**HERWIG: an event generator for MSSM processes**

Stefano Moretti  
CERN Theory Division, CH-1211 Geneva 23, Switzerland and  
Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK

**Abstract.** The HERWIG event generator was widely used throughout the workshop, particularly in the emulation of Supersymmetric (SUSY) and Higgs processes in the context of the Minimal Supersymmetric Standard Model (MSSM). We briefly review here its main features in this respect.

**Keywords.** Monte Carlo programs, Event generation, Supersymmetry, MSSM processes

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1. Introduction

HERWIG is a general-purpose Monte Carlo (MC) event generator for high-energy processes, providing a full simulation of hard lepton-lepton, lepton-hadron and hadron-hadron scattering and soft hadron-hadron collisions in a single package, comprising:

- Initial- and final-state QCD jet evolution with soft gluon interference taken into account via angular ordering;
- Colour coherence of (initial and final) partons in all hard subprocesses, including the production and decay of heavy quarks and SUSY particles;
- Spin correlations in the decay of heavy fermions;
- Lepton beam polarisation in selected processes;
- Azimuthal correlations within and between jets due to gluon interference and polarisation;
- A cluster model for jet hadronisation based on non-perturbative gluon splitting, and a similar cluster model for soft and underlying hadronic events;
- A space-time picture of event development, from parton showers to hadronic decays, with an optional colour rearrangement model based on space-time structure.

Several of these features were already present in HERWIG versions 5.1–5.9 and were described accordingly in some detail in Ref. [1]. The HERWIG source codes, together with other useful files and information, can be obtained from the following web site:

[http://hepwww.rl.ac.uk/theory/seymour/herwig/](http://hepwww.rl.ac.uk/theory/seymour/herwig/)
2. The MSSM in HERWIG

Starting from version 6.1 [2], HERWIG includes the production and decay of (s)particles, as given by the MSSM. A detailed description of their implementation can be found in [3], which complements the current HERWIG manual [4]. The last two successive versions are documented in [5].

The HERWIG particle content is listed in Tab. 1. For sparticles that mix, the subscripts label the mass eigenstates in the ascending order of mass. The two Higgs Doublet Model (2HDM) Higgs sector, intrinsic to the MSSM, is also included. The three neutral Higgs bosons are denoted by $h^0$, $H^0$ and $A^0$, whereas the charged ones by $H^\pm$.

| Particle  | Spin | Particle  | Spin |
|-----------|------|-----------|------|
| quark     | $q$  | 1/2 squarks | $\tilde{q}_{L,R}$ 0 |
| charged lepton | $\ell$ | 1/2 charged sleptons | $\ell_{L,R}$ 0 |
| neutrino  | $\nu$ | 1/2 sneutrino | $\tilde{\nu}$ 0 |
| gluon     | $g$  | 1 gluino   | $\tilde{g}$ 1/2 |
| photon    | $\gamma$ | 1 photino | $\tilde{\gamma}$ 1/2 |
| neutral gauge boson | $Z^0$ | 1 zino | $\tilde{Z}$ 1/2 |
| neutral Higgs bosons | $h^0$, $H^0$, $A^0$ | 0 neutral Higgsinos | $\tilde{H}_{1,2}^0$ 1/2 |
| charged gauge boson | $W^\pm$ | 1 wino | $\tilde{W}^{\pm}$ 1/2 |
| charged Higgs boson | $H^\pm$ | 0 charged Higgsino | $\tilde{H}^{\pm}$ 1/2 |
| graviton  | $G$  | 2 gravitino | $\tilde{G}$ 3/2 |

W$^{\pm}$, $H^\pm$ mix to form 2 chargino mass eigenstates $\chi_{1,2}^\pm$
$\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}_{1,2}^0$ mix to form 4 neutralino mass eigenstates $\chi_{1,2,3,4}^0$
$\tilde{t}_L$, $\tilde{t}_R$ (and similarly $\tilde{b}$, $\tilde{\tau}$) mix to form the mass eigenstates $\tilde{t}_{1,2}$

HERWIG does not contain any built-in models for Supersymmetry-breaking scenarios. In all cases the general MSSM particle spectrum and decay tables must be provided just like those for any other particles. A package, ISAWIG, has been created to work with ISAJET [6] to produce a file containing the SUSY particle masses, lifetimes, couplings and mixing parameters. This package takes the outputs of the ISAJET MSSM programs and produces a data file in a format that can be read into HERWIG for the subsequent process generation. The user can produce a similar file provided that the correct format is used. To this end, we invite the consultation of the ISAWIG webpage:

http://www-thphys.physics.ox.ac.uk/users/PeterRichardson/HERWIG/isawig.html

where some example of input files can be found (the SUSY benchmark points recommended in Ref. [7] are already available). Our MSSM conventions are described in [3]. The mass spectrum and decay modes, being read from input files, are completely general, however, the following caveats are to be borne in mind: (i) SUSY particles do not radiate (which is reasonable if their decay lifetimes are much shorter than the QCD confinement scale); (ii) CP-violating SUSY phases are not included.

