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CompHEP/SUSY package

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Abstract

The CompHEP software package allows the evaluation of cross section and decays of elementary particles with a high level of automation. Arbitrary tree level processes can be calculated starting from the set of vertices prescribed by a given physical model. This note describes the details of the Minimal Supersymmetric Standard Model (MSSM) implementation in the CompHEP package, and the notation for the particles and parameters of the MSSM in CompHEP.

1 Introduction

The CompHEP package [1] allows to generate automatically the Feynman diagrams for a process describing collisions or decays of elementary particles starting from the Feynman rules. CompHEP performs symbolic calculation of the squared matrix element and numerical integration over multiparticle phase space for the physical process. The goal of the CompHEP/SUSY package is to develop the description of the Minimal Supersymmetric Standard Model (MSSM) and some of its extensions in the CompHEP format.

We have used the description of the MSSM physical spectrum and the Lagrangian for 3 generations of quarks and leptons given in [2]. The LanHEP software package [3] was used to generate the Feynman rules for the MSSM Lagrangian. LanHEP allows to write the Lagrangian in terms of initial fields (multiplets) before $SU(2) \times U(1)$ breaking, to use the superpotential formalism and the 2-component spinor notation. Thus the LanHEP input model description is compact and close to textbook formulae. LanHEP outputs the Feynman rules as CompHEP tables describing the physical model (a LaTeX output is also possible). The Feynman rules were successfully compared with the ones listed in [2], as well as with many results of other publications. The comparison to GRACE/SUSY program was successfully done for many processes.

We have used the notation of independent parameters same as in the ISASUSY package [9] which is more popular than one of [2] (we give explicit mass matrices below). We also add the effective Higgs potential to the tree level MSSM Lagrangian to incorporate the radiative corrections to the masses and couplings of Higgs bosons in a gauge invariant way.

Several CompHEP/SUSY models can be found on the WWW page http://theory.sinp.msu.ru/~semenov/mssm.html

The basic CompHEP/SUSY implementation of MSSM assumes massless fermions of the 1st and 2nd generation, and left/right-handed states for the corresponding sfermions. Stops, sbottoms and staus are mass eigenstates, the mixing due to fermion masses and trilinear soft coupling constants is taken into account in the calculation of the sfermion masses and interaction vertices. In the existing extension of the basic CompHEP/SUSY model, the fermion masses and sfermions mixing of the 2nd generations are also taken into account. We neglect the mixing of the different flavour left-handed squarks due to off-diagonal soft masses and Cabbibo-Kobayashi-Maskawa (CKM) matrix elements [4]. To keep our model explicitly gauge invariant, we assume that only the Cabbibo angle contribute to the CKM matrix, and that the soft masses for the 1st and 2nd sfermion generations are equal.

Besides the basic MSSM, there is a CompHEP/SUSY model with R-parity violation. Some other extensions will be described in forthcoming publications.

2 Model parameters

First, the user has access to the Standard Model parameters. We list those parameters with their default values. Some parameters, like s-, c-quark masses, CKM parameters do not appear in the basic CompHEP
MSSM since we neglect them. (Note that the default values might be changed in future versions).

| Parameter | Value |
|-----------|-------|
| Electromagnetic coupling constant at $M_Z$ | 0.31223 |
| Strong coupling constant at $M_Z$ | 1.238 |
| Sinus of the Weinberg angle, $\sin \theta_W$ | 0.473 |
| Parameter of CKM matrix (sinus of Cabibbo angle) | 0.221 |
| Parameter of CKM matrix | 0.041 |
| Parameter of CKM matrix | 0.0035 |
| Mass of $Z$ boson | 91.1884 |
| Mass of muon | 0.1057 |
| Mass of tau-lepton | 1.777 |
| Mass of c-quark | 1.42 |
| Mass of s-quark | 0.2 |
| Mass of t-quark | 175 |
| Mass of b-quark | 4.62 |
| Width of t-quark | 1.7524 |
| $Z$ boson width | 2.4944 |
| $W$ boson width | 2.08895 |

The following parameters are specific for the MSSM, they describe essentially MSSM extended Higgs sector and soft supersymmetry breaking potential. Our conventions correspond to the ISASUSY notation.

