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HERWIG 6.3 Release Note

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Abstract

A new release of the Monte Carlo program HERWIG (version 6.3) is now available. The main new features are new (MRST) built-in parton distribution functions, more SM gauge boson production processes, $2 \to 3$ MSSM Higgs production processes, an option to handle negative event weights, and an interface to the CIRCE beamstrahlung program.

Contents

1 Introduction

The last major public version (6.2) of HERWIG was reported in detail in [1]. In this note we describe the main modifications and new features included in intermediate versions and the latest public version, 6.3.

Please refer to [1] and to the present paper if using version 6.3 of the program.

1.1 Availability

The new program can be obtained from the following web site:

`http://hepwww.rl.ac.uk/theory/seymour/herwig/`

This will temporarily be mirrored at CERN for the next few weeks:

`http://home.cern.ch/seymour/herwig/`

1.2 Increased common block size

To take account of the increased energy and complexity of interactions at LHC and future colliders, the default value of the parameter `NMXHEP`, which sets the array sizes in the standard `/HEPEVT/` common block, has been increased to 4000.

1.3 ISAWIG update

ISAWIG is an interface which allows SUSY spectra and decay tables generated by ISAJET [2] to be read into HERWIG. A new version (1.104) of ISAWIG which works with ISAJET7.51 and includes pions for AMSB models has been released. (Note: we have been unable to generate SUGRA point 6 with this version of ISAJET.)

The previous version of ISAWIG, 1.103, fixed a bug in chargino and sfermion mixing matrices. The problem was in the conversion between the convention of ISAJET and Haber and Kane.

For fuller details see the ISAWIG web site:

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

2 New Parton Distribution Functions

The default parton distributions in HERWIG were very old and did not include fits to any of the HERA data. In the past users could link to PDFLIB in order to use more recent PDFs. However as this no longer seems to be maintained several new PDFs have been included in the new version.

`NSTRU`	Description
6	Central α_S and gluon leading-order fit of [3]
7	Higher gluon leading-order fit of [3]
8	Average of central and higher gluon leading-order fits of [3]

It should be noted that we have only added leading-order fits because the evolution algorithms in HERWIG, in particular the backward-evolution algorithm for initial-state parton showering, are only leading-order and therefore inconsistencies could occur with next-to-leading-order distributions.

The new default structure function set `NSTRU`=8 is the average of two of the published fits [3], because this has been found [4] to be closer to the central value of more recent next-to-leading-order fits. The other fits can then be used to assess the effects of varying the high-x gluon.

3 New Processes

3.1 New gauge boson production processes

Standard Model gauge boson production gives rise to important backgrounds for new physics searches at LHC. Two new classes of processes are included.

3.1.1 IPROC=2800–2825: Gauge boson pair production

The code already included in HERWIG for $e^+e^- \to$ WW/ZZ [5] was adapted for hadron-hadron collisions, including photons and the photon/Z interference for the resonant diagrams.

IPROC	Process
2800	WW production in hadron-hadron collisions
2810	ZZ production in hadron-hadron collisions (including photon terms)
2815	ZZ production in hadron-hadron collisions (Z only)
2820	WZ production in hadron-hadron collisions (including photon terms)
2825	WZ production in hadron-hadron collisions (Z only)

All of these processes use a cut `EMMIN` (default value 20 GeV) on the mass of the gauge bosons produced. The cut `PTMIN` (default 10 GeV) on the transverse momentum of the bosons is also used. Both these cuts should not be taken to zero simultaneously if photon terms are included. The phase space for these processes contains a number of peaks and it was therefore necessary to use an adaptive multi-channel phase-space integration method which is described below.

A number of new subroutines, given in Table 1, were added for these processes.

3.1.2 IPROC=2900–2916: $ZQ\bar{Q}$ production

IPROC	Process
2900+`IQ`	$gg + q\bar{q} \to ZQ\bar{Q}$ for massless Q and $\bar{Q}$ (`IQ`=1…6 for $Q = d \ldots t$)
2910+`IQ`	$gg + q\bar{q} \to ZQQ$, for massive Q and Q (`IQ`=1…6 for $Q = d \ldots t$)

The matrix elements of [6] were used for the massless case and an independent calculation, using the approach of [7], which was checked both for gauge invariance and against the massless case for the massive result.

