# Present status of GRACE/SUSY

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**Abstract**

We have developed the system for the automatic computation of cross sections, `GRACE/SUSY` , including the one-loop calculations for processes of the minimal supersymmetric extension of the standard model. For an application, we investigate the pair-production of the heavy chargino in electron-positron collisions.

## 1 Introduction

From the theoretical point of view, it has been a promising hypothesis that there exists a symmetry called supersymmetry (SUSY) between bosons and fermions at the unification-energy scale [1]. In particular, the minimal supersymmetric extension of the standard model (MSSM) has been extensively studied in the past decade, because it has the simplest structure and contains the least number of particles, and yet it is complex enough to describe the most essential feature characteristic to any theory of SUSY.

Since it is a broken symmetry at the electroweak-energy scale, the relic of SUSY is expected to remain as a rich spectrum of SUSY particles, partners of usual matter fermions, gauge bosons and Higgs scalars, named sfermions, gauginos and higgsinos, respectively. The quest of these new particles has been one of the most important issues of the high-energy physics at future colliders of sub-TeV-region or TeV-region energies.

For the simulations of the experiments, we have to calculate the cross sections for the processes with more than three final particles because most kinds of particles decay to two or more particles. Several groups independently developed computer systems which automate the perturbative calculation in the standard model (SM) with different methods [2, 3, 4, 5, 6], and also have been developing the systems of the automatic computation in the MSSM, `GRACE/SUSY` [7, 8, 9], `FeynArts-FormCalc` [10] and `CompHEP` [11].

For more than five years, the Minami-Tateya group has been developing the system of the automatic computation of the supersymmetric processes [7, 8]. Compared with `GRACE` [2] for the SM, `GRACE/SUSY` [9] for the MSSM has very complicated structure. This is caused not only by the complicacy of the MSSM lagrangian itself but also by the several historical reasons in the course of the development of `GRACE` and `GRACE/SUSY` .

(1) In `GRACE` for the SM, the so-called Kyoto convention [12] is used for the Feynman rule, in which, for example, the fermion propagator is given by $\frac{-1}{\gamma\cdot p-m}$, while in `GRACE/SUSY` the international convention of the Feynman rules is adopted. The Feynman rule of the interaction vertex differs also in two conventions.

(2) At the first phase of the construction of GRACE/SUSY , we referred to the MSSM model lagrangian presented by Hikasa [13] and coded the model definition files based on it. The first paper [14] on the MSSM processes are computed based on these model definition files. Later, we noticed that the European people, in particular, the package of the generator SUSYGEN [15] defines the allowed region of the parameters $\mu$ and $\tan\beta$ differently from the Hikasa's manuscript. This caused some confusion in the international collaborations. Therefore, we have decided to have our own model lagrangian for the MSSM at hand. Kuroda has computed the complete lagrangian of the MSSM [16] using the European convention: namely, the positive chargino is called a particle and the ranges of $\mu$ and $\tan\beta$ are defined as $0 \leq \tan\beta \leq 1$ and $-\infty \leq \mu \leq +\infty$ .

(3) In addition, the GRACE system consists of several components, for example, the package for the Feynman-graph generation [17], the module for the calculation of the helicity amptiludes CHANEL [18]. We had to modify and expand them for the construction of GRACE/SUSY. For loop calculations, we also needed to expand the package to GRACE/1LOOP [19].

In this paper, we provide the present status of GRACE/SUSY , especially on the development of the loop calculations for the MSSM.

## 2 GRACE/SUSY/1LOOP

For discovery experiments, we have to calculate cross sections not only for processes of new-particle productions but also for their background processes. For this purpose, GRACE/SUSY is well established at the tree level, and is widely used (for example, see [20]). On the other hand, we need loop corrections for precise measurements. The first step to apply GRACE/SUSY to calculations at the one-loop level was a process of the SM-particle production [21] . Recently, we have been developing the system for the automatic computation of the MSSM at the one-loop level GRACE/SUSY/1LOOP , which is applicable to processes of the MSSM-particle production.