In addition to the decay modes implemented in the ISAJET package ISAWIG also includes the calculation of all 2-body squark/slepton and 3-body gaugino/gluino R-parity
violating (RPV) decay modes (alas, RPV lepton-gaugino and slepton-Higgs mixing is not considered).

The emulation of RPV processes is also a feature of the production stage. Tab. 2 illustrates all MSSM modes available at present (version 6.4). Here, $\text{IPROC}$ is the input label selecting the hard process.

**Table 2.** The MSSM hard scattering processes implemented in HERWIG.

| $\text{IPROC}$ | $2 \rightarrow 2$ MSSM processes in $\ell^+ \ell^-$ ($\ell = e, \mu$) |
|----------------|---------------------------------------------------------------|
| 700-99         | R-parity conserving SUSY processes                           |
| 700            | $\ell^+ \ell^- \rightarrow 2$-sparticle processes (sum of 710–760) |
| 710            | $\ell^+ \ell^- \rightarrow$ neutralino pairs (all neutralinos) |
| 706+1IN1+IN2   | $\ell^+ \ell^- \rightarrow \chi_m^0 \chi_m^0$ (IN1, 2=neutralino mass eigenstate) |
| 730            | $\ell^+ \ell^- \rightarrow$ chargino pairs (all charginos) |
| 728+2IC1+IC2   | $\ell^+ \ell^- \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^-$ (IC1, 2=chargino mass eigenstate) |
| 740            | $\ell^+ \ell^- \rightarrow$ slepton pairs (all flavours)    |
| 736+5IL        | $\ell^+ \ell^- \rightarrow \tilde{\ell}_L R \tilde{\ell}_L L$ (IL = 1, 2, 3 for $\ell = \tilde{e}, \tilde{\mu}, \tilde{\tau}$) |
| 737+5IL        | $\ell^+ \ell^- \rightarrow \tilde{\ell}_L \tilde{\ell}_L^*$ (IL as above) |
| 738+5IL        | $\ell^+ \ell^- \rightarrow \tilde{\ell}_L \tilde{\ell}_R^*$ (IL as above) |
| 739+5IL        | $\ell^+ \ell^- \rightarrow \tilde{\ell}_R \tilde{\ell}_R^*$ (IL as above) |
| 740            | $\ell^+ \ell^- \rightarrow$ squark pairs (all flavours)      |
| 757+4IQ        | $\ell^+ \ell^- \rightarrow \tilde{q}_L \tilde{q}_L^* R$ (IQ = 1...6 for $\tilde{q} = \tilde{d}...\tilde{t}$) |
| 758+4IQ        | $\ell^+ \ell^- \rightarrow \tilde{q}_L \tilde{q}_L^*$ (IQ as above) |
| 759+4IQ        | $\ell^+ \ell^- \rightarrow \tilde{q}_L \tilde{q}_R^*$ (IQ as above) |
| 760+4IQ        | $\ell^+ \ell^- \rightarrow \tilde{q}_L \tilde{q}_R^*$ (IQ as above) |