In both cases the decay of the Z is fully included and is selected using `MODBOS`. `PTMIN` controls the minimum transverse momentum of the outgoing quarks. As with gauge boson pair production it was necessary to use an optimized multi-channel phase-space integrator which is described below.

A number of new subroutines, given in Table 1, were added for these processes.

3.1.3 Optimized phase space

The phase space for both gauge boson pair production and $ZQ\bar{Q}$ is complicated, as these processes are both treated as $2 \to 4$ processes. In order to obtain a reasonable efficiency it was necessary to adopt a multi-channel approach based on that described in [8, 9].

In each case a number of different channels are included which attempt to map the phase space for the different processes. The default weights for these different channels have been chosen to optimize the efficiency for the Tevatron and LHC; a choice of which to use is made based on the beam energy. However, the choice is affected by the phase space cuts applied. Therefore if these are significantly altered the weights for the different channels need re-optimizing.

This is controlled by the new variable `OPTM` (default `.FALSE.`). If `OPTM=.TRUE.`, before performing the initial search for the maximum weight HERWIG will attempt to optimize the efficiency using the procedure suggested in [9].

This is done by generating IOPSTP (default 5) iterations of IOPSH (default 100000) events. The choice of IOPSTP and IOPSH is a compromise between run time and accuracy. The value of IOPSH should not be significantly reduced because the procedure attempts to minimize the error on the Monte Carlo evaluation of the cross section and if IOPSH is small the error on the error can be significant. If you need to re-optimize the weights we would recommend a long run just to optimize the weights which can then be used in all the runs to generate events. The new subroutine HWIPHS was added to initialize the phase space.

3.2 New $2 \to 3$ MSSM Higgs production processes

A large number of final states involving the production of both neutral and charged Higgs bosons of the Minimal Supersymmetric Standard Model (MSSM) have been made available in version 6.3. They all proceed via $2 \to 3$ body hard scattering subprocesses. They are listed below, with corresponding process numbers (IQ and ISQ are as detailed in the following subsections). Further details of their implementation can be found in [10].

The new subroutines introduced to administer the following processes are HWHIBQ and HWH2BH for IPROC=3500, plus HWHISQ and HWH2SH for IPROC=3100, 3200. In addition, HWHIGQ has been modified to accommodate the IPROC=3800 series. Finally, the matrix element NME=200, describing the $1 \to 3$ body heavy-quark decays via a virtual $H^\pm$ boson is now available and a new function, HWDHWT, has been introduced to this end. This can be used to emulate e.g. $t \to bH^+(\to f\bar{f}')$ decays.

IPROC	Process
3100+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}'^* H^\pm$ (ISQ=IPROC−3100 as from first table below)
3200+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}'^* h, H, A$ (ISQ=IPROC−3200 as from second table below)
3500	$bq \to bq'H^\pm$ + ch. conj.
3710	$q\bar{q} \to q'\bar{q}'h$
3720	$q\bar{q} \to q'\bar{q}'H$
3810+IQ	$gg + q\bar{q} \to Q\bar{Q}h$ (all q flavours in s-channel, IQ as usual for Q flavour)
3820+IQ	$gg + q\bar{q} \to Q\bar{Q}H$ (")
3830+IQ	$gg + q\bar{q} \to Q\bar{Q}A$ (")
3839	$gg + q\bar{q} \to b\bar{t}H^+$ + ch. conjg. (all q flavours in s-channel)
3840+IQ	$gg \to Q\bar{Q}h$ (IQ as above)
3850+IQ	$gg \to Q\bar{Q}H$ (")
3860+IQ	$gg \to Q\bar{Q}A$ (")
3869	$gg \to b\bar{t}H^+$ + ch. conjg.
3870+IQ	$q\bar{q} \to Q\bar{Q}h$ (all q flavours in s-channel, IQ as above)
3880+IQ	$q\bar{q} \to Q\bar{Q}H$ (")
3890+IQ	$q\bar{q} \to Q\bar{Q}A$ (")
3899	$q\bar{q} \to b\bar{t}H^+$ + ch. conjg. (all q flavours in s-channel)

3.2.1 IPROC=3110–3178: charged Higgs plus squark pair production

The production of charged Higgs bosons of the MSSM in association with squark pairs, of bottom and top flavours only, is implemented via the 3100 series of IPROC numbers, as follows.

