HERWIG for Hadron-Hadron Physics

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Abstract

HERWIG is a general-purpose particle physics event generator, which includes the simulation of any combination of hard lepton, hadron or photon scattering and soft hadron-hadron collisions in one package. It uses the parton-showrer approach for initial-state and final-state QCD radiation, including colour coherence effects and azimuthal correlations both within and between jets.

This article describes HERWIG version 5.6, and gives a brief review of the physics underlying HERWIG, with particular emphasis on hadron-hadron collisions. Details are given of the input and control parameters used by the program.

Program Summary

Name: HERWIG (for Hadron Emission Reactions With Interfering Gluons).
Current version: 5.6, released January 1993.
Main reference: Version 5.1 was described in [1]. Developments since then are listed below.
Size: Approx. 14000 lines of Fortran source code.
Type: Parton shower with cluster fragmentation and soft underlying event models, plus a library of hard sub-processes.

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1 Introduction

HERWIG is a general-purpose event generator for high energy hadronic processes, with particular emphasis on the detailed simulation of QCD parton showers. The program has the following special features:

- Simulation of any combination of hard lepton, hadron or photon scattering and soft hadron-hadron collisions in one package.
- Colour coherence of partons (initial and final) in hard subprocesses.
- Heavy flavour hadron production and decay with QCD coherence effects.
- QCD jet evolution with soft gluon interference via angular ordering.
- Backward evolution of initial-state partons including interference.
- Azimuthal correlations within and between jets due to interference.
- Azimuthal correlations within and between jets due to gluon polarization.
- Cluster hadronization of jets via non-perturbative gluon splitting.
- A similar cluster model for soft and underlying hadronic events.

The program operates by setting up parameters in common blocks and then calling a sequence of subroutines to generate an event. Parameters not set in the main program HWIGPR are set to default values in the main initialization routine HWIGIN.

To generate events the user must first set up the beam particle names PART1, PART2 (type CHARACTER*4) in the common block /HWBEAM/, and the beam momenta PBEAM1, PBEAM2 (in GeV/c), a process code IPROC and the number of events required MAXEV in /HWPROC/. See Sect. 5 for beams and processes available.

All analysis of generated events (histogramming, etc.) should be performed by the user-provided routines HWABEG (to initialize), HWANAL (to analyse an event) and HWAEND (to terminate). The default HWANAL subroutine writes event and jet information and stable particle data on unit LWEVT defined in HWIGIN (or simply returns if LWEVT = 0). See HWANAL for details of event information written.

A detailed event summary is printed out for the first MAXPR events (default MAXPR = 1). Set IPRINT = 2 to list the particle identity codes and (simplified) particle decay schemes used in the program.

The programming language is standard Fortran 77 as far as possible. However, the following may require modification for running on computers other than Vax's:

- Most common blocks are inserted by INCLUDE 'HERWIG56.INC' Vax Fortran statements (see the documentation file for contents of HERWIG56.INC).
- Many common blocks are initialized by BLOCK DATA HWUDAT. Although BLOCK DATA is standard Fortran 77, it can cause linkage problems for some systems.
- Subroutine HWUTIM (returning CPU time left) is machine dependent.

If you use HERWIG, please always quote the version number, as the program is continuously evolving, and results obtained with one version may be improved (or worsened) in later versions. The subject of how to reference the program and the various aspects of the model is discussed in the final section of this report.
2 Physics Underlying HERWIG

The physics that underlies the original program was presented in detail in Ref. [2]. More recent improvements are discussed in Refs. [3-9]. Other relevant theoretical background may be found in Refs. [10-14]. We limit ourselves here to a review of the key components of the program and their theoretical basis.

The main theoretical justification for QCD Monte Carlo simulations lies in the factorization theorems for hard processes. This property is illustrated in Fig. 1 for the process \( pp \rightarrow W^+ + X \), with \( W^+ \rightarrow t\bar{b} \). Quarks and antiquarks are represented by single colour lines, gluons by double lines (the so-called planar approximation). Dotted lines represent colour-singlet particles (W bosons or leptons). Note that Fig. 1 is not a Feynman diagram: it represents the coherent sum of many real and virtual diagrams which are summed by the branching algorithm.

A process such as that in Fig. 1 can be factorized into the following subprocesses.

1. **Final state emission.** An outgoing virtual parton with large time-like mass generates a shower of partons with lower virtuality. The amount of emission depends on the upper limit on the virtual mass of the initiating parton, which is controlled by the momentum transfer scale \( Q \) of the hard subprocess, to be discussed below.

2. **Initial state emission.** A parton constituent of an incident hadron with low space-like virtuality radiates time-like partons. In the process it decreases its energy to a fraction \( x \) of that of the hadron, and increases its space-like virtual mass. This mass is bounded in absolute value by the scale \( Q \) of the hard subprocess. The initial state emission process leads to the evolution of the structure function \( F(x, Q) \) of the incident hadron.

3. **Elementary hard subprocess.** This can be computed exactly to finite order in perturbation theory. For the process of Fig. 1 it is given by the \( q\bar{q} \rightarrow W \rightarrow q\bar{q} \) amplitude squared. The hard subprocess momentum transfer scale \( Q \), given here by the mass of the virtual \( W^+ \), sets the boundary conditions for the initial and final state parton showers. A large variety of QCD and electroweak hard processes have the same basic structure as in Fig. 1, with different elementary subprocess matrix elements.

4. **Hadronization process.** In order to construct a realistic simulation one needs to convert the partons into hadrons. This process takes place at a low momentum transfer scale, for which the strong coupling \( \alpha_s \) is large and perturbation theory is not applicable. Therefore we need to add to the above perturbative QCD processes a phenomenological hadronization model which fortunately (see later) does not conceal the perturbative structure.

An important consequence of the factorization theorem is that the distributions for any hard QCD process are obtained from the same four subprocesses described above. In lepton-lepton collisions we have only to consider the elementary and final state emission subprocesses, while in lepton-hadron collisions we need to consider also the emission from one incoming parton. In hadron-hadron collisions there is emission from two incoming partons: one from each hadron. In addition, in processes involving incoming hadrons there may be soft emission due to the presence of 'spectator' partons.

As a consequence of factorization, one can construct a single Monte Carlo program, such as HERWIG, which can in principle simulate all hard processes. The main theoretical advantage of a such a universal program is that the phenomenological parameters in the hadronization
model can be tuned simultaneously by fitting data at different machines and energies. This enhances the predictive power of the program.

If one studies only totally inclusive quantities, the hard process of Fig. 1 is infrared finite. However we are interested also in exclusive distributions and for these we need to introduce a cutoff. In HERWIG this is done by requiring that the partons are emitted with a transverse momentum larger than some finite value $Q_0$, which is selected in such a way that $\alpha_s(Q_0)$ is still a small number. (In fact the cutoff depends on the type of parton involved, as explained in Sect. 6, but we can take $Q_0$ here to represent the smallest cutoff.) As observed in some next-to-leading analyses [15], a transverse momentum cutoff corresponds to the MS scheme for the regularization of QCD.

In the Monte Carlo simulation one describes the entire process, within the resolution implied
by the cutoff $Q_0$, at the exclusive level. This can be done because the final and initial state emission processes also have a factorized structure, as we shall illustrate. Factorization in these cases holds to the leading order in collinear and infrared logarithms. However, as we shall recall, for some important distributions factorization can be extended beyond leading order.

We now discuss the above subprocesses separately in more detail.

### 2.1 Final state emission

Parton emission factorizes as a successive branching process which is characterized by the following properties:

1. The energy fractions are distributed according to the Altarelli-Parisi splitting functions.
2. The full available phase space is restricted to an angular-ordered region. Such a restriction is the result of interference and takes leading infrared singularities correctly into account. At each branching, the angle between the two emitted partons is smaller than that of the previous branching.
3. The emission angles are distributed according to the Sudakov form factors, which sum the virtual corrections. The Sudakov form factor normalizes the branching distributions to give the probabilistic interpretation needed for a Monte Carlo simulation. This fact is a consequence of field theory, in particular of unitarity and of the infrared finiteness of inclusive quantities.
4. The azimuthal angular distribution in each branching is determined by two effects: a) for a soft emitted gluon the azimuth is distributed according to the eikonal dipole distribution [2]; b) for non-soft emission one finds azimuthal correlations due to spin effects. See [3-5] for the method used to implement these correlations in full, to leading collinear logarithmic accuracy, in HERWIG.
5. In each branching the scale of $\alpha_s$ is the relative transverse momentum of the two emitted partons.
6. In the case of heavy flavour production the mass of the quark modifies the angular-ordered phase space. The most important effect is that the soft radiation in the direction of the heavy quark is depleted. One finds that the emission within an angle of order $M/E$ vanishes (with $M$ and $E$ the mass and energy of the heavy quark emitting the soft gluon). This angular screening determines [6,16,17] the shape of the heavy flavour jet, which could prove to be an important signature. The angular screening can easily be taken into account in the coherent branching algorithm and is consistently included in HERWIG [6].

A branching algorithm characterized by the above properties will be called coherent final state branching and, in general, gives parton distributions which are correct to leading infrared order. In particular this algorithm correctly described inter-jet distributions such as the string effects in three-jet events [18].