**Table 2.** Continues.

| $\text{IPROC}$ | $2 \rightarrow 2$ MSSM processes in $\ell^+ \ell^-$ ($\ell = e, \mu$) |
|----------------|---------------------------------------------------------------|
| 800-99         | R-parity violating SUSY processes                             |
| 800            | Single sparticle production, sum of 810–840                  |
| 810            | $\ell^+ \ell^- \rightarrow \chi_m^0 \nu_*$, (all neutralinos) |
| 810+IN         | $\ell^+ \ell^- \rightarrow \chi_m^0 \nu_*$, (IN=neutralino mass state) |
| 820            | $\ell^+ \ell^- \rightarrow \tilde{\chi}_1^- e_1^+ $ (all charginos) |
| 820+IC         | $\ell^+ \ell^- \rightarrow \tilde{\chi}_2^- e_1^+$, (IC=chargino mass state) |
| 830            | $\ell^+ \ell^- \rightarrow \tilde{\nu}_e Z^0$ and $\ell^+ \ell^- \rightarrow \tilde{\ell}_1^+ W^-$ |
| 840            | $\ell^+ \ell^- \rightarrow \tilde{\nu}_e h^0 / A^0$ and $\ell^+ \ell^- \rightarrow \tilde{\ell}_1^+ H^-$ |
| 850            | $\ell^+ \ell^- \rightarrow \tilde{\nu}_e \gamma$            |
| 860            | Sum of 870 and 880                                          |
| 870            | $\ell^+ \ell^- \rightarrow \ell^+ \ell^-$, via LLE only     |
| 867+3IL1+IL2   | $\ell^+ \ell^- \rightarrow \ell^+ \ell^+$ (IL1, 2=1,2,3 for $\ell = e, \mu, \tau$) |
| 880            | $\ell^+ \ell^- \rightarrow dd$, via LLE and LQD             |
| 877+3IQ1+IQ2   | $\ell^+ \ell^- \rightarrow d d \tilde{l}_1 \tilde{l}_2^*$ (IQ1, 2=1,2,3 for $d, s, b$) |

**Table 2.** Continues.

| $\text{IPROC}$ | $2 \rightarrow 2$ MSSM processes in hadron-hadron |
|----------------|---------------------------------------------------------------|
| 3000-9999      | R-parity conserving SUSY processes                           |
| 3000           | 2-parton $\rightarrow$ 2-sparticle processes (sum of those below) |
| 3010           | 2-parton $\rightarrow$ 2-sparton processes                  |
| 3020           | 2-parton $\rightarrow$ 2-gaugino processes                  |
| 3030           | 2-parton $\rightarrow$ 2-slepton processes                  |
Table 2. Continues.

| PROC   | 2→2 MSSM Higgs processes in hadron-hadron                                                                 |
|--------|------------------------------------------------------------------------------------------------------------|
| 4000   | R-parity violating SUSY processes via LQD                                                                  |
| 4000   | single particle production, sum of 4010–4050                                                             |
| 4010   | $\bar{u}_i d_k \rightarrow \chi_i^0 l_i^+, d_j d_k \rightarrow \chi_j^0 \nu_j$ (all neutralinos)            |
| 4010+IN| $\bar{u}_i d_k \rightarrow \chi_i^0 l_i^+, d_j d_k \rightarrow \chi_j^0 \nu_j$ (IN=neutralino mass state)   |
| 4020   | $\bar{u}_i d_k \rightarrow \chi_i^- \nu_i$, $d_j d_k \rightarrow \chi_j^- e_j^+$ (all charginos)          |
| 4020+IC| $\bar{u}_i d_k \rightarrow \chi_i^0 \nu_i$, $d_j d_k \rightarrow \chi_j^0 \nu_j$ (IC=chargino mass state) |
| 4040   | $u_i d_k \rightarrow \tilde{\tau}_i^+ Z^0$, $u_j d_k \rightarrow \tilde{\nu}_i W^+$ and $d_j d_k \rightarrow \tilde{\nu}_j W^-$ |
| 4050   | $u_i d_k \rightarrow \tilde{\nu}_i h^0/A^0$, $u_j d_k \rightarrow \tilde{\nu}_i H^+$ and $d_j d_k \rightarrow \tilde{\nu}_j H^-$ |
| 4060   | Sum of 4070 and 4080                                                                                       |
| 4070   | $\bar{u}_i d_k \rightarrow \bar{u}_i d_m$ and $\bar{d}_j d_k \rightarrow \bar{d}_j d_m$, via LQD only       |
| 4080   | $\bar{u}_i d_k \rightarrow \nu_i l_i^+$ and $\bar{d}_j d_k \rightarrow \tilde{l}_j^+ l_j^-$, via LQD and LLE |

Table 2. Continues.

| PROC   | 2→2 MSSM Higgs processes in $\ell^+ \ell^-$ ($\ell = e, \mu$)                                               |
|--------|---------------------------------------------------------------------------------------------------------------|
| 910    | $\ell^+ \ell^- \rightarrow \nu, \bar{\nu} h^0 + e^+ e^-$ $h^0$                                             |
| 920    | $\ell^+ \ell^- \rightarrow \nu, \bar{\nu} H^0 + e^+ e^-$ $H^0$                                             |
| 960    | $\ell^+ \ell^- \rightarrow Z^0 h^0$                                                                          |
| 970    | $\ell^+ \ell^- \rightarrow Z^0 H^0$                                                                          |
| 955    | $\ell^+ \ell^- \rightarrow H^+ H^-$                                                                           |
| 965    | $\ell^+ \ell^- \rightarrow A^0 h^0$                                                                          |
| 965    | $\ell^+ \ell^- \rightarrow A^0 H^0$                                                                          |