| Parameter | Description |
|-----------|-------------|
| $\tan \beta$ | Ratio of the vacuum expectation values of the Higgs doublets |
| $M_A$ | Mass of the pseudoscalar Higgs |
| $\mu$ | Higgs mass parameter |
| $M_{1}$ | $U(1)$ gaugino mass |
| $M_{2}$ | $SU(2)$ gaugino mass |
| $M_{3}$ | Gluino mass |
| $M_{L2}$ | Left-handed slepton mass, 2nd generation |
| $M_{L3}$ | Left-handed slepton mass, 3rd generation |
| $M_{R2}$ | Right-handed slepton mass, 2nd generation |
| $M_{R3}$ | Right-handed slepton mass, 3rd generation |
| $M_{Q2}$ | Left-handed squark mass, 2nd generation |
| $M_{Q3}$ | Left-handed squark mass, 3rd generation |
| $M_{U2}$ | Right-handed u squark mass, 2nd generation |
| $M_{U3}$ | Right-handed u squark mass, 3rd generation |
| $M_{D2}$ | Right-handed d squark mass, 2nd generation |
| $M_{D3}$ | Right-handed d squark mass, 3rd generation |
| $A_t$ | Trilinear coupling for top quark |
| $A_b$ | Trilinear coupling for b-quark |
| $A_\tau$ | Trilinear coupling for $\tau$-lepton |

We assume here that soft masses for the first generation coincide with the parameters of the second generation, but in future extensions the parameters $M_{L1}, M_{R1}, \ldots$ may appear.

The derived parameters needed for a given process such as physical masses, mixings and so on are computed from those listed above and their values can be found in the CompHEP Constraints menu.

## 3 Model particles

The notation for gauge bosons are the same as in the CompHEP Standard Model: $A$, $Z$, $W^+$, $W^-$, $G$. The gluino is named as $\tilde{G}$ (with mass $M_{G3}$). The notation for other particles follows with more details.
3.1 Charginos

Two charginos $\chi_1^+, \chi_2^+$ are mass eigenstates resulting from mixing of charged wino and higgsino. CompHEP names for these two particles are $~1+, ~2+$. Two mixing matrices are involved to diagonalize the mass matrix of charginos:

$$\begin{pmatrix}
Z_{m11} & Z_{m21} \\
Z_{m12} & Z_{m22}
\end{pmatrix}
\begin{pmatrix}
M_2 & \sqrt{2}M_W \sin \beta \\
\sqrt{2}M_W \cos \beta & \mu
\end{pmatrix}
\begin{pmatrix}
Z_{p11} & Z_{p12} \\
Z_{p21} & Z_{p22}
\end{pmatrix} = \text{diag}(MC_1, MC_2).$$

The values of the chargino masses $MC_1, MC_2$, and mixing elements $Z_{mij}, Z_{pij}$ can be found in the CompHEP Constraints menu.

3.2 Neutralinos

The four neutralinos $\chi_0^i$ are named $~o1, ~o2, ~o3, ~o4$. The 4x4 mixing matrix $Z_{nij}$ is defined in the bino-wino-higgsino basis, so

$$Z_n^{-1} M_N Z_n = \text{diag}(MNE_1, MNE_2, MNE_3, MNE_4),$$

where

$$M_N = \begin{pmatrix}
M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\
0 & M_2 & M_Z \cos \beta \cos \theta_W & -M_Z \sin \beta \cos \theta_W \\
-M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \cos \theta_W & 0 & -\mu \\
M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & -\mu & 0
\end{pmatrix}.$$

The values of $Z_{n11}, ..., Z_{n44}$ and masses $MNE_1, ..., MNE_4$ are in the CompHEP Constraints menu. Note that our definition of the mixing matrix is the inverse of that commonly used, the same is true for charginos and sfermions.

3.3 Sleptons

For each of the 3 lepton generations, there are two charged sleptons and one sneutrino. For the 3rd generation, the stau mixing matrix is:

$$M_\tau^2 = \begin{pmatrix}
M_{L_{3L}}^2 + m_\tau^2 + M_Z^2 \cos 2\beta (-\frac{1}{2} + \sin^2 \theta_W) & m_\tau (A_\tau - \mu \tan \beta) \\
m_\tau (A_\tau - \mu \tan \beta) & M_{R_{1R}}^2 + m_\tau^2 - M_Z^2 \cos 2\beta \sin^2 \theta_W
\end{pmatrix}$$

The following table summarizes the notation for particles and parameters used in the basic CompHEP/SUSY model.