The coherent branching correctly describes [19-21] also the next-to-leading corrections to the distributions of soft partons, i.e. partons with momentum small compared with the hard scale $Q$ but still large compared with the QCD scale $\Lambda_{\overline{MS}}$. This fact is very important because the perturbative expansion for these distributions is singular. Therefore the next-to-leading corrections are large and for a reliable calculation at present energies they need to be taken into account. The importance of the next-to-leading contributions is clear in the LEP data on the multiplicity and inclusive distributions in the soft region [22].

In the literature one can find different prescriptions for the branching subprocess (with different phase space and/or argument of $\alpha_s$, or without the angular screening due to the heavy quark mass). Some of these algorithms are based on old and partial results of perturbative QCD studies, and do not give the correct results even to leading infrared order.
2.2 Initial state emission

The theoretical analysis of this process is more complex than for the final-state case. Even to leading order, the structure function and associated radiation have only been analyzed quite recently for small \( x \) [23], \( x \) being the energy fraction of the incoming parton after the emission of initial state radiation. For lepton-hadron processes \( x \) corresponds to the Bjorken variable, while for hadron-hadron processes \( x \) is related to \( Q^2/\hat{s} \).

The main result is that for any value of \( x \), even for \( x \to 0 \), the initial state emission process factorizes and can be described as a branching process suitable for Monte Carlo simulations, which we shall call coherent initial state branching. The properties which characterize this branching include all the properties discussed above for the final state emission. In the initial state emission the angular ordering restriction of the phase space (point 2 in the previous list) applies to the angles \( \theta_i \) between the incoming hadron and the emitted time-like partons \( i \).

In the case of small values of \( x \), the initial state branching process has the following additional properties, which are however not yet fully included in HERWIG:

7. For small \( x \) there are virtual corrections which are not included in the Sudakov form factors. These corrections are important in the case in which the energy fraction \( z_i \) of an exchanged space-like gluon is soft (\( z_i \to 0 \)). In this case the Altarelli-Parisi splitting function contributes with a singular term of the type \( C_A/z_i \) or \( C_F/z_i \), according to whether the exchanged gluon is generated by a gluon or a quark. These virtual corrections exponentiate, giving a non-Sudakov form factor [23]. The important feature of this form factor is that it screens the \( 1/z_i \) singularity. This is the same effect as that of the Regge trajectory in the Lipatov equation [24].

8. A second important effect in the branching with a soft exchanged gluon is related to the angular ordering. For small \( z_i \) the angular ordering condition \( \theta_{i+1} > \theta_i \) gives \( q_{t,i+1} > q_{t,i} \), where \( q_{t,i} \) is the transverse momentum of the \( i \)-th emission. Therefore for \( z_i \to 0 \) the lower bound on \( q_{t,i+1} \) vanishes, giving singular \( \ln z_i \) contributions. However, these singular terms are cancelled by contributions from the non-Sudakov form factor.

A branching algorithm which includes these properties for small \( x \) leads to a structure function which satisfies the Lipatov equation for \( x \to 0 \) and the Altarelli-Parisi equation for finite \( x \). Such an algorithm has been used to begin the construction of a new Monte Carlo simulation program [25], but much further work is needed before these developments can be included in a fully exclusive event generator.

For the moment, in HERWIG we take into account the fact that the most important singularities at small \( x \), coming from the region \( z_i q_{t,i} < q_{t,i+1} < q_{t,i} \) for \( z_i \to 0 \), are partially cancelled by contributions from the non-Sudakov form factor. Thus we ignore the non-Sudakov form factor and correspondingly reduce the phase space to the \( q_t \)-ordered region \( q_{t,i} < q_{t,i+1} \) for \( z_i \to 0 \). This algorithm corresponds to neglecting non-leading singular contributions but generates an anomalous dimension which is correct in this region up to three loops.

For large \( x \), the coherent branching correctly sums [7] not only the leading but also the next-to-leading contributions. This accuracy allows us to identify the relation between the QCD scale used in the Monte Carlo program and the fundamental parameter \( \Lambda_{\text{MS}} \). This is achieved by using the one-loop Altarelli-Parisi splitting functions and the two-loop expression for \( \alpha_s \) with the following universal relation between the scale parameter \( \Lambda_{\text{MC}} \) used in the simulation and \( \Lambda_{\text{MS}} \):

\[
\Lambda_{\text{MC}} = \exp \left( \frac{67 - 3\pi^2 - 10N_f/3}{2(33 - 2N_f)} \right) \Lambda_{\text{MS}} \sim 1.569 \Lambda_{\text{MS}} \quad \text{for } N_f = 5. \tag{2.1}
\]

Therefore a Monte Carlo simulation with next-to-leading accuracy can be used to determine \( \Lambda_{\text{MS}} \) from semi-inclusive data at large momentum fractions.


2.3 Elementary hard subprocess

In HERWIG version 5.6 there is a fairly large library of QCD and electroweak elementary subprocesses (see Sect. 5).

From the point of view of QCD coherence, the elementary subprocess plays an important role in defining the phase space of the initial and final state branching subprocesses. As we have seen, these branchings are ordered in angle from a maximum to a minimum value. The minimum values is fixed by the cutoff \( Q_0 \), but the maximum value is determined by the elementary subprocess and is due to interference among soft gluons. The general result \([2,19,26]\) is that the initial and final branchings are approximately confined within cones around the incoming and outgoing partons from the elementary subprocess. For the branching of parton \( i \), the aperture of the cone is defined by the direction of the other parton \( j \) which is colour-connected to \( i \).

For a general process there are various contributions with different colour connections. The HERWIG library of elementary subprocesses includes the separate colour connection contributions. See Sect. 3.2 and [2] for discussions of the most complex case, namely the \( 2 \rightarrow 2 \) QCD subprocesses generating two-jet events with high transverse energy. The relation between soft gluon interference and the colour connection structure of the elementary subprocess leads to detectable effects, such as the string effect in three jet events \([18]\) and the correct distribution of a third jet in \( pp \) collisions \([27]\).

Another important function of the elementary subprocess is to set up the polarizations of any electroweak bosons or gluon jets that may be involved. These polarizations give rise to angular asymmetries and correlations in boson decays and jet fragmentation. They are included in HERWIG for most of the subprocesses provided, using the approach of Refs. \([3-5]\) to generate all correlations in jet fragmentation to leading-logarithmic accuracy.

2.4 Hadronization process

For the most complicated hard processes such as that in Fig. 1, we have three type of non-perturbative contributions to consider: (a) the representation of the incoming partons as constituents of the incident hadrons; (b) the conversion of the emitted partons into outgoing hadrons; (c) the ‘underlying soft event’ associated with the presence of spectator partons.

We refer to all of these as aspects of ‘hadronization’. We first recall briefly the relevant features of perturbative field theory, then discuss the models used for (b) and (c) in the following Subsections.

The treatment of the incoming parton is related to the factorization theorem for collinear singularities. The distribution of the parton's longitudinal momentum fraction at a low space-like scale \( Q \), is described by a phenomenological input structure function. The transverse momentum at such a scale has a distribution characteristic of the size of the hadron.

Perturbative studies do not provide information on the confinement mechanism which converts the emitted partons into hadrons below the time-like cutoff scale \( Q_0 \). However, provided this mechanism does actually exist, perturbative QCD predicts \([28,29]\) that in hard processes confinement of partons is local in colour and independent of the hard scale \( Q \). This ‘preconfinement’ property is due to the Sudakov form factor. In QED this form factor depletes the cross section for emission of a single charge without an accompanying cloud of photons, within a given resolution. Similarly, in QCD the Sudakov form factor inhibits the separation of the colour charges forming a singlet. In the emission of jets of partons, one finds \([28]\) in perturbative QCD, as well as in the Monte Carlo simulations \([11]\), that the mass distribution of two partons...
forming a colour singlet is concentrated around values of the order of $Q_0$ and is independent of the hard scale $Q$ for large $Q$.

This property is confirmed by the phenomenological analysis of jet fragmentation by the St. Petersburg group [29]. In this analysis the fragmentation functions for $\pi$, $K$ and $p$ production in $e^+e^-$ annihilation at various high energies $Q$ were compared with the fragmentation function for partons, computed by resumming leading perturbative contributions. The result is that these fragmentation functions are proportional to the parton-fragmentation functions. The proportionality constants $K_\pi$, $K_K$ and $K_p$ are independent of $Q$ and correspond to the hadronization conversion factors from partons to hadrons. Thus partons are converted into hadrons locally in phase space, a property that has been named Local Parton Hadron Duality (LPHD).

2.5 Cluster hadronization model

The preconfinement property is used in HERWIG by assuming a cluster hadronization model which is local in colour and independent of the hard process and the energy [2,12]. After the perturbative parton branching process, all outgoing gluons are split non-perturbatively, as shown in Fig. 1, into light ($u$ or $d$) quark-antiquark or diquark-antidiquark pairs (the default option is to not allow diquark splitting). At this point, each jet consists of a set of outgoing quarks and antiquarks (also possibly some diquarks and antidiquarks), and, in the case of spacelike jets, a single incoming valence quark or antiquark. The latter is replaced by an outgoing spectator carrying the opposite colour and the residual flavour and momentum of the corresponding beam hadron.