We adopt the renormalization scheme of the MSSM as follows:

- the gauge-boson sector: the conventional approach [22]
  (Renormalization constants of wavefunctions are introduced to unmixed bare states and mass counterterms are introduced to mixed mass eigenstates.)

- the Higgs sector: the Dabelstein's approach [23] ; the chargino sector and the neutralino sector: the Kuroda's approach [24] (see also [25])
  (Renormalization constants of wavefunctions are introduced only to unmixed bare states.)

- the matter-fermion sector and the sfermion sector: the Kyoto approach [12]
  (Renormalization constants of wavefunctions are introduced only to mixed mass eigenstates.)

As an application of GRACE/SUSY/1LOOP, we consider chargino-pair productions in electron-positron collisions [26, 27] . For the calculations of cross sections, we use the same

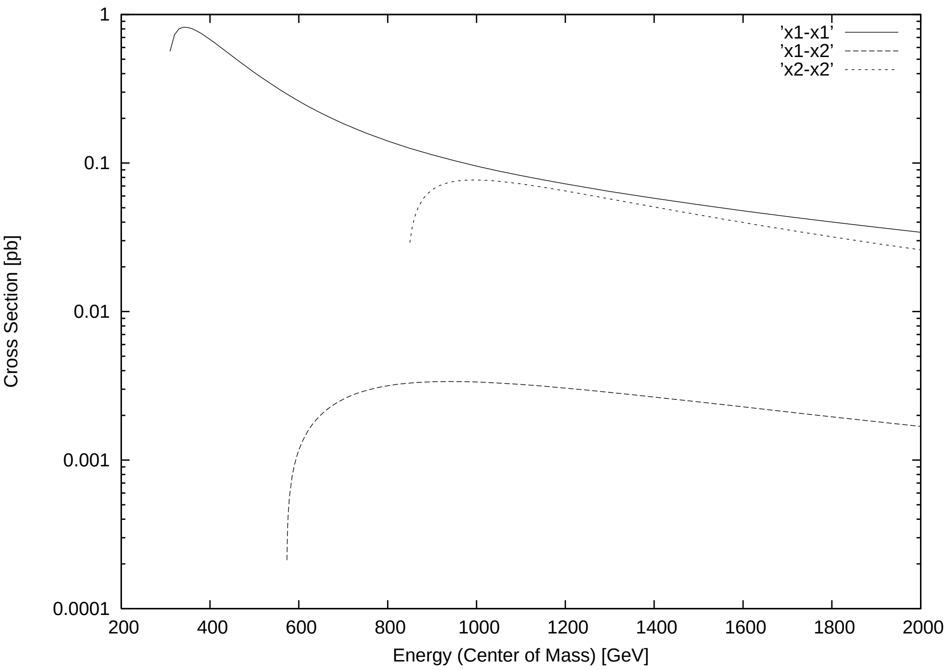


Figure 1: Cross-sections at the tree-level for $e^+e^- \to \tilde{\chi}_{\mathrm{i}}^+\tilde{\chi}_{\mathrm{j}}^-$ (i, j = 1 or 2). Solid line, dashed line and dotted line indicate cross sections for chargino1-pair production, chargino1-chargino2 production and chargino2-pair production, respectively.

input parameters as in ref. [26], $M\tilde{\chi}_1^+ = 150$ GeV, $M\tilde{\chi}_2^+ = 420$ GeV, $M\tilde{\chi}_1^0 = 75$ GeV, $\tan\beta = 5$, $A_f = M_F = 500$ GeV, $M\tilde{\nu} = 500$ GeV and $M_{A^0} = 150$ GeV.