| flavour      | $e$      | $\mu$   | $\tau$ | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|--------------|----------|---------|--------|---------|-----------|------------|
| fermion      | $e$      | $m$     | $l$    | $n_e$   | $n_\mu$   | $n_\tau$   |
| left scalar  | $eL$     | $mL$    | $lL$   | $n_eL$  | $n_\mu L$ | $n_\tau L$ |
| right scalar | $eR$     | $mR$    | $lR$   | $n_eR$  | $n_\mu R$ | $n_\tau R$ |
| light scalar | ~11      | ~12     | ~11    | ~11     | ~11       | ~11        |
| heavy scalar | ~11      | ~12     | ~11    | ~11     | ~11       | ~11        |
| left scalar mass | MSel | MSmL | MSl | MSne | MSnmu | MSntau |
| right scalar mass | MSelR | MSmLR | MSlR | MSneL | MSnmuL | MSntaul |
| light scalar mass | MSe | MSm | MSl | MSne | MSnmu | MSntau |
| heavy scalar mass | MSeL | MSmL | MSlL | MSneL | MSnmuL | MSntaul |
| $M_{LL}$     | $M_{LR}$ | $M_{RR}$ | $Z_{LL}$ | $Z_{2L}$ | $Z_{1R}$ | $Z_{2R}$ |
| $\theta$     |          |         |        |         |          |          |

3
The parameters $M_{LL}$, $M_{LR}$, and $M_{RR}$ are the elements of the slepton squared mass matrix to be diagonalized (in $\text{GeV}^2$); the $Z_{1L/R}$ values set the mixing of $s_{L/R}$ left/right states into the $s_{1,2}$ mass states:

\[
\begin{align*}
    s_L &= s_1 Z_{1L} + s_2 Z_{2L}, \\
    s_R &= s_1 Z_{1R} + s_2 Z_{2R},
\end{align*}
\]

and $\theta$ is the mixing angle which allows to represent the latter formulae as

\[
\begin{align*}
    s_L &= s_1 \cos \theta - s_2 \sin \theta, \\
    s_R &= s_1 \sin \theta + s_2 \cos \theta.
\end{align*}
\]

The $\theta$ value is given in radians.

### 3.4 Squarks

There are two squarks corresponding to each of the 6 quarks of the Standard Model. The mass matrices for up and down squarks of the 3rd generation are:

\[
\begin{align*}
    M_t &= \begin{pmatrix}
    M_{Q_t}^2 + m_t^2 + M_Z^2 \cos 2\beta & m_t(A_t - \mu \cot \beta) & M_{tL}^2 + m_t^2 + \frac{2}{3} M_Z^2 \cos 2\beta \sin^2 \theta_W \\
    m_t(A_t - \mu \cot \beta) & M_{tR}^2 + m_t^2 + \frac{2}{3} M_Z^2 \cos 2\beta \sin^2 \theta_W \\
    M_{tL}^2 + m_t^2 + \frac{2}{3} M_Z^2 \cos 2\beta \sin^2 \theta_W \\
    \end{pmatrix}, \\
    M_b &= \begin{pmatrix}
    M_{Q_b}^2 + m_b^2 + M_Z^2 \cos 2\beta & m_b(A_b - \mu \tan \beta) & M_{bL}^2 + m_b^2 + \frac{2}{3} M_Z^2 \cos 2\beta \sin^2 \theta_W \\
    m_b(A_b - \mu \tan \beta) & M_{bR}^2 + m_b^2 + \frac{2}{3} M_Z^2 \cos 2\beta \sin^2 \theta_W \\
    M_{bL}^2 + m_b^2 + \frac{2}{3} M_Z^2 \cos 2\beta \sin^2 \theta_W \\
    \end{pmatrix}.
\]

The following table summarizes the particles and values used in the basic model. The notation is similar to the one used for sleptons.

| flavour    | $d$ | $u$ | $s$ | $c$ | $b$ | $t$ |
|------------|-----|-----|-----|-----|-----|-----|
| fermion    |     |     |     |     |     |     |
| left scalar| $\bar{d}L$ | $uL$ | $sL$ | $cL$ | $bL$ | $tL$ |
| right scalar| $\bar{d}R$ | $uR$ | $sR$ | $cR$ | $bR$ | $tR$ |
| light scalar|     |     |     |     |     |     |
| heavy scalar|     |     |     |     |     |     |
| light scalar mass | $M_{dL}$ | $M_{sL}$ | $M_{cL}$ | $M_{bL}$ | $M_{tL}$ |
| heavy scalar mass |     |     |     |     |     |     |
| $M_{LL}$   | $M_{LR}$ | $M_{RR}$ | $Z_{1L}$ | $Z_{2L}$ | $Z_{1R}$ | $Z_{2R}$ |
| $\theta$   |     |     |     |     |     |     |

### 3.5 Higgs particles

The Higgs particles: $h^0$, $H^0$, $H^\pm$, $A^0$ are named in CompHEP as h, H, H+/H-, H3 correspondingly. Their masses are denoted as $M_h$, $M_H$, $M_{Hc}$, $M_{H3}$.