Table 2. Continues.

| PROC   | 2→2 MSSM Higgs processes in hadron-hadron                                                                  |
|--------|---------------------------------------------------------------------------------------------------------------|
| 3310,3315| $q\bar{q} \rightarrow W^{\pm} h^0, H^{\pm} h^0$                                                             |
| 3320,3325| $q\bar{q} \rightarrow W^{\pm} H^0, H^{\pm} H^0$                                                             |
| 3335   | $q\bar{q} \rightarrow H^\pm A^0$                                                                            |
| 3350   | $q\bar{q} \rightarrow W^{\pm} H^{\mp}$                                                                     |
| 3355   | $q\bar{q} \rightarrow H^\pm H^{\mp}$                                                                        |
| 3360,3365| $q\bar{q} \rightarrow Z^0 h^0, A^0 h^0$                                                                     |
| 3370,3375| $q\bar{q} \rightarrow Z^0 H^0, A^0 H^0$                                                                     |
| 3410   | $bg \rightarrow b h^0$ + ch. conj.                                                                           |
| 3420   | $bg \rightarrow b H^0$ + ch. conj.                                                                           |
| 3430   | $bg \rightarrow b A^0$ + ch. conj.                                                                           |
| 3450   | $bg \rightarrow t H^-$ + ch. conj.                                                                           |
| 3610   | $q\bar{q}/gg \rightarrow h^0$                                                                               |
| 3620   | $q\bar{q}/gg \rightarrow H^0$                                                                               |
| 3630   | $q\bar{q}/gg \rightarrow A^0$                                                                               |
HERWIG: an event generator for MSSM processes

Table 2. Continues. (For the definition of ISQ, see [5].)

| IPROC | 2 → 3 MSSM Higgs processes in hadron-hadron |
|-------|---------------------------------------------|
| 3100+ISQ | $gg/qar{q} \rightarrow qar{q}^*H^\pm$ |
| 3200+ISQ | $gg/qar{q} \rightarrow qar{q}^*h, H, A$ |
| 3500 | $bq \rightarrow bq'H^\pm + \text{ch. conj.}$ |
| 3710 | $qq' \rightarrow q'q'H^0$ |
| 3720 | $qq' \rightarrow q'q'H^0$ |
| 3810+IQ | $gg + qq \rightarrow Q\bar{Q}h^0$ (IQ for Q flavour) |
| 3820+IQ | $gg + qq \rightarrow Q\bar{Q}H^0$ ( IQ ) |
| 3830+IQ | $gg + qq \rightarrow Q\bar{Q}A^0$ ( IQ ) |
| 3839 | $gg + qq \rightarrow b\bar{b}H^0 + \text{ch. conjg.}$ |
| 3840+IQ | $gg \rightarrow Q\bar{Q}h^0$ ( IQ as above) |
| 3850+IQ | $gg \rightarrow Q\bar{Q}H^0$ ( IQ ) |
| 3860+IQ | $gg \rightarrow Q\bar{Q}A^0$ ( IQ ) |
| 3869 | $gg \rightarrow b\bar{b}H^0 + \text{ch. conjg.}$ |
| 3870+IQ | $qq' \rightarrow Q\bar{Q}h^0$ ( IQ as above) |
| 3880+IQ | $qq' \rightarrow Q\bar{Q}H^0$ ( IQ ) |
| 3890+IQ | $qq' \rightarrow Q\bar{Q}A^0$ ( IQ ) |
| 3899 | $qq' \rightarrow b\bar{b}H^0 + \text{ch. conjg.}$ |

The Matrix Elements (MEs) used for the hard scatterings have been listed in [3], with the treatment of the different colour connections in SUSY QCD processes described in [8] (which also supersedes the standard QCD algorithm of [1]).

Spin correlations are available in processes where SUSY particles are produced (and top quarks and $\tau$ leptons as well), as described in [9]. Whenever these particles decay, 3- and 4-body MEs are used to describe their dynamics (with or without the spin correlations). In the case of $\tau$ leptons, an interface to TAUOLA [10] is also available.

Finally, polarisation has been implemented for incoming leptonic beams in SUSY processes. These effects are included both in the production of SUSY particles and via the spin correlation algorithm in their decays.

References

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