`IPROC`	partons	$\to$	spartons	Higgs
3110	$gg+q\bar{q}$	$\to$	$\tilde{q}_i\tilde{q}_j^{'*}$	$H^\pm$
3111	$gg+q\bar{q}$	$\to$	$\tilde{b}_1\tilde{t}_1^*$	H^+
3112	$gg+q\bar{q}$	$\to$	$\tilde{b}_1\tilde{t}_2^*$	H^+
3113	$gg+q\bar{q}$	$\to$	$\tilde{b}_2\tilde{t}_1^*$	H^+
3114	$gg+q\bar{q}$	$\to$	$\tilde{b}_2\tilde{t}_2^*$	H^+
3115	$gg+q\bar{q}$	$\to$	$\tilde{t}_1\tilde{b}_1^*$	H^-
3116	$gg+q\bar{q}$	$\to$	$\tilde{t}_1\tilde{b}_2^*$	H^-
3117	$gg+q\bar{q}$	$\to$	$\tilde{t}_2\tilde{b}_1^*$	H^-
3118	$gg+q\bar{q}$	$\to$	$\tilde{t}_2\tilde{b}_2^*$	H^-

Add 30(60) to `IPROC` for $gg(q\bar{q})$-only initiated processes

Their phenomenological relevance has been discussed in [11].

3.2.2 IPROC=3210–3298: neutral Higgs plus squark pair production

The production of neutral Higgs bosons of the MSSM in association with squark pairs, of bottom and top flavours only, is implemented via the 3200 series of `IPROC` numbers, as follows.

`IPROC`	partons	$\to$	spartons	Higgs
3210(3220)[3230]	$gg+q\bar{q}$	$\to$	$\tilde{q}_i\tilde{q}_j^*$	$h(H)[A]$
3211(3221)[3231]	$gg+q\bar{q}$	$\to$	$\tilde{b}_1\tilde{b}_1^*$	$h(H)[A]$
3212(3222)[3232]	$gg+q\bar{q}$	$\to$	$\tilde{b}_1\tilde{b}_2^*$	$h(H)[A]$
3213(3223)[3233]	$gg+q\bar{q}$	$\to$	$\tilde{b}_2\tilde{b}_1^*$	$h(H)[A]$
3214(3224)[3234]	$gg+q\bar{q}$	$\to$	$\tilde{b}_2\tilde{b}_2^*$	$h(H)[A]$
3215(3225)[3235]	$gg+q\bar{q}$	$\to$	$\tilde{t}_1\tilde{t}_1^*$	$h(H)[A]$
3216(3226)[3236]	$gg+q\bar{q}$	$\to$	$\tilde{t}_1\tilde{t}_2^*$	$h(H)[A]$
3217(3227)[3237]	$gg+q\bar{q}$	$\to$	$\tilde{t}_2\tilde{t}_1^*$	$h(H)[A]$
3218(3228)[3238]	$gg+q\bar{q}$	$\to$	$\tilde{t}_2\tilde{t}_2^*$	$h(H)[A]$

Add 30(60) to `IPROC` for $gg(q\bar{q})$-only initiated processes

Their phenomenological relevance has been discussed in [11, 12].

3.2.3 IPROC=3500: charged Higgs boson from bq-initiated processes

This process is relevant for charged Higgs scalar production at large $\tan\beta$ values, see [13].

3.2.4 IPROC=3710–3720: neutral Higgs production via weak boson fusion

These processes are the MSSM counterparts of the SM process of weak vector-vector fusion in hadronic collisions (`IPROC`=1900). They are computed using the same subroutines and setting the Φ^0VV couplings to $\sin(\beta-\alpha)$ for $\Phi^0=h^0$ (`IPROC`=3710) and to $\cos(\beta-\alpha)$ for $\Phi^0=H^0$ (`IPROC`=3720), respectively, where $V=W^\pm,Z^0$. (There is no A^0VV coupling at tree level.)