As may be seen in Fig. 1, a colour line can now be followed, in the planar approximation, from each quark to an antiquark or diquark with which it can form a colour-singlet cluster. These clusters satisfy the 'pre-confinement' discussed above—they have a distribution of mass and spatial size that peaks at low values, falls rapidly for large cluster masses and sizes, and is asymptotically independent of the hard subprocess scale.

The clusters thus formed are fragmented into hadrons. If a cluster is too light to decay into two hadrons, it is taken to represent the lightest single hadron of its flavour. Its mass is shifted to the appropriate value by an exchange of momentum with a neighbouring cluster in the jet. Those clusters massive enough to decay into two hadrons, but below a fission threshold to be specified below, decay isotropically into pairs of hadrons selected in the following way: a flavour $f$ is chosen at random from among $u, d, s$, the six corresponding diquark flavour combinations, and $c$. For a cluster of flavour $f_1f_2$, this specifies the flavours $f_1f$ and $ff_2$ of the decay products, which are then selected at random from tables of hadrons of those flavours. The hadrons can be $J^P = 0^-, 1^+$ or $2^+$ mesons, or $1^+$ or $2^+$ baryons. For charmed hadrons, some of these states are just educated guesses. For $b$- and $t$-flavoured hadrons, only $J^P = 0^-$ mesons and $\frac{1}{2}^+$ baryons are included, and their binding energies are neglected. No diquark-antidiquark combinations are allowed. The selected choice of decay products is accepted in proportion to the density of states (phase space times spin degeneracy) for that channel. Otherwise, $f$ is rejected and the procedure is repeated. In this way one obtains an unbiased selection of decay products that conserve flavour.

A small fraction of clusters have masses too high for isotropic two-body decay to be a reasonable ansatz, even though the cluster mass spectrum falls rapidly (faster than any power) at high masses. These are fragmented using an iterative fission model until the masses of the fission products fall below the fission threshold. In the fission model the produced flavour $f$
is limited to \( u, d \) or \( s \) and the product clusters \( f_1 f \) and \( f_2 f_2 \) move in the directions of the original constituents \( f_1 \) and \( f_2 \) in their c.m. frame. Thus the fission mechanism is not unlike string fragmentation \([30]\). There are three fission parameters, \( \text{CLMAX} \), \( \text{CLPOW} \) and \( \text{PSPLT} \). The maximum cluster mass parameter \( \text{CLMAX} \) specifies the fission threshold \( M_f \) according to the formula

\[
M_f \text{CLPOW} = \text{CLMAX} \text{CLPOW} + (Q_1 + Q_2) \text{CLPOW}
\]

where \( Q_1 \) and \( Q_2 \) are the virtual mass cutoffs corresponding to flavours \( f_1 \) and \( f_2 \). The parameter \( \text{PSPLT} \) specifies the mass spectrum of the produced clusters, which is taken to be \( M \text{PSPLT} \) within the allowed phase space. Provided the parameter \( \text{CLMAX} \) is not chosen too small (typically it is about 4 GeV), the gross features of events are insensitive to the details of the fission model, since only a small fraction of clusters undergo fission. However, the production rates of high-\( p_t \) or heavy particles (especially baryons) are affected, because they are sensitive to the tail of the cluster mass distribution.

Unstable hadrons from clusters produced in the both the hard and soft components of the event decay according to simplified decay schemes, which can be tabulated by specifying the print option \( \text{IPRINT} = 2 \). All decays are assumed to be quasi-two or -three body and modes are invented where necessary to make the branching ratios add up to 100%. Phase space distributions are assumed except for the decays of \( b \) and \( t \)-flavoured hadrons, for which a spectator model with charged-current decay of the heavy quark is assumed. Note that in the case of top decay the \( t \) quark is assumed to hadronize and depolarize before decaying, only if its mass is less than 130 GeV. Otherwise it decays before cluster formation (see section 3.5). After a \( b \) or \( t \) decay, secondary parton showers are produced by outgoing partons as discussed in Ref. \([6]\); these are hadronized in the same way as primary jets. \( B \) decays can also optionally be performed using the more phenomenological models implemented in the EURODEC and CLEO B decay packages.

### 2.6 Underlying Soft Event

In hadron-hadron and lepton-hadron collisions there are ‘beam clusters’ containing the spectators from the incoming hadrons. In the formation of beam clusters, the colour connection between the spectators and the initial-state parton showers is cut by the forced emission of a soft quark-antiquark pair. The underlying soft event in a hard hadron-hadron collision is then assumed to be a soft collision between the two beam clusters. In a lepton-hadron collision the corresponding ‘soft hadronic remnant’ is represented by a soft collision between the beam cluster and the adjacent cluster, i.e. the one produced by the forced emission mentioned above.

The necessity of adding an underlying soft event to the hard emission described in Subsect. 2.1 and 2.2 was analysed in Ref. \([14]\), in which the “pedestal height” in hadronic jet production, i.e. the mean transverse energy per unit rapidity accompanying a high-transverse-energy jet, was studied. The observed pedestal height and its dependence on jet transverse energy \([31]\) are accounted for by superposing on the hard emission an underlying event structure similar to that of a minimum-bias collision.

The model used for the underlying event is based on the minimum-bias \( pp \) event generator of the UA5 Collaboration \([32]\), modified to make use of our cluster fragmentation algorithm. The model starts from a parametrization of the \( pp \) inelastic charged multiplicity distribution as a negative binomial. As an option, for underlying events the value of \( \sqrt{s} \) used to choose the multiplicity \( n \) may be enhanced by a parameter \( \text{ENSOF} \) to allow for an enhanced underlying activity in hard events. The actual charged multiplicity is then taken to be \( n \) plus the sum of
the moduli of the charges of the colliding hadrons or clusters. Next the clusters are hadronized using the model described above.

If the charged multiplicity from the beam clusters is equal to the selected value, no further clusters are created. If it is greater than the selected value, the beam cluster hadronization is redone. If it is less, 'soft clusters' $q\bar{q}$, $q\bar{q}q$, ..., are created and hadronized until the selected multiplicity is either reached, in which case cluster production stops, or else overshot, in which case the whole procedure is repeated, starting from the beam cluster hadronization.

The produced quarks $q$, that define the flavour of the soft clusters are taken to be $u$ or $d$ only. The cluster masses are chosen from the distribution

$$P(M) \propto (M - M_0) \exp\left[-a(M - M_0)\right]$$

where $M_0 = 1$ GeV and $a = 2$ GeV$^{-1}$. Since we use the same hadronization model for soft clusters as for those that come from parton branching, our scheme differs from the original UA5 Monte Carlo in requiring no further parameters to specify the hadron distribution from a cluster of a given mass and flavour.

Once the preselected charged multiplicity has been achieved, the cluster momenta are generated with a simple longitudinal phase-space distribution and limited transverse momenta, as explained in Refs. [2,32].

3 Hadron-Hadron Processes

In this section we give additional details of the processes relevant to the simulation of hadron-hadron collisions.

3.1 Structure Functions

HERWIG contains both sets of EHLQ and Duke and Owens structure functions, together with the Owens set 1.1, which is the default. The variable NSTRU controls which is used, as listed in Sect. 6. In addition an interface to the PDFLIB structure function library[33] is provided, although the library itself does not come with the program. PDFLIB structure function sets are selected by setting the variable MODPDF non-negative. The scale used in the structure functions for each sub-process is discussed below. Recall that the backward evolution algorithm ensures that for any slice through $(x, Q^2)$ space, the probability distribution generated by HERWIG agrees with that predicted by the selected structure function set.

3.2 QCD Hard Sub-processes

The QCD $2 \rightarrow 2$ processes in HERWIG are generated according to the exact leading-order matrix elements for massless partons, but with kinematics generated with the masses given by the RMASS(i) values. The phase-space is controlled by the parameters PTMIN and PTMAX for the transverse momentum of the outgoing partons, and YJMIN and YJMAX for the rapidities of both outgoing partons in the laboratory frame. The transverse momentum distribution is generated according to $dP_{T}/P_{T}^{pow}$, and is reweighted to the correct distribution so that PTPOW only affects the efficiency of event generation, and not any physical distributions. The scale used in the structure functions is

$$Q^2 = \frac{2s\bar{u}}{s^2 + t^2 + \bar{u}^2}.$$
Some QCD 2 → 2 processes, for example \( qq' \rightarrow qq' \), only have one colour-flow diagram, but for the majority a number of different diagrams is possible, each of which contributes to the amplitude of the process. Thus the cross-section contains interference terms between different colour flows, which in general are suppressed both by powers of the number of colours, \( N_c \), and by dynamical effects. Note that in the ‘planar approximation’, \( N_c \rightarrow \infty \), this interference disappears leaving only the direct, or ‘planar’, terms. For the parton shower algorithm to evolve this state in a probabilistic way however, one must neglect the interference effects entirely. In HERWIG this is done by distributing the corresponding terms in the cross-section between the direct terms, in such a way that the following conditions are satisfied:

- the full term should have the same pole structure and crossing symmetry as the planar term;
- the full term should remain positive definite in order to be interpreted as a probability distribution; and
- the sum of the full terms should give the exact lowest-order matrix element.

