵ Meiji Gakuin University, Yokohama, Kanagawa, 244-8539, Japan
E-mail: dd146101@cc.seikei.ac.jp

Abstract. Within the framework of the MSSM (Minimal Supersymmetric Standard Model), we investigate the 1-loop effects of SUSY (supersymmetric) particles on the Z,higgs production at the ILC. Three sets of the SUSY parameters are proposed which are consistent with the observed higgs mass, the muon g-2, the dark matter (DM) abundance and the decay branching ratio of B meson. In addition, We investigate the 1-loop effects on \(h\) production using \(W\)-fusion approximation at the ILC. We discuss on the possibility of discovering the signals consistent with SUSY as well as of experimentally distinguishing the proposed sets of SUSY parameters.

1. Introduction
The supersymmetric (SUSY) model [1] is considered as one of the promising candidates for the theory beyond the standard model. The experimental confirmation of the SUSY particles (sparticles) is an important subject of the present and future collider experiments. Since high luminosity is expected at the ILC experiments [2], we should calculate the physical observables with the accuracy better than the experimental data. We have calculated several cross sections and decay branching ratios at 1-loop level with GRACE/SUSY-loop system [3, 4, 5]. In this paper we report numerical results of the cross section of \(e^{-}e^{+} \rightarrow Z,h\). (The same observable calculated in the previous work [6], and we confirmed almost same numerical results at the same assumption for the MSSM input parameters. We also calculated the \(W\) fusion approximation of \(e^{-}e^{+} \rightarrow \nu_{\mu}\bar{\nu}_{\mu},h\), where the SM 1-loop correction has already been calculated with using GRACE [7]).

2. Selection of the MSSM parameter sets
We have considered the experimental constraints (Table 1) in selection of the typical sets of MSSM parameters. We selected three sets [19] which consistent with next constraints. We have calculated the cross section of \(e^{+}e^{-} \rightarrow Z,h\) at the 1-loop level in these sets. We used MicrOMEGAs [11] in the estimation of the MSSM prediction for the dark matter (DM) thermal relic density(1), [8, 9, 10]. The program package SuSpect2 [18] are used for the muon g-2
anomalous magnetic moment (2), [12, 13], the $B$ meson rare decay branching ratio (3), [14] and the observed higgs mass (4), [15, 16]. Moreover, we set the sparticle masses which meet the recent LHC bound (5), [17].

**Table 1.** The experimental constraints for MSSM parameters.

| Constraint                        | Numerical value         |
|-----------------------------------|-------------------------|
| (1) DM thermal relic density      | $\Omega h^2 = 0.1198 \pm 0.0026$ |
| (2) muon $g-2$ anomalous magnetic moment | $a^{\text{exp}} - a^{\text{SM}} = (2.88 \pm 0.63 \pm 0.49) \times 10^{-9}$ |
| (3) $B$ meson rare decay branching ratio | $\text{Br}(B\to \chi_1 \gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$, $\text{Br}(B_s \to \mu^+ \mu^-) = (3 \pm 1) \times 10^{-9}$ |
| (4) Higgs mass                    | $m_h(\text{exp}) = 125.09 \pm 0.24 \text{GeV}$ |
| (5) LHC direct search of sparticles | $m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 1.5 \text{TeV}$ |

In Table 2, we show the set which is adopted for the calculation of $e^+e^- \to \nu_e \bar{\nu}_e h$ cross section with the $W$ fusion approximation. It is noted that the set is consistent with the constraints (1),(3),(4),(5). In other words, we have not considered the muon $g-2$ constraint (2) in table 2. We have shown in the previous work [19] that the anomaly (2) can only be explained by MSSM with $m_{\tilde{\chi}^0_1} \lesssim 450 \text{ GeV}$. Here, we set $m_{\tilde{\chi}^0_1}$ (neutralino1 mass) = 552.8 GeV and calculated $\sqrt{s} = 500 \text{ GeV}$, so the channel $e^-e^+ \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 h$ is not considered.

**Table 2.** The MSSM mass spectra of the set which we selected for the $\nu_e \bar{\nu}_e h$ cross section calculation(The units are GeV except the mixing angles $\theta$ and $\tan\beta$).