These reactions are two of the major direct production channels of neutral CP-even Higgs bosons of the MSSM at hadron colliders, such as the LHC (see e.g. [14]).

3.2.5 IPROC=3811–3899: Higgs boson plus heavy quark pair production

For the case of neutral Higgs states, `IPROC`=3810+`IQ` corresponds to h^0 production, `IPROC`=3820+`IQ` to H^0 and `IPROC`=3830+`IQ` to A^0. (For the last case, the variable `PARITY` is set to -1.) Note also the production of charged Higgs states, via `IPROC`=3839, 3869 and 3899, in association with pairs of top-bottom quarks.

In the usage of the `IPROC` numbers corresponding to neutral Higgs states, when b-quarks are involved in gg-fusion modes (`IPROC`(+30)=3845, 3855 or 3865), the user should take care to avoid double-counting the chosen process with the corresponding $2 \to 1$ and $2 \to 2$ cases of `IPROC`=3610–3630 and `IPROC`=3410–3430 initiated by quark-antiquark annihilation, i.e. $b\bar{b} \to$ Higgs, and (anti)quark-gluon scattering, i.e. $bg \to b$ Higgs, respectively: see [15]. Similar arguments hold for the charged Higgs states, as the gg-induced process (`IPROC`(+30)=3869) is an alternative implementation of `IPROC`=3450 [16].

The associate production of neutral Higgs bosons (both CP-even and CP-odd) of the MSSM with heavy $Q\bar{Q}$ pairs ($Q = b$ and t) is of extreme phenomenological relevance as a discovery mode of Higgs scalars, both at the Tevatron (Run 2) and the LHC (see e.g. [14, 17]), as is the case of the charged Higgs channel [16, 18].

4 Negative Weights Option

A Monte Carlo program generates N_w weights $\{w_i\}$ such that the estimated cross section is

$$\sigma = \frac{1}{N_w}\sum_{i=1}^{N_w} w_i \equiv \overline{w}\ . \tag{1}$$

The corresponding error depends on the width of the weight distribution:

$$\frac{\delta\sigma}{\sigma} = \frac{1}{\sqrt{N_w}}\frac{\delta w_{\rm rms}}{\overline{w}}\ . \tag{2}$$

If only *positive weights* are generated, and there exists a maximum weight $w_{\max}$, then *unweighted* events can be generated by 'hit and miss': $w_i' = 0$ or 1 with probability $P(w_i' = 1) = w_i/w_{\max}$. Then

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{w_{\max}-\overline{w}}{N_w\overline{w}}} = \sqrt{\frac{w_{\max}-\overline{w}}{N_e w_{\max}}} \sim \frac{1}{\sqrt{N_e}} \tag{3}$$

where $N_e = N_w\overline{w}/w_{\max}$ is the number of *events* generated. The time needed (especially for detector simulation) depends mainly on the number of events. Hence the inefficiency of 'hit and miss' is not necessarily a disaster. This is the usual approach adopted in Monte Carlo event generators.

Negative weights can be generated by subtraction procedures for matrix element corrections. These are not a problem of principle but prevent naive 'hit and miss'. To generalize 'hit and miss', one can generate unweighted events ($w_i' = 1$) and 'antievents' ($w_i' = -1$) with

$$\begin{aligned} \mathrm{sign}(w_i') &= \mathrm{sign}(w_i)\ , & (4)\\ P(w_i' = \pm 1) &= |w_i|/|w|_{\max}\ . & (5) \end{aligned}$$

Then

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\overline{|w|}|w|_{\max}-\overline{w}^2}{N_w\overline{w}^2}} \sim \frac{1}{\sqrt{N_e}}\frac{\overline{|w|}}{\overline{w}} \tag{6}$$

where $N_e = N_w\overline{|w|}/|w|_{\max}$ is now the total number of *events+antievents* generated. Again, the time needed is almost proportional to N_e, so this is tolerable as long as $\overline{|w|} \sim \overline{w}$. The cross section after any cuts that may be applied is

$$\sigma_c = \frac{\overline{|w|}}{N_e}(N_+ - N_-) \tag{7}$$

where N_+ events and N_- antievents pass the cuts.