It is well known that the masses of Higgs bosons in the MSSM are significantly shifted by the radiative corrections. There are several techniques to compute the corrections to Higgs masses. We use the effective potential (see [3, 4] and references therein) to keep the explicit gauge invariance of the CompHEP model. The Higgs potential now is an extension of the MSSM potential:
\[ V_{eff} = m_{11}^2 (H_1 H_1^+) + m_{22}^2 (H_2 H_2^+) - [m_{12}^2 (e H_1 H_2) + h.c.] \\
+ \frac{1}{2} \left[ \frac{1}{4} (g^2 + g^2) + \lambda_1 \right] (H_1 H_1^+)^2 + \frac{1}{2} \left[ \frac{1}{4} (g^2 + g^2) + \lambda_2 \right] (H_2 H_2^+)^2 \\
+ \frac{1}{4} \left[ (g^2 - g^2) + \lambda_3 \right] (H_1 H_1^+)(H_2 H_2^+) + \left[ - \frac{1}{2} g^2 + \lambda_4 \right] (e H_1 H_2)^2 \\
+ \left( \lambda_5 (e H_1 H_2)^2 + \frac{1}{4} (\lambda_0 (H_1 H_1^*) + \lambda_7 (H_2 H_2^*) \right)(e H_1 H_2) + h.c. \]

The case of all \( \lambda_i \) being zero corresponds to the original tree-level MSSM potential.

Here the parameters \( m_{11}, m_{22} \) can be fixed by the condition of potential minimization, and the parameter \( m_{12} \) can be fixed if we choose \( M_A \) as independent variable. Then the masses of Higgs bosons and mixing angle \( \alpha \) can be derived (see [6] for formulae).

Analytical formulae for \( \lambda_i \) are given, for example, in [7]. The CompHEP notation for \( \lambda_i \) is \( d1h1 \ldots d1h7 \).

Many authors use different approaches to calculate Higgs masses, involving diagrammatic calculation rather than effective potential and RGE. So, many articles and computer programs calculate only the CP-even Higgs masses rather than the full \( \lambda_i \) set. This relates in particular to the FeynHiggs package. Note that such a prescription bounds only several of the 7 parameters, and we have to deal with \( \lambda_i \)’s to keep our model gauge invariant.

In the case when the Higgs masses are given, we derive the values for \( \lambda_{1,2,3,4} \) assuming that \( M_H, M_h, M_{H^\pm} \) and \( \alpha \) are independent variables. The masses \( M_h, M_H, M_{H^c} \) and \( \sin \alpha \) become free parameters. Then we use the FeynHiggsFast package [8] to evaluate these parameters. This approach allows us to take into account the corrections to the Higgs masses and also to self-interaction vertices (see the discussion in [9]).

4 Width parameters

There is a number of parameters representing particle widths. In the current version these values are set by the user. These parameters can be important in case of s-channel resonant production of a particle.

- \( wC_1, wC_2 \) — the widths of two charginos;
- \( wNE_2, wNE_3, wNE_4 \) — the widths of three neutralinos (except the lightest one);
- \( wSG \) — the width of gluino;
- \( wSe_1, wSe_2, wSmu_1, wSmu_2, wStau_1, wStau_2 \) — the widths of charged sleptons;
- \( wSne, wSnu, wSntau \) — the widths of sneutrinos;
- \( wSu_1, wSu_2, wSd_1, wSd_2, wSs_1, wSs_2, wSc_1, wSc_2, wSbot_1, wSbot_2, wStop_1, wStop_2 \) — the widths of squarks;
- \( wh \) — width of light CP-even Higgs;
- \( wHh \) — width of heavy CP-even Higgs;
- \( wHc \) — width of charged Higgs;
- \( wH3 \) — width of CP-odd Higgs.

5 SUGRA and GMSB models

The number of independent parameters in the MSSM can be reduced in the context of the SUGRA or GMSB models. More specifically, the parameters of soft SUSY breaking terms (gaugino masses \( M_1, M_2, M_3 \), sparticle masses \( M_L, M_R, M_Q \),...), trilinear couplings \( A_t, A_b, A_{\tau} \) are computed from just a few parameters.
It is possible to link CompHEP/SUSY with the ISASUSY package \cite{ISASUSY}, which includes SUGRA and GMSB models. For this, Isajet library should be installed on the computer. ISASUGRA is used to calculate soft SUSY breaking masses and couplings which were CompHEP independent variables. The masses of the particles are calculated by CompHEP from these soft parameters as before. In particular, masses of CP-even Higgs particles are calculated by \texttt{FeynHiggsFast} package, while ISASUSY gives the mass of the CP-odd Higgs boson.