| $h$    | $H$ | $A$ | $H^+$ | $\tilde{\chi}^0_1$ | $\tilde{\chi}^0_2$ | $\tilde{\chi}^0_3$ | $\tilde{\chi}^0_4$ |
|--------|-----|-----|-------|---------------------|---------------------|---------------------|---------------------|
| 125.2  | 2000| 2000| 2002  | 552.8               | 588.2               | 614.8               | 1376                |
| $\tilde{\chi}^+_1$ | $\chi^+_2$ | $\tilde{\ell}_1$ | $\tilde{\ell}_2$ | $\tilde{\nu}_t$ | $\tilde{\nu}_\tau$ | $\tilde{\tau}_1$ | $\tilde{\tau}_2$ |
| 583.3  | 1376| 601.5| 651.7 | 641.9               | 646.9               | 589.5               | 662.5               |
| $\tilde{u}_1$ | $\tilde{u}_2$ | $\tilde{d}_1$ | $\tilde{d}_2$ | $\tilde{i}_1$ | $\tilde{i}_2$ | $\tilde{b}_1$ | $\tilde{b}_2$ |
| 5000   | 5000| 4800| 5000  | 1798               | 2508               | 2200               | 2501               |
| $\theta_e$ | $\theta_b$ | $\theta_t$ | $M_1$ | $M_2$ | $M_3$ | $\mu$ | $\tan\beta$ |
| 1.164  | 1.539| 1.481| 585.0 | 1370               | 2500               | 586                | 30                 |
3. Numerical Results

We show total cross sections for associate higgs particle production processes at future linear collider in Figure 1. $\sqrt{s} = 250$ GeV is adopted for the precision verification of $e^- e^+ \rightarrow Z\ell$. Since $\sigma(e^- e^+ \rightarrow \nu\bar{\nu}h)$ is larger than $\sigma(e^- e^+ \rightarrow Z\ell)$ and $\sigma(e^- e^+ \rightarrow \nu\bar{\nu}h)$ via the W-fusion are dominant contribution for $\sqrt{s} \gtrsim 500$ GeV.

Figure 1. The $\sqrt{s}$ dependence of the total cross sections at the ILC for different final states. $\nu\bar{\nu}h(3\text{gen})$ stands for the sum of $\nu\bar{\nu}h$, $\nu\bar{\nu}h$ and $\nu\bar{\nu}h$.

For $\sqrt{s} = 250(500)$ GeV, the 1-loop correction at $\cos\theta = 0$, namely, $\delta_{\text{SM}} \equiv \frac{d\sigma_{\text{loop}}^{\text{SM}} - d\sigma_{\text{tree}}}{d\sigma_{\text{tree}}} = -11(9)\%$, and $\delta_{\text{MSSM}} \equiv \frac{d\sigma_{\text{loop}}^{\text{MSSM}} - d\sigma_{\text{tree}}}{d\sigma_{\text{tree}}} = -9(11)\%$. We have confirmed forward-backward symmetry of the angular distribution even at the 1-loop level.

Figure 2. Angular distribution of cross section in $e^+ e^- \rightarrow Z\ell$. The left (a) and right (b) figures show results for $\sqrt{s} = 250$ GeV and $\sqrt{s} = 500$ GeV, respectively.
We define the ratio of the differential cross sections [20],

\[ \delta_{\text{susy}} \equiv \delta_{\text{MSSM}} - \delta_{\text{SM}} = \frac{d\sigma_{\text{MSSM}}^{1\text{loop}}}{d\sigma_{\text{tree}}} - \frac{d\sigma_{\text{SM}}^{1\text{loop}}}{d\sigma_{\text{tree}}} . \] (1)

We show \( \delta_{\text{susy}} \) in Figure 3. \( \delta_{\text{susy}} \) is 1–2% in the entire region and is larger than the statistical error. It means that the 1-loop contribution of the MSSM could be measured at both \( \sqrt{s} = 250 \) GeV and 500 GeV. In addition, the difference between set2 and set3 is also larger than the statistical error at \( \sqrt{s} = 250 \text{ GeV} \).

![Figure 3](image)

**Figure 3.** Correction ratio \( \delta_{\text{susy}} \) in \( e^+ e^- \rightarrow Zh \). The left (a) and right (b) figures show results for \((\sqrt{s}, L) = (250 \text{ GeV}, 250 \text{ fb}^{-1}) \) and \((\sqrt{s}, L) = (500 \text{ GeV}, 500 \text{ fb}^{-1}) \), respectively.

For \( \sqrt{s} = 500 \) GeV, the single Higgs production \( e^- e^+ \rightarrow \nu_e, \bar{\nu}_e, h \) with the W-fusion approximation is also calculated. We choose the W-fusion type 239 diagrams from the full 1-loop 13793 diagrams. An example is shown in Figure 4.

![Figure 4](image)

**Figure 4.** An example of Feynman diagrams in which the virtual W pair exists in the internal lines. stops (\( \tilde{t} \)) and sbottoms (\( \tilde{b} \)) contribute in the 1-loop.