In fact these are sufficient to uniquely specify the distribution for all 2 → 2 processes. This distribution is illustrated in Fig. 2 for the \( qq \rightarrow qq \) case, where the interference term is shown in the centre of the first line, and distributed between the two diagrams in the second. Note that although the interference term has little colour suppression, \( \sim 1/N_c \), it is strongly dynamically suppressed by its pole structure, \( \sim s/t \) compared to \( s^2/t^2 \). These diagrams are then generated by HERWIG as two competing sub-processes (see Sect. 13 of [1] for the complete list of QCD 2 → 2 sub-processes together with their colour flows). Once a sub-process has been generated, gluon emission from each external line is confined to a cone defined by that line and its colour connected partner.

### 3.3 Direct Photon Sub-Processes

The first paragraph of the previous section also applies to direct photon sub-processes. The colour flow is simple because each parton configuration corresponds to only one colour diagram.
(see Sect. 14 of [1]). Note that the phase-space parameters control the parton momenta before initial-state evolution, so that the resulting momenta can be pushed outside the requested phase-space boundaries by recoils from the initial-state radiation.

At present only lowest order single-photon processes are included, although double-photon production will also be in the next version to be released. The next-to-leading order corrections to single- and double-photon production are dominated by photon radiation from outgoing quarks in QCD 2 → 2 and single-photon processes respectively. Although this is included in HERWIG, and works very well for e⁺e⁻ annihilation, a number of improvements are needed before this treatment is efficient enough or accurate enough for serious use in hadron-hadron collisions (see [34] and Sect. 7).

### 3.4 Heavy Flavour Production

The comments in Sect. 3.2 also apply to heavy flavour production by QCD processes, except that the full mass-dependent matrix elements are used. All sub-processes which result in the requested flavour are generated, including pair production e.g. \( gg \rightarrow bb \), and flavour excitation e.g. \( gb \rightarrow gb \). It should be noted that not all structure function sets include the heavy quark sea so cannot produce flavour-excitation events. In fact this is the case for HERWIG's default set.

Single top quarks can also be created by electroweak flavour excitation by W exchange e.g. \( qb \rightarrow qt \). The matrix elements used include the full top-mass dependence, but neglect all other parton masses. This will obviously not work with structure function sets which do not include the b-quark sea. Heavy flavours can also be produced by charged-current Drell-Yan processes e.g. \( qq' \rightarrow W^+ \rightarrow tb \), by Higgs boson decays, and by baryon-number violating events, which are all discussed below.

### 3.5 Heavy Flavour Decays

If the top (or a heavier generation) quark is heavier than about 130 GeV, it will decay too quickly to form hadrons first. In HERWIG this is treated as the weak decay of a free quark immediately after perturbative parton showering. No attempt is made to simulate the slowing of the top quark by partial hadronization before decay. Top quarks which are lighter than 130 GeV, and b-quarks, are hadronized using the standard cluster algorithm. The resulting heavy flavoured hadrons are then decayed using the spectator model. This means that, for example, a \( B^- \) meson is split into a collinear \( b\bar{u} \) pair with equal velocities, and then the \( b \)-quark decays as a free quark. Whether the decay happens before or after hadronization it is treated as a new source of coherent radiation, producing a parton shower before finally decaying to hadrons, exactly like a hard sub-process. See Ref. [6] for details of the treatment of colour coherence in these showers.

Users may wish to change the decay fractions for heavy quarks, for example to force a leptonic decay in every event. This can be done by modifying the contents of `COMMON/HWUFHV/`:

- `FBTM(1,1), FBTM(2,1), ..., FBTM(6,1)` are the \( b \)-quark decay fractions into the 6 doublets \((d,u)\), \((s,c)\), \((b,t)\), \((v,\mu)\), \((\tau,\nu_e)\) respectively. `FBTM(1,2)` etc are the corresponding \( \bar{b} \) fractions. Thus to get all \( b \)-hadrons to decay to muons, while keeping the default decay fractions for \( b \)-hadrons, one would set `FBTM(J,1) = 0` for \( J \neq 5 \) and `FBTM(5,1) = 1`, without changing `FBTM(J,2)`. `FTOP` is the corresponding array for the top quark, while `FHVV` is for quarks heavier than top. All these quantities can be changed from event to event.
3.6 Electroweak Boson Production

Electroweak gauge bosons are produced as intermediaries in the Drell-Yan type processes,

\[ q\bar{q} \rightarrow Z^0/\gamma \rightarrow t\bar{t}, \quad (3.2) \]
\[ q\bar{q}' \rightarrow W^\pm \rightarrow q'q^\prime, \quad (3.3) \]
\[ q\bar{q}' \rightarrow W^\pm \rightarrow t\nu, \quad (3.4) \]
as well as in association with jets,

\[ q\bar{q} \rightarrow W^\pm g, \quad (3.5) \]
\[ qg \rightarrow W^\pm q, \quad (3.6) \]

and in Higgs boson decays and baryon-number violating events, which are discussed below. In accordance with this notation, in the first case the gauge boson decay is considered part of the hard sub-process, and its decay products are chosen by the process code as shown in Sect. 5. In the other cases they are considered to be the final-state of the hard sub-process or decay, and are decayed at a later stage of event processing, with decay products chosen as discussed in the following section.

The matrix elements neglect the parton masses except in \( W \rightarrow t\bar{b} \), which uses the full dependence on top and bottom quark masses. In the Drell-Yan process (3.2), the mass spectrum is limited by the parameters \( \text{EMIN} \) and \( \text{EMAX} \), and is generated according to \( dm/m^\text{EMPOW} \). In the charged current cases, the full mass spectrum from threshold to \( \sqrt{s} \) is generated, but is dominated by the resonant region, \( m \sim m_W \). The scale used for the structure functions is the invariant mass of the pair, \( Q^2 = m^2 \).

In the \( W^+ \) jet process, the matrix elements neglect all parton masses. The full \( W \) mass spectrum is generated, but is again dominated by the resonance region. The phase-space is controlled by \( \text{PTMIN}, \text{PTMAX}, \text{PTPOW}, \text{YJMIN}, \) and \( \text{YJMAX} \), just as for QCD \( 2 \rightarrow 2 \) sub-processes. Note that both the \( W \) and the outgoing jet are confined to the given rapidity interval. The scale used in the structure functions is the transverse mass, \( Q^2 = p_T^2 + m^2 \).

3.7 Electroweak Boson Decays

Processes where the gauge boson decay is not considered part of the hard sub-process, its decay products are controlled by the variable \( \text{MODBOS}(i) \). This controls the decay of the \( i \)th gauge boson per event:

<table>
<thead>
<tr>
<th>( \text{MODBOS}(i) )</th>
<th>( W ) Decay</th>
<th>( Z ) Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>1</td>
<td>( q\bar{q} )</td>
<td>( q\bar{q} )</td>
</tr>
<tr>
<td>2</td>
<td>( e\nu )</td>
<td>( e^+e^- )</td>
</tr>
<tr>
<td>3</td>
<td>( \mu\nu )</td>
<td>( \mu^+\mu^- )</td>
</tr>
<tr>
<td>4</td>
<td>( \tau\nu )</td>
<td>( \tau^+\tau^- )</td>
</tr>
<tr>
<td>5</td>
<td>( e\nu &amp; \mu\nu )</td>
<td>( e^+e^- ) &amp; ( \mu^+\mu^- )</td>
</tr>
<tr>
<td>6</td>
<td>all</td>
<td>( \nu\nu )</td>
</tr>
<tr>
<td>7</td>
<td>all</td>
<td>( b\bar{b} )</td>
</tr>
<tr>
<td>&gt; 7</td>
<td>all</td>
<td>all</td>
</tr>
</tbody>
</table>

All entries of \( \text{MODBOS} \) default to 0. Bosons which are produced in pairs (i.e. from Higgs decay) are symmetrized in \( \text{MODBOS}(i) \) and \( \text{MODBOS}(i + 1) \). For processes which directly produce gauge
bosons, the event weight includes the branching fraction to the requested decay, but this is only true for Higgs production if decay to $WW/ZZ$ is forced and not if all decays are allowed. One cannot safely alter $MODBOS$ from event to event, because the corresponding changes in the branching fractions would bias the weight distribution. The spin-correlations in the decays are included for all production processes.

3.8 Higgs Boson Production

Higgs bosons are produced through the 'gluon fusion' and 'WW fusion' mechanisms[34]. Note that the former is actually the sum of $gg \rightarrow H$ and $q\bar{q} \rightarrow H$, and the latter is the sum of $WW \rightarrow H$ and $ZZ \rightarrow H$.

The gluon fusion process uses the lowest order (one-loop) diagram, and only considers top quarks in the loop. For Higgs masses which are lighter than the top quark this leads to a small ($\sim 10\%$) over-estimate of the cross-section, but has no effect for $m_H \gg m_t$. The only parameter to control the phase-space is $\text{GAMMA}X$, described below. The scale used in the structure functions is the generated mass, $Q^2 = m^2 \approx m_H^2$.