To allow for the possibility of negative weights, a new logical parameter `NEGWTS` has been introduced. The default (`NEGWTS=.FALSE.`) is as before: negative weights are forbidden. If one is detected, a non-fatal warning is issued and the event weight is set to zero.

If `NEGWTS=.TRUE.`, negative weights are allowed. Statistics are computed and printed accordingly. If unweighted events are requested (`NOWGT=.TRUE.`), the initial search stores the maximum and mean absolute weights, $|w|_{\max}$ and $\overline{|w|}$. Events and antievents are selected according to Eqs. (4,5) and `EVWGT` is reset to $\overline{|w|}\mathrm{sign}(w_i)$, so that the numerator in Eq. (7) is the sum of `EVWGT`s for contributing (anti)events.

5 CIRCE Interface

Simulation of beamstrahlung is now available, via an interface to the CIRCE program [19]. It is implemented as a modification of the standard bremsstrahlung implementation, so is only available for processes for which that is available. The produced radiation is treated in the collinear limit, i.e. `COLISR` and the option `WWA` in routine `HWEGAM` are forcibly set `.TRUE.`.

For both types of distribution function, $f_{e/e}$ and $f_{\gamma/e}$, we use a simplifying approximation: where the correct result should use the convolution of beamstrahlung and bremsstrahlung, we actually use the sum of the two. For the photon distribution this is quite reasonable, but for the electron it is perhaps more questionable. It boils down to the replacement:

$$f_{e/e}(x) = \int_x^1 \frac{dz}{z} f_{e/e,\mathrm{brem}}\Big(z\Big) f_{e/e,\mathrm{beam}}\Big(\frac{x}{z}\Big) \to f_{e/e,\mathrm{brem}}(x) + f_{e/e,\mathrm{beam}}(x) - \delta(1-x). \tag{8}$$

This is good to the extent that both distributions are dominated by the $x \to 1$ region. A small utility program can be obtained from the HERWIG web page to test this approximation. For example, for TESLA running at 500 GeV, the integral over $f_{e/e}(x)$ for large x, relevant for threshold shapes, is accurate to 1% for $x > 0.95$ and to 10% for $x > 0.99$, and the value of $f_{e/e}((\frac{90}{500})^2)$, relevant for radiative return to the Z, is accurate to 2%.

In order for the distribution to be probabilistic, the coefficient of the delta function has to remain positive. If it is not, HERWIG will terminate. This can be prevented by adjusting the `ZMXISR` parameter: the default value, `ZMXISR`=0.999999 is too large and HERWIG will fail, but reducing it to `ZMXISR`=0.99999 works fine for all the parameter sets currently available. It is straightforward to check that `ZMXISR` values in this range do not have an influence on any physical observables, by rerunning with it further reduced.

The interface is controlled by five new variables, which are given in the following table together with their default values:

`CIRCOP`	0
`CIRCAC`	2
`CIRCVR`	7
`CIRCRV`	9999 12 31
`CIRCCH`	0

CIRCOP is the main control option: CIRCOP=0 switches off beamstrahlung and uses standard HERWIG; CIRCOP=1 switches to collinear kinematics, but still leaves beamstrahlung switched off; CIRCOP=2 uses only beamstrahlung; and CIRCOP=3 uses both beamstrahlung and bremsstrahlung. CIRCOP=0 and CIRCOP=3 should therefore be regarded as 'off' and 'on', respectively, with the other two options mainly for cross-checking purposes. The variables CIRCAC, CIRCVR, CIRCRV and CIRCCH are simply passed to CIRCE as its input variables acc, ver, rev and chat, as described in its documentation. The default values correspond to the most up-to-date revision of version 7 of the TESLA parametrization, with minimal output.