We confirmed cancellation of ultraviolet and infrared divergences, and the photon cut-off energy independence. The Energy distribution and correction ratio \( \delta_{\text{susy}} \) in W fusion are shown in Figure 5. Where, \( E_h \) is single generation energy of higgs particle. The 1-loop correction at \( E_h \)
\[ \delta_{\text{SM}} = \frac{d\sigma_{\text{SM}}}{dE} \quad \text{and} \quad \delta_{\text{MSSM}} = \frac{d\sigma_{\text{MSSM}}}{dE} \]

In the entire region, \( \delta_{\text{susy}} \approx 11\% \sim 17\% \). It is larger than the error of the Monte Carlo integration. It means that the MSSM signal is verifiable, but this results are preliminary and necessary to be scrutinized more.

\[ \delta_{\text{susy}}(\%) \]

Figure 5. The energy distribution and correction ratio \( \delta_{\text{susy}} \) in \( e^-e^+ \rightarrow \nu_e \bar{\nu}_e h \). The left figure shows energy distribution at \( \sqrt{s} = 500 \) GeV and The right figure shows the correction ratio \( \delta_{\text{susy}} \).

4. Summary
We selected sets that are consistent with higgs mass, \( B \) physics, DM relic density, LHC direct search of sparticles, and muon \( g-2 \) (only in \( Zh \) production). We have probed statistical significance at both of \( \sqrt{s} = 250 \) GeV and 500 GeV. At \( \sqrt{s} = 250 \) GeV, three sets are distinguishable. The results of \( W \) fusion approximation in \( e^-e^+ \rightarrow \nu_e \bar{\nu}_e h \) are preliminary, but the 1-loop effect of supersymmetry would be verifiable at \( \sqrt{s} = 500 \) GeV in the future linear collider.

5. References
[1] S. P. Martin, Adv. Ser. Direct. High Energy Phys. 18, 1 (1998), hep-ph/9709356v7 (2016).
[2] H. Baer, T. Barklow, K. Fujii, Y. Gao, A. Hoang, S. Kanemura, J. List, H. E. Logan, A. Nomerotski, M. Perelstein, et al. (2013), arXiv:1306.6352.
[3] J. Fujimoto, T. Ishikawa, M. Jimbo, T. Kaneko, K. Kato, S. Kawabata, T. Kon, M. Kuroda, Y. Kurihara, Y. Shimizu, and H. Tanaka, Comput. Phys. Commun., 153, 106 (2003).
[4] J. Fujimoto, T. Ishikawa, Y. Kurihara, M. Jimbo, T. Kon, and M. Kuroda, Phys. Rev. D, 75, 113002 (2007).
[5] M. Jimbo, T. Kon, Y. Kouda, M. Ichikawa, Y Kurihara, T Ishikawa, K Kato, and M. Kuroda, (2017) arxiv:1703.07671 [hep-ph]
[6] J. Cao, C. Han, J. Ren, L. Wu, J. Yang, M. Jin and Y. Zhang,, Chin. Phys. C40, 113104 (2016)
[7] G. Blanger , F. Boudjema , J. Fujimoto , T. Ishikawa , T. Kaneko , K. Kato, and Y. Shimizu, Physics Letters B 559 (2003)
[8] A. Ibarra, A. Pierce, N. R. Shah, and S. Vogl, Phys. Rev. D, 91, 095018 (2015).
[9] J. Ellis, K. A. Olive, and J. Zheng, Eur. Phys. J., C74, 2947 (2014).
[10] K. A. Olive, PoS, PLANCk2015, 093 (2015).
[11] G. Bélanger, F. Boudjema, A. Pukhov, and A. Semenov, Comput. Phys. Commun., 149, 103 (2002).
[12] A. Hoecker and W. J. Marciano, The Muon Anomalous Magnetic Moment, in Particle Data Group, Chin. Phys., C38, 090001 (2014); p.649 (updated August 2013), references therein.
[13] G. C. Cho, K. Hagiwara, Y. Matsumoto, and D. Nomura, JHEP, 11, 068 (2011).
[14] Amhis, Y. and others, FERMILAB-PUB-15-004-PPD, (2014)
[15] ATLAS Collaboration, Phys. Lett., B716, 1 (2012).
[16] CMS Collaboration, Phys. Lett., B716, 30 (2012).
[17] ATLAS Collaboration, JHEP, 09, 176 (2014).
[18] A. Djouadi, J.-L. Kneur, and G. Moultaqa, Comput. Phys. Commun., 176, 426 (2007).
[19] Y. Kouda, T. Kon, Y. Kurihara, T. Ishikawa, M. Jimbo, K. Kato, and M. Kuroda, Prog Theor Exp Phys doi:10.1093/ptep/ptx048 2017 5, 053B0 (2017).
[20] W. Hollik and C. Schappacher, Nucl. Phys., B545, 98–140 (1999).