The $WW$ fusion process uses the full $2 \rightarrow 3$ matrix element for $qq' \rightarrow q''q'''WW \rightarrow q''q''',H$, in the $s$-channel approximation. The phase-space is only controlled by $\text{GAMMA}X$. The scale used in the structure functions is the average momentum transfer of the quarks, i.e. the $W$ mass, $Q^2 = m_W^2$.

For both processes the use of the $s$-channel approximation results in unitarity violation for $m \gg m_W$, $s \gtrsim a m_W^2$, (where $s = q^2$). To regularize this, the $m_H \Gamma_H$ in the propagator should be replaced by $\sqrt{s} \Gamma_H(s)$. The variable $\text{IOPHIG}$ controls this procedure:

<table>
<thead>
<tr>
<th>IOPHIG</th>
<th>Choose $s$ according to</th>
<th>Reweight?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$s^2 / ( (s - m_H^2)^2 + m_H \Gamma_H )$</td>
<td>Yes</td>
</tr>
<tr>
<td>1</td>
<td>$1 / ( (s - m_H^2)^2 + m_H \Gamma_H )$</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>$s^2 / ( (s - m_H^2)^2 + m_H \Gamma_H )$</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>$1 / ( (s - m_H^2)^2 + m_H \Gamma_H )$</td>
<td>No</td>
</tr>
</tbody>
</table>

where reweighting means weighting the distribution back to

$$
\frac{\sqrt{s} \Gamma_H(s)}{(s - m_H^2)^2 + \sqrt{s} \Gamma_H(s)}
$$

(3.7)

The default is $\text{IOPHIG} = 1$. The difference between options 0 and 1 is purely in the weight distribution produced. Options 2 and 3 are intended primarily for users who wish to supply their own unitarity conserving reweighting function at the point indicated in routine $WHWHIGM$. In all cases, the distribution is restricted to the range $|m_H - \text{GAMMA}X \times \Gamma_H, m_H + \text{GAMMA}X \times \Gamma_H|$. $\text{GAMMA}X$ defaults to 10, but in the non-perturbative region $m_H \gtrsim 1$ TeV should be reduced to protect against poor weight distributions. These considerations do not affect the distribution noticeably for $m_H \lesssim 500$ GeV, and $\text{GAMMA}X$ can safely be increased if necessary.

3.9 Higgs Boson Decays

For each Higgs production process, $\text{ID}$ controls the Higgs decay: $\text{ID}=1-6$ for quarks, 7-9 for leptons, 10/11 for $WW/ZZ$ pairs, and 12 for photons. In addition $\text{ID}=0$ gives quarks of all flavours, and $\text{ID}=99$ gives all decays. For each process, the average event weight includes the branching fraction to the requested decay. The branching ratios to quarks use the next-to-leading logarithm corrections, modified slightly to avoid producing $qq$ pairs below threshold,
which should correspond to bound-state meson production. The decays to $WW/ZZ$ pairs allow one or both bosons to be off-shell, and correctly includes the EPR-type correlations between the decays of the two bosons.

3.10 Point-like Photon Reactions

When studying photon-hadron collisions to the leading order $\alpha_s \alpha_{EM}$ the photon can behave in one of two ways. As a hadron ('resolved photon'), that is as a partonic collection of quarks and gluons with a default structure function given by Drees and Grassie, or as a point-like object. The former is simulated by specifying a photon beam, $\text{PART1} = \text{'GAMA'}$, and asking for a hadronic sub-process, for example $\text{IPROC} = 1500$, whilst the point-like photon sub-processes require $\text{IPROC} = 5000 + \text{IQ}$. Both photon-gluon fusion and Compton scattering are included. When IQ is set non-zero, i.e. a quark flavour is specified, then massive matrix elements are used and the kinematics treated exactly using light-cone momentum fractions. The phase-space sampling is treated as for a QCD $2 \rightarrow 2$ scattering, see above. In the point-like photon case the soft underlying event is treated in analogy with DIS. Note that for fixed target applications event generation should be performed in the centre-of-mass frame and afterwards boosted to the lab frame.

3.11 Baryon Number Violating Processes

Recently, the possibility of observing baryon-number violating interactions at supercolliders has been raised (for a review, see [35]). Such interactions typically produce of the order of $1/\alpha_{\text{weak}}$ electroweak gauge bosons, some Higgs bosons and quarks and leptons of all generations. It is also possible that other multi-W phenomena could be observed at supercolliders, due to the large volume of phase space at these energies.

At present, the theoretical predictions of the expected rate contain large uncertainties. Consequently, simulations are required to determine what experimental limits can be placed on the cross section, and to investigate experimental signatures of baryon or lepton number violation. An event generator HERBVI has been written [36] in order to be able to perform such simulations. This package interfaces to the main HERWIG simulation, and should be useful in the coming period of detailed experiment design for the LHC and SSC. More details are available from the authors, see Sect. 8.

4 New Features of Recent Versions

Version 5.1 of HERWIG was described in detail in [1]. Since then the following new features were added in version 5.2:

- New $e^+ e^-$ processes:
  - two photon processes, $\text{IPROC} = 500 + \text{ID}$ where $\text{ID} = 0-10$ is the same as in Higgs processes for $q\bar{q}$, $\ell\bar{\ell}$, and $W^+ W^-$. The phase space is controlled by $\text{EMMIN}$, $\text{EMMAX}$ for the CMF mass, $\text{PTMIN}$, $\text{PTMAX}$ for the transverse momentum of the CMF in the lab, and $\text{CTMAX}$ for the CMF angle of the outgoing particles.
  - photon-W fusion, $\text{IPROC} = 550 + \text{ID}$ where $\text{ID} = 0-9$ is the same as in Higgs processes, except that $\text{ID} \geq 1$ or 2 both give the sum of $d\bar{u}$ and $u\bar{d}$ etc. The phase space is
controlled by EMMIN, EMMAX only. The full $2 \rightarrow 3$ matrix elements for $\gamma e \rightarrow f \bar{f}^\prime \nu$ are used, so the cross-section for real $W$ production is correctly included.

- $ZZ$ pair production, $\text{IPROC} = 250$ is treated just like $WW$ production, and is based on the program kindly supplied by Zoltan Kunszt[37].

- **New $ep$ processes:**
  - the phase space for BGF is now controlled by EMMIN, EMMAX as above. The default values are 0 and $\sqrt{s}$ respectively, corresponding to the behaviour of version 5.1.
  - $J/\psi$ production from BGF, $\text{IPROC} = 9104$ is now available.
  - $WW$ fusion to Higgs is now available in $ep$, $\text{IPROC} = 9500 + \text{ID}$.

- $\text{IPROC} = 1600 + \text{ID}$ now gives the sum of gluon fusion and $qq$ fusion. This is especially important in $e^+e^-$ if $\tan \beta$ is large, when it is dominated by $e^+e^- \rightarrow e^+e^- \gamma \rightarrow e^+e^- b\bar{b}H$.

- Users can now force $Z \rightarrow b\bar{b}$ decays, with MODBOS($i$) = 7 (for a complete list see Sect. 3.7). For example, $\text{IPROC} = 250, \text{MODBOS}(1) = 7, \text{MODBOS}(2) = 0$ gives $ZZ$ production with one $Z$ decaying to $b\bar{b}$.

- All Higgs vertices now include an enhancement factor to account for non-SM couplings. ENHANC($ID$), where $ID = 1-11$ is the same as for Higgs production, holds the ratio of the amplitude for the given vertex to that of the SM. This of course only simulates the chargeless scalars of any extended model, and not the pseudoscalars or charged Higgses.

- The heavy quark content of the photon now uses the corrections to the Drees-Grassie distribution functions for light quarks, see [38].

- A new structure function set, Owens1.1, similar to DukeOwens1, but fitted to new data[39] is available via NSTRU = 5, and is now the default structure function set.

In version 5.3:

- $O(\alpha_s)$ jet production in $ep$ processes has been included ($\text{IPROC} = 9200$ etc), with $Q^2$ range controlled by $\text{Q2MIN}, \text{Q2MAX}$ and minimum jet transverse momentum (in the hard subprocess CMF) set by $\text{PTMIN}$. The new subroutines were written by Sebastian Brandis and we are grateful to him for permission to use his code.

- Minor bugs have been fixed in the backward evolution of quarks into photons, hadronic processes in $e^+e^-$, remnant hadronization in $ep$, and in the generation of weighted events (ie with $\text{NOWGT} = \text{.FALSE.}$).

In version 5.4:

- A correction to hard gluon emission in $e^+e^-$ events has been added[9] and is now the default process. This uses the $O(\alpha_s)$ matrix element to add events in the 'back-to-back' region of phase-space corresponding to a $qq$ pair recoiling from a very hard gluon. Although this is asymptotically negligible, and cannot be produced within the shower itself, it has a sizeable effect at LEP energies. As a result, the default parameters have been retuned, and show a marked improvement in agreement with OPAL data for event shapes sensitive to three jet configurations[40]. The uncorrected process has been retained for comparative purposes and is available as $\text{IPROC} = 120 + \text{IQ}$.
• Photons are now included in time-like parton showering\cite{9}. The infrared cutoff is VPCUT, which defaults to $\sqrt{s}$ corresponding to no emission. Agreement with LEP data is satisfactory if used together with the matrix element correction to produce photons in the back-to-back region. The results are insensitive to VPCUT variations in the range 0.1–1.0 GeV.