First, we calculate cross sections at the tree-level. The numerical results shown in Figure 1 indicate that the cross sections for the production of chargino2 (heavy chargino) pair are comparable to those for the production of chargino1 (light chargino) pair in the TeV region. Thus we investigate the loop calculation for the production of chargino2 pair.

| $C_{\mathrm{UV}}$ | 1-loop (pb) |
|---|---|
| 0 | $-0.1913091178482273$ |
| 100 | $-0.1913091178449565$ |
| $\lambda$ | 1-loop + soft$\gamma$ (pb) |
| $1.0 \times 10^{-20}$ | $-7.433338646007673 \times 10^{-2}$ |
| $1.0 \times 10^{-23}$ | $-7.433338646189581 \times 10^{-2}$ |
| $k_{\mathrm{c}}$ | 1-loop + soft$\gamma$ + hard$\gamma$ (pb) |
| $1.0 \times 10^{-1}$ | $0.1374 \times 10^{-2}$ ($\pm 0.000345 \times 10^{-2}$) |
| $1.0 \times 10^{-3}$ | $0.1368 \times 10^{-2}$ ($\pm 0.000473 \times 10^{-2}$) |

Table 1. The invariance checks of cross sections on $C_{\mathrm{UV}}$, $\lambda$ and $k_{\mathrm{c}}$.

For the one-loop calculations, we have to check the invariance of cross sections varying three parameters, the UV constant ($C_{\mathrm{UV}}$), the fictitious photon mass ($\lambda$) and the cutoff energy of the soft photon ($k_{\mathrm{c}}$). The invariance checks at $\sqrt{s} = 1900$ GeV are shown in

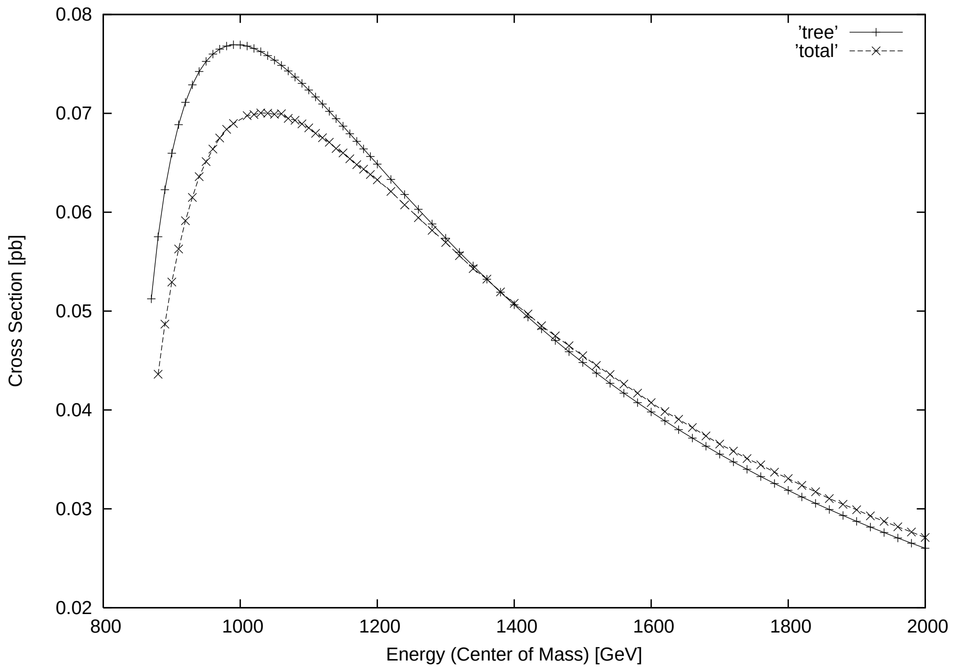


Figure 2: Cross-sections at the tree-level (solid line) and total cross sections at the one-loop level (dashed line) for $e^+e^- \to \tilde{\chi}_2^+\tilde{\chi}_2^-$ .

Table 1.

In Figure 2, numerical results are shown for the cross sections at the tree-level and the cross sections at the one-loop level which include all contributions from loop diagrams, soft-photon and hard-photon emissions.

# 3 Conclusion and outlook

We have developed the system `GRACE/SUSY/1LOOP` for the automatic computation of cross sections of the MSSM-particle production, including the one-loop calculations For an application, we have investigated the pair-production of the heavy chargino in electron-positron collisions, and tuned up our system.

Remaining tasks for us are:

- checking `GRACE/SUSY/1LOOP` with the non-linear gauge in the MSSM (Checking `GRACE` with the non-linear gauge has already been done in the SM [28].)
- checking `GRACE/SUSY/1LOOP` for the invariance on the UV constant with other processes

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