SUGRA option:

| CompHEP notation | parameters                                      |
|-------------------|-------------------------------------------------|
| \texttt{tb}       | ratio of vacuum expectation value                |
| \texttt{suM0}     | $M_0$ - universal mass for scalars              |
| \texttt{suMHF}    | $M_{1/2}$ universal mass for fermions            |
| \texttt{suA0}     | $A_0$ universal trilinear coupling               |
| \texttt{suMU}     | \texttt{sign}($\mu$) - sign of higgsino mass parameter |
| \texttt{suMODE}   | choose the mSUGRA model                          |

Here \texttt{suMODE=1} means default SUGRA calculation, \texttt{suMODE=2} is SUGRA with true gauge coupling unification at the GUT scale.

GMSB option:

| CompHEP notation | parameters                                      |
|-------------------|-------------------------------------------------|
| \texttt{tb}       | ratio of vacuum expectation value                |
| \texttt{gmLAM}    | $\Lambda$ — SUSY breaking parameter             |
| \texttt{gmMES}    | $M_{\text{MES}}$ messenger mass                 |
| \texttt{gmN5}     | $N_5$ effective number of messenger generations |
| \texttt{gmMU}     | \texttt{sign}($\mu$) - sign of higgsino mass parameter |
| \texttt{gmMODE}   | should be 1 (reserved for extensions)            |

6 Massive fermions of the second generation

There is an extension of the basic CompHEP/SUSY model which takes into account the masses of the fermions of the second generation and the mixing of the corresponding scalar superpartners. We introduce the parameters for trilinear couplings $A_m$, $A_c$, $A_s$ for muon, $c$- and $s$-quarks. The sfermion names and parameters read as:

| flavour          | $\mu$ | $s$ | $c$ |
|------------------|-------|-----|-----|
| fermion          | $m$   | $s$ | $c$ |
| light scalar     | $\tilde{m}_1$ | $\tilde{s}_1$ | $\tilde{c}_1$ |
| heavy scalar     | $\tilde{m}_2$ | $\tilde{s}_2$ | $\tilde{c}_2$ |
| light scalar mass| $M_{\text{SMu1}}$ | $M_{\text{SS1}}$ | $M_{\text{Sc1}}$ |
| heavy scalar mass| $M_{\text{SMu2}}$ | $M_{\text{SS2}}$ | $M_{\text{Sc2}}$ |
| $M_{\text{LL}}$  | $M_{\text{SMuLL}}$ | $M_{\text{SSL}}$ | $M_{\text{ScLL}}$ |
| $M_{\text{LR}}$  | $M_{\text{SMuLR}}$ | $M_{\text{SSLR}}$ | $M_{\text{ScLR}}$ |
| $Z_{\text{1L}}$  | $Z_{122}$ | $Z_{222}$ | $Z_{u22}$ |
| $Z_{\text{2L}}$  | $Z_{125}$ | $Z_{225}$ | $Z_{u25}$ |
| $Z_{\text{1R}}$  | $Z_{152}$ | $Z_{522}$ | $Z_{u52}$ |
| $Z_{\text{2R}}$  | $Z_{155}$ | $Z_{555}$ | $Z_{u55}$ |
| $\theta$         | $M_{\text{SMuth}}$ | $M_{\text{SSth}}$ | $M_{\text{Scth}}$ |
7 R-parity violation

We have implemented in CompHEP the MSSM extension with R-parity violation. We incorporate here only the trilinear terms breaking the leptonic number. The superpotential reads:

\[ W_{RPV} = \lambda_{ijk} \epsilon L_i L_j E_k + \lambda'_{ijk} \epsilon L_i Q_j D_k, \]

where the indices \( i, j, k \) enumerate 3 generation of matter fields.

The CompHEP notation reads \( LL_{ijk} \) for \( \lambda_{ijk} \) and \( Lq_{ijk} \) for \( \lambda'_{ijk} \). A lot of processes were compared with the SUSYGEN package \cite{10} with good agreement. The values for \( \lambda_{ijk} \) should be set twice greater in SUSYGEN than in CompHEP due to the different convention.

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