• $W$ decay correlations and width are now correctly included in $W$+jet production (previous versions used unpolarized, on-shell approximations).

• An inconsistency in the argument used for $\alpha_s$ in the branching $g \to q\bar{q}$ has been removed. The change is a non-leading correction but leads to slightly more quarks in gluon jets.

• A new parameter B1LIM has been introduced for $B$ cluster hadronization If $M_c$ is the $B$ cluster mass and $M_0$ the threshold for its decay into 2 hadrons, the probability of its decay into a single $B$ hadron is: 1 if $M_c < M_0$, 0 if $M_c > (1 + B1LIM)M_0$, with a linear interpolation ie. $1 - (M_c - M_0)/(B1LIMM_0)$ if $M_0 < M_c < (1 + B1LIM)M_0$. Thus the default value $B1LIM = 0$ gives the same as previous versions, while $B1LIM > 0$ gives a harder $B$ spectrum.

• $B$ decays can now be performed by the EURODEC or CLEO Monte Carlo packages. The new variable BDECAY controls which package is used: 'HERW' for HERWIG; 'EURO' for EURODEC; 'CLEO' for CLEO. The EURODEC package can be obtained from the CERN program library. The CLEO package is available by kind permission of the CLEO collaboration, and can be obtained from Luca Stanco.

In version 5.5:

• The Sudakov form factors can now be calculated using the one-loop or two-loop $\alpha_s$, according to the variable SUDORD (default value = 1). The parton showering still incorporates the two-loop $\alpha_s$ in either case but if SUDORD = 1 this is done using the veto algorithm, whereas if SUDORD = 2 no vetoes are used in the final-state evolution. This means that the relative weight of any shower configuration can be calculated in a closed form, and hence that showers can be 'forced'. For example, a package of routines should be available soon for forcing jets to contain photons, which will therefore drastically improve the efficiency of photon FSR studies. To next-to-leading order the two possibilities SUDORD = 1 or 2 should be identical, but they differ at beyond-NLO, so some results may change a little. Previous versions were equivalent to SUDORD = 1.

• $\alpha_{em}$ is now multiplied by the factor ALPFAC (default value = 1) for all quark-photon vertices in jets, and in the 'dead zone' in $e^+e^-$. This is a cheap way of improving the efficiency of photon FSR studies, which should not be needed once photon forcing is available. Note that results at small $y_{cu}$ become sensitive to ALPFAC above about 5.

• A new parameter CLPOW (default value = 2) is available in the cluster hadronization model. A cluster of mass $M_c$ made of quarks of mass $M_1$, $M_2$ is split into lighter clusters before decaying if

$$M_C^{CLPW} > CLMAX^{CLPW} + (M_1 + M_2)^{CLPW}$$

(4.1)

Thus the previous value was CLPW = 2, like the new default. Smaller values will increase the yield of heavier clusters (and hence of baryons) for heavy quarks, without affecting light quarks much. For example, the default value gives no $b$-baryons (for the default value of CLMAX) whereas CLPW = 1 makes $b$-baryons/$b$-hadrons about 1/4.
• The event record has been modified to retain entries for all partons before hadronization (with status ISTHEP = 2). During hadronization, the gluons are split into $q\bar{q}$, while other partons are copied to a location (indicated by JDAHEP(1, *)) where their momenta may be shifted slightly, to conserve momentum during heavy cluster splitting. Previously the original momenta were shifted, so momentum appeared not to be conserved at the parton level.

• Minor improvements have been made to: NLO correction to Higgs decays to $q\bar{q}$; pt spectra of outgoing electrons in two-photon processes; quark-mass effects in $\gamma W$ fusion; $WW$ spectrum below threshold in $e^+e^-$; $t\bar{b}$ spectrum in $W$ Drell-Yan (IPROC = 1406).

• Bugs preventing the use of Sudakov form factor tables from disk and gluon $\rightarrow$ diquarks splitting option under some circumstances, together with other minor bugs and machine-dependences, have been fixed.

In version 5.6:

• Decays of very heavy quarks (top and higher generations) can occur either before or after hadronization. At present all top quarks will decay before/after hadronizing if the top mass is greater/less than 130 GeV. This can be changed in subroutine HWDTOP. All higher (> 3) generations now decay before hadronization. Note that the new statement CALL HWDHQK must appear in the main program between the calls to HWBGEN and HWCFOR to carry out any decays before hadronization.

• Bugs in the subroutine HWHDOA for $O(\alpha_s)$ jet production in DIS have been corrected by J. Chyla, who has also extended this process into the photoproduction region. If $Q_2$ < $2 \times 10^{-6}$ (the new default), the kinematic lower limit on $Q_2$ is computed and used. New options IPROC = 9250–9277 use various approximations to the neutral-current matrix element, as specified in the documentation file.

• The photoproduction processes have also been extended from the original heavy quark production program, to include all quark pair production (IPROC = 9100–9106) and QCD Compton (IPROC = 9110–9122), as well as the sum of the two (IPROC = 9130). The possible flavours for the 9100, 9110 and 9130 processes are limited by the input parameters IFLMIN and IFLMAX (defaults are 1 and 3, i.e. only u, d, s flavours). The corresponding Charged Current processes are now provided via the IPROC = 9140–9144 codes.

• All the DIS processes IPROC = 9000–9599 are now available in $e^+e^-$ as well as lepton-hadron collisions. The program generates a photon from the second beam (only) in Weizsacker-Williams approximation and uses Drees-Grassie structure functions for DIS on the photon.

• Pointlike photon-hadron scattering to produce QCD jets is available as IPROC = 5000. This is suitable for fixed-target photoproduction, provided events are generated in a frame in which the target has high momentum, and then boosted back to the lab. IPROC = 5000 + IQ generates only those processes involving quark flavour IQ, using exact kinematics and light-cone momentum fraction. In both cases, after event generation the hard subprocess code IHPR0 is set to 51, 52 or 53 for $\gamma q \rightarrow gq$, $\gamma q \rightarrow gq$, or $\gamma g \rightarrow gq$. 

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• The default limits on $Q^2$ in DIS processes ($Q_{\text{MIN}}, Q_{\text{MAX}}$) have been set very small/large ($0, 10^{10}$) and are reset to the kinematic limits unless changed by the user. This means the default $Q_{\text{MIN}}$ is not suitable for simple NC DIS ($\text{IPROC} = 9000$ etc), but is appropriate for jet and heavy quark photoproduction.

• A new parameter $N_{\text{MXJET}}$, the maximum number of outgoing partons in a hard subprocess (default 200) has been introduced in the common block file HERWIG56. INC.

• For technical reasons, some HERWIG status codes $\text{ISTHEP}$ between 153 and 165 have changed their meanings. See the Table in the documentation file.

• Bugs in the hadronization of diquark-antidiquark clusters have been fixed. Any such clusters with masses below threshold for decay into baryon-antibaryon are shifted to the threshold via a transfer of 4-momentum to a neighbouring cluster.

• A bug in the default pion structure function (no gluons) is fixed.

5 Beams and Processes

A number of variables must be set in the main program to specify what is to be simulated:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>PART1</td>
<td>Type of particle in beam 1</td>
<td>$p$</td>
</tr>
<tr>
<td>PART2</td>
<td>Type of particle in beam 2</td>
<td>$p$</td>
</tr>
<tr>
<td>PBEAM1</td>
<td>Momentum of beam 1</td>
<td>20000.0</td>
</tr>
<tr>
<td>PBEAM2</td>
<td>Momentum of beam 2</td>
<td>20000.0</td>
</tr>
<tr>
<td>IPROC</td>
<td>Type of process to generate</td>
<td>1500</td>
</tr>
<tr>
<td>MAXEV</td>
<td>Number of events to generate</td>
<td>100</td>
</tr>
</tbody>
</table>

Note that in HERWIG the beam momenta $P_{\text{BEAM1}}$ and $P_{\text{BEAM2}}$ are both assumed to be large. Therefore fixed-target experiments should be simulated in a moving frame, such as the overall centre-of-mass frame, and then boosted back into the laboratory. The hadron beams handled in HERWIG at present are protons, neutrons, pions, and their anti-particles. In addition, photons can either be treated as point-like, or resolved like hadrons, as can leptons through the Weizsacker-Williams approximation for the emission of a photon.