CIRCE can be obtained from

http://heplix.ikp.physik.tu-darmstadt.de/nlc/beam.html

6 Minor Changes and Bug Fixes

- In the INCLUDE file, common blocks have been regrouped so that all commons that were present in version 6.1 are unchanged. All new variables since version 6.1 are in /HWGRAV/, /HWPMRS/, /HWCIRC/, /HW6202/, /HW6203/ or /HW6300/. From now on all common blocks will be frozen and new variables introduced in version x.yyy will be put in a new common block /HWxyyy/.
- In HWHDYP lepton mass effects are corrected.
- In HWHIGS a factor of 2 excess in the cross section for Higgs production by gluon or quark fusion is corrected.
- In HWUDKL safety against numerical overflows for long-lived particles is improved.
- In HWUMBW Breit-Wigner smearing of W and Z boson masses is enabled.
- A work-around to overcome problems with the new DEC UNIX Fortran compiler has been implemented.
- In IPROC=3610–30, top quark decays now take place. Previously tops produced in these processes were missed by the decayer and formed top hadrons. In addition, changes in the value of IPROC during generation of these processes have been eliminated.
- Gluon spin correlations have been corrected in $gg \to A^0$ (IPROC=3630) and implemented in $gg \to$ Graviton (IPROC=4200 etc.).
- Underlying event suppression by IPROC→IPROC+10000 is now enabled in all SUSY processes.
- CKM matrix element bugs in W+Higgs and heavy quark+Higgs production (IPROC/100=33,34) have been corrected.
- The default maximum number of errors in event generation is now set to MAX(10,MAXEV/100).
- A dummy time subroutine TIMEL has been included. It should be deleted and replaced by a system or CERN Library routine giving TRES= CPU time remaining (seconds) if this is needed, e.g. to terminate batch jobs. The dummy returns TRES=10^{10}.

Routine	Description
CIRCEE	Dummy CIRCE routine – delete if using CIRCE
CIRCES	Dummy CIRCE routine – delete if using CIRCE
CIRCGG	Dummy CIRCE routine – delete if using CIRCE
HWDHWT	Subroutine for top decay via a virtual $H^{\pm}$
HWH2BH	Matrix element for $H^{\pm}$ production via bq-fusion
HWH2DD	Function to return the D function of [6]
HWH2F1	Subroutine to return the F function of [7] for a fixed first momentum
HWH2F2	Subroutine to return the F function of [7] for a fixed second momentum
HWH2F3	Subroutine to return the F function of [7] for all first and second momenta
HWH2M0	Subroutine to compute the massless matrix element for $Q\bar{Q}Z$
HWH2MQ	Subroutine to compute the massive matrix element for $Q\bar{Q}Z$
HWH2PS	Subroutine to perform the phase-space for Z+two jets
HWH2P1	Subroutine to select quark masses for HWH2PS
HWH2P2	Subroutine to select quark masses for HWH2PS
HWH2SH	Matrix element for squark pair plus Higgs production
HWH2SS	Subroutine to return the S function of [6]
HWH2T1	Function to return the T_1 function of [6]
HWH2T2	Function to return the T_2 function of [6]
HWH2T3	Function to return the T_3 function of [6]
HWH2T4	Function to return the T_4 function of [6]
HWH2T5	Function to return the T_5 function of [6]
HWH2T6	Function to return the T_6 function of [6]
HWH2T7	Function to return the T_7 function of [6]
HWH2T8	Function to return the T_8 function of [6]
HWH2T9	Function to return the T_9 function of [6]
HWH2T0	Function to return the T_{10} function of [6]
HWHDYQ	Subroutine for $Q\bar{Q}Z$
HWHGBP	Main routine for gauge boson pair production in hadron-hadron
HWHGBS	Phase space for gauge boson pair production in hadron-hadron
HWHGB1	Selects gauge boson mass for HWHGBS
HWHGB2	Matrix element for WW in hadron-hadron
HWHGB3	Matrix element for ZZ in hadron-hadron
HWHGB4	Matrix element for WZ in hadron-hadron
HWHGB5	Selects t and u for HWHGBS
HWHIBQ	Subroutine for $H^{\pm}$ production via bq-fusion
HWHISQ	Subroutine for squark pair plus Higgs production
HWHV2J	Master subroutine for all gauge boson + two jet processes
HWIPHS	Subroutine to initialize the optimized phase space
HWSMRS	Subroutine for MRST PDFs
TIMEL	Dummy time subroutine – see Sect. 6

Table 1: New subroutines for version 6.3.

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