The currently available processes for hadron-hadron collisions, $\text{IPROC}$, are as follows. For the complete list for all beam types, see the documentation file.
<table>
<thead>
<tr>
<th>IPROC</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350</td>
<td>$qq \rightarrow Z^0 / \gamma \rightarrow ll$ (all lepton species)</td>
</tr>
<tr>
<td>1350+IL</td>
<td>$qq \rightarrow Z^0 / \gamma \rightarrow ll$ (IL=1,2,3 for $l = e, \mu, \tau$)</td>
</tr>
<tr>
<td>1400</td>
<td>$qq \rightarrow W^\pm \rightarrow q'q''$ (all flavours)</td>
</tr>
<tr>
<td>1400+IQ</td>
<td>$qq \rightarrow W^\pm \rightarrow q'q''$ ($q'$ or $q''$ as below)</td>
</tr>
<tr>
<td>1450</td>
<td>$qq \rightarrow W^\pm \rightarrow l\nu_l$ (all lepton species)</td>
</tr>
<tr>
<td>1450+IL</td>
<td>$qq \rightarrow W^\pm \rightarrow l\nu_l$ (IL as above)</td>
</tr>
<tr>
<td>1499</td>
<td>$qq \rightarrow W^\pm \rightarrow$ anything</td>
</tr>
<tr>
<td>1500</td>
<td>QCD 2 → 2 hard parton scattering</td>
</tr>
<tr>
<td>1600+ID</td>
<td>$gg/gq \rightarrow H^0$ (ID as in IPROC=300+ID)</td>
</tr>
<tr>
<td>1700+IQ</td>
<td>QCD heavy quark production ($IQ=1,2,3,4,5,6$ for $q = d, u, s, c, b, t$)</td>
</tr>
<tr>
<td>1800</td>
<td>QCD direct photon + jet production</td>
</tr>
<tr>
<td>1900+ID</td>
<td>$W^+W^- \rightarrow H^0$ (ID as in IPROC=300+ID)</td>
</tr>
<tr>
<td>2000</td>
<td>$t$ production via $W$ exchange (sum of 2001-2008)</td>
</tr>
<tr>
<td>2001-4</td>
<td>$ub \rightarrow dt, \ db \rightarrow ut,\ db \rightarrow ut ,\ ub \rightarrow dt$</td>
</tr>
<tr>
<td>2005-8</td>
<td>$cb \rightarrow st,\ sb \rightarrow cl ,\ sb \rightarrow ct,\ cb \rightarrow st$</td>
</tr>
<tr>
<td>2100</td>
<td>$W^\pm$ + jet production</td>
</tr>
<tr>
<td>2110</td>
<td>$W^\pm$ + jet production (Compton only: $gq \rightarrow Wq$)</td>
</tr>
<tr>
<td>2120</td>
<td>$W^\pm$ + jet production (Annihilation only: $q\bar{q} \rightarrow Wq$)</td>
</tr>
<tr>
<td>5000</td>
<td>Pointlike photon-hadron jet production (all flavours)</td>
</tr>
<tr>
<td>5000+IQ</td>
<td>Pointlike photon-hadron jet production (quark flavour IQ)</td>
</tr>
<tr>
<td>7000-999</td>
<td>Baryon-number violating interactions (HERBVI)</td>
</tr>
<tr>
<td>8000</td>
<td>Minimum bias soft hadron-hadron event</td>
</tr>
<tr>
<td>10000+IP</td>
<td>as IPROC=IP but with soft underlying event suppressed (soft remnant fragmentation suppressed in lepton-hadron)</td>
</tr>
</tbody>
</table>
6 Input Parameters

The quantities that may be regarded as adjustable parameters are

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCDLAM</td>
<td>$\Lambda_{QCD}$ (see below)</td>
<td>0.20</td>
</tr>
<tr>
<td>RMASS(1)</td>
<td>Down quark mass</td>
<td>0.32</td>
</tr>
<tr>
<td>RMASS(2)</td>
<td>Up quark mass</td>
<td>0.32</td>
</tr>
<tr>
<td>RMASS(3)</td>
<td>Strangem quark mass</td>
<td>0.50</td>
</tr>
<tr>
<td>RMASS(4)</td>
<td>Charmed quark mass</td>
<td>1.80</td>
</tr>
<tr>
<td>RMASS(5)</td>
<td>Bottom quark mass</td>
<td>5.20</td>
</tr>
<tr>
<td>RMASS(6)</td>
<td>Top quark mass</td>
<td>100.0</td>
</tr>
<tr>
<td>RMASS(13)</td>
<td>Gluon effective mass</td>
<td>0.75</td>
</tr>
<tr>
<td>VQCUT</td>
<td>Quark virtuality cutoff (added to</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>quark masses in parton showers)</td>
<td></td>
</tr>
<tr>
<td>VGCUT</td>
<td>Gluon virtuality cutoff (added to</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>effective mass in parton showers)</td>
<td></td>
</tr>
<tr>
<td>VPCUT</td>
<td>Photon virtuality cutoff in parton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>showers</td>
<td>$\sqrt{s}$</td>
</tr>
<tr>
<td>CLMAX</td>
<td>Maximum cluster mass parameter</td>
<td>3.50</td>
</tr>
<tr>
<td>CLPOW</td>
<td>Cluster cutoff power parameter</td>
<td>2.00</td>
</tr>
<tr>
<td>PSPLT</td>
<td>Split cluster spectrum parameter</td>
<td>1.00</td>
</tr>
<tr>
<td>B1LIM</td>
<td>Control of b-cluster decay threshold</td>
<td>0.00</td>
</tr>
<tr>
<td>QDIQK</td>
<td>Maximum scale for gluon–diquarks</td>
<td>0.00</td>
</tr>
<tr>
<td>PD1QK</td>
<td>Gluon–diquarks rate parameter</td>
<td>5.00</td>
</tr>
<tr>
<td>QSPAC</td>
<td>Cutoff for spacelike evolution</td>
<td>2.50</td>
</tr>
<tr>
<td>PTRMS</td>
<td>Intrinsic $p_T$ in incoming hadrons</td>
<td>0.00</td>
</tr>
<tr>
<td>ENSOF</td>
<td>Enhancement of underlying event</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Notes on parameters:

- **QCDLAM** can be identified at high momentum fractions ($x$ or $z$) with the fundamental 5-flavour QCD scale $\Lambda_{MS}^{(5)}$. However, this relation does not necessarily hold in other regions of phase space, since higher order corrections are not treated precisely enough to remove renormalization scheme ambiguities [7].

- **RMASS(1,2,3,13)** are effective light quark and gluon masses used in the hadronization phase of the program. They can be set to zero provided the parton shower cutoffs VQCUT and VGCUT are large enough to prevent divergences (see below).

- For cluster hadronization, it must be possible to split gluons into $q\bar{q}$, i.e. RMASS(13) must be at least twice the lightest quark mass. Similarly it may be impossible for heavy-flavoured clusters to decay if RMASS(4,5) are too low.

- **VQCUT** and **VGCUT** are needed if the quark and gluon effective masses become small. The condition to avoid divergences in parton showers is

$$\frac{1}{Q_i} + \frac{1}{Q_j} < \frac{1}{Q_{CDL3}} \quad (6.1)$$

for either $i$ or $j$ or both gluons, where $Q_i = \text{RMASS}(i) + \text{VQCUT}$ for quarks, $\text{RMASS}(13) + \text{VGCUT}$ for gluons, and $Q_{CDL3}$ is the equivalent $\Lambda^{(3)}$ computed from QCDLAM. In the notation
of Ref. [7] and Sect. 2, QCDL3 is the 3-flavour equivalent of QCDL5 where

\[ QCDL5 = QCDLAM \times \exp \left( \frac{151 - 9 \pi^2}{138} \right) / \sqrt{2} = 1.109 \times QCDLAM. \]  

(6.2)

We have approximately

\[ QCDL3 \simeq QCDL5 \times L_{b,c}^{107/1725} L_{b,c}^{107/2025} \exp \left( \frac{L_b + L_c}{27} \right) \]  

(6.3)

where \( L_{b,c} = 2 \ln(m_{b,c}/QCDL5) \), giving a default value of \( QCDL3 \simeq 0.40 \).

- \( VPCUT \) does not have a significant effect on the number of photons after isolation cuts, if set in the range 10 MeV–1 GeV. The default value, \( VPCUT = \sqrt{s} \), means that no photon emission is allowed.

- \( CLMAX \) and \( CLP0W \) determine the maximum allowed mass of a cluster made from quarks \( i \) and \( j \) as follows

\[ M_{CLP0W} < CLMAX^{CLP0W} + (RMASS(i) + RMASS(j))^{CLP0W}. \]  

(6.4)

Since the cluster mass spectrum falls rapidly at high mass, results become insensitive to \( CLMAX \) and \( CLP0W \) at large values of the former.

- \( PSPLT \) determines the mass distribution in the cluster splitting \( C_1 \rightarrow C_2 + C_3 \) when \( C_1 \) is above the maximum allowed mass. The masses of \( C_2 \) and \( C_3 \) are generated uniformly in \( M_{PSPLT} \). As long as the number of split clusters is small, dependence on \( PSPLT \) is weak.

- \( B1LIM \) controls the shape of the threshold for decays of \( b \)-flavoured clusters to hadrons. If \( B1LIM = 0 \), the default, all clusters heavy enough to decay to two hadrons do so. For \( B1LIM > 0 \) the probability of two-hadron decay rises linearly from 0 at the threshold to 1 a factor of \( 1 + B1LIM \) above it.

- \( QDIQK \) greater than twice the lightest diquark mass enables non-perturbative gluon splitting into diquarks as well as quarks. The probability of this is \( PDIQK \times dQ/Q \) for scales \( Q \) below \( QDIQK \). The diquark masses are taken to be the sum of constituent quark masses. Thus the default value \( QDIQK = 0 \) suppresses gluon \( \rightarrow \) diquark splitting.

- \( QSPAC \) is the scale below which the structure functions of incoming hadrons are frozen and non-valence constituent partons are forced to evolve to valence partons.

- \( PTRMS \) is the width of the (Gaussian) intrinsic transverse momentum distribution of valence partons in incoming hadrons at scale \( QSPAC \).

- \( ENSOF \) is the enhancement factor used in choosing the multiplicity of the underlying soft event. The multiplicity distribution is taken to be that of a \( pp \) collision at c.m. energy \( ENSOF \times \sqrt{s} \).

In practice, the parameters that have been found most effective in fitting data are \( QCDLAM \), the gluon effective mass \( RMASS(13) \), and the cluster mass parameter \( CLMAX \). Note that \( QSPAC \), \( PTRMS \) and \( ENSOF \) do not affect lepton-lepton collisions.

The default parameter values have been found to give good agreement with event shape distributions at LEP [40,41].
A number of further parameters are needed to control the program and to turn various options on or off:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPRINT</td>
<td>Printout option</td>
<td>1</td>
</tr>
<tr>
<td>MAXPR</td>
<td>Number of events to print out</td>
<td>1</td>
</tr>
<tr>
<td>MAXER</td>
<td>Maximum number of errors</td>
<td>10</td>
</tr>
<tr>
<td>LWEVT</td>
<td>Unit for writing output events</td>
<td>0</td>
</tr>
<tr>
<td>LRSUD</td>
<td>Unit for reading Sudakov table</td>
<td>0</td>
</tr>
<tr>
<td>LWSUD</td>
<td>Unit for writing Sudakov table</td>
<td>7</td>
</tr>
<tr>
<td>SUDORD</td>
<td>Order of $\alpha_s$ to use for Sudakov table</td>
<td>1</td>
</tr>
<tr>
<td>NRN(1)</td>
<td>Random number seed 1</td>
<td>17673</td>
</tr>
<tr>
<td>NRN(2)</td>
<td>Random number seed 2</td>
<td>63565</td>
</tr>
<tr>
<td>WGTMAX</td>
<td>Max weight (0 to search for it)</td>
<td>0.0</td>
</tr>
<tr>
<td>NOWGT</td>
<td>Generate unweighted events</td>
<td>.TRUE.</td>
</tr>
<tr>
<td>AZSOFT</td>
<td>Soft gluon azimuthal correlations</td>
<td>.TRUE.</td>
</tr>
<tr>
<td>AZSPIN</td>
<td>Gluon spin azimuthal correlations</td>
<td>.TRUE.</td>
</tr>
<tr>
<td>NCOLO</td>
<td>Number of colours</td>
<td>3</td>
</tr>
<tr>
<td>NFLAV</td>
<td>Number of (producible) flavours</td>
<td>6</td>
</tr>
<tr>
<td>MODPDF</td>
<td>PDFLIB structure function set</td>
<td>-1</td>
</tr>
<tr>
<td>NSTRU</td>
<td>Input structure function set (1,2: Duke-Owens 1,2; 3,4: EHLQ 1,2)</td>
<td>1</td>
</tr>
<tr>
<td>EPOLN</td>
<td>Electron beam polarization in DIS</td>
<td>0.0</td>
</tr>
<tr>
<td>BGSHAT</td>
<td>Scale $s$ for boson-gluon fusion</td>
<td>.TRUE.</td>
</tr>
<tr>
<td>PTMIN</td>
<td>Min $p_T$ in hadronic jet production</td>
<td>10.0</td>
</tr>
<tr>
<td>PTMAX</td>
<td>Max $p_T$ in hadronic jet production</td>
<td>$10^8$</td>
</tr>
<tr>
<td>PTPOW</td>
<td>$1/p_T^{PTPOW}$ for jet sampling</td>
<td>4.0</td>
</tr>
<tr>
<td>YMIN</td>
<td>Min jet rapidity</td>
<td>8.0</td>
</tr>
<tr>
<td>YMAX</td>
<td>Max jet rapidity</td>
<td>8.0</td>
</tr>
<tr>
<td>EMMIN</td>
<td>Min dilepton mass in Drell-Yan</td>
<td>10.0</td>
</tr>
<tr>
<td>EMMAX</td>
<td>Max dilepton mass in Drell-Yan</td>
<td>$10^8$</td>
</tr>
<tr>
<td>EMPOW</td>
<td>$1/m^{EMPOW}$ for Drell-Yan sampling</td>
<td>4.0</td>
</tr>
<tr>
<td>Q2MIN</td>
<td>Min $Q^2$ in deep inelastic</td>
<td>9999.5</td>
</tr>
<tr>
<td>Q2MAX</td>
<td>Max $Q^2$ in deep inelastic</td>
<td>10000.5</td>
</tr>
<tr>
<td>Q2POW</td>
<td>$1/Q^2Q2POW$ for sampling</td>
<td>2.5</td>
</tr>
<tr>
<td>THMAX</td>
<td>Max thrust in 3 parton production</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Printout options are:

- $\text{IPRINT} = 0$: Print program title only
- $\text{IPRINT} = 1$: Print selected input parameters
- $\text{IPRINT} = 2$: 1 + table of particle codes and properties
- $\text{IPRINT} = 3$: 2 + tables of Sudakov form factors

See Sect. 8 of [1] on form factors for details of LBSUD and LWSUD.

Regardless of the value of SUDORD, the two-loop $\alpha_s$ is used throughout the program. If SUDORD = 1, this is implemented in the branching algorithm by generating the distributions according to the one-loop $\alpha_s$ and correcting to the two-loop $\alpha_s$ using the veto algorithm. However, with SUDORD = 2 the distributions are directly generated using the two-loop $\alpha_s$ because this is
what is used in the Sudakov form factor. The two possibilities are identical to next-to-leading order, but differ at the next order, so some small numerical difference may be noticeable.

The quantities from PTMIN onwards control the region of phase space in which events are generated and the importance sampling inside those regions. See Sect. 11 of [1] on event weights for further details on these quantities and the use of WGTMAX and NOWGT.

For processes involving $W$, $Z$ and/or Higgs bosons, there are additional parameters to control decay modes and Higgs production options: see Sect. 3 for details.

In addition there are options to give different weights to the various flavours of quarks and diquarks, and to resonances of different spins. So far, these options have not been used. See the comments in the initialization routine HWIGIN for details.

7 Future Plans

HERWIG is unlikely ever to reach the status of a finished product, being continually improved and extended, with new version releases occurring regularly. In the near future the following new subprocess are envisaged. The Drell-Yan sub-process is being extended to allow production of an additional, neutral vector boson ($Z'$), as is the $e^+e^-$ annihilation process. This opportunity is also being taken to rationalize all the electroweak couplings appearing in the program and to place them in one common block, initialised in HWIGIN. New $2 \rightarrow 2$ sub-processes being incorporated include: direct QCD $\gamma\gamma$ production, including the gluon fusion box diagram; Higgs plus jet production, to allow studies of high $p_T$ Higgs production; Higgs plus vector boson production; and various double electroweak boson production processes, with optional anomalous couplings. In the more distant future it can be anticipated that particle production from beyond the minimal standard model will start to be included.

In version 5.4, a correction to the distributions of hard gluon (and photon) emission in $e^+e^-\rightarrow$hadrons was added. This uses the $O(\alpha_s)$ matrix element in the region of phase-space which cannot be populated by the parton shower. However, no attempt is made to match the two methods at the boundary, or to use the matrix element to correct the distribution within the shower's phase-space. Work is currently under way to implement both of these, as well as to extend the correction to arbitrary pairs of showering partons. This is particularly important for direct photons in hadron-hadron collisions, where a significant fraction of the photons which are observable after isolation cuts are expected to come from this region.

For direct photon studies, and some studies of heavy quark correlations, it is important to be able to build jets which contain a given vertex, to avoid having to generate many jets and reject almost all of them. A common example is being able to generate gluon jets which create a $b$-quark pair through the vertex $g \rightarrow bb$. Most of the machinery to be able to do this was added in version 5.5, where the parameter choice SUDORD = 2 calculates the Sudakov form factors in a closed form that does not require any vetoes in the shower algorithm. This means that the relative probability of any given configuration can be calculated, and hence that jets can be forced into any required configuration while retaining control over the relative probabilities. However, the book-keeping required to, for example, produce a gluon jet in which one of the gluons decays to $bb$ but the choice of which is made with the correct relative probabilities, is far from straightforward and has not yet been implemented. It will however be included in a released version soon.
8 Practical Matters

The HERWIG program can be obtained from the CERNLIB program library, or copied from any of the following DECNET locations:

- CERN: VXCERN::DISK$CR:[WEBBER.HERWIG]HERWIG56.*
- Fermilab: FNAL::USR$ROOT2:[WEBBER.HERWIG]HERWIG56.*
- Cambridge: CBHEP::DISK$USER1:[THEORY.HERWIG]HERWIG56.*

The files are as follows:

- HERWIG56.COM sample VAX command file for HERWIG56.TST, 1 block
- HERWIG56.DOC documentation file, 304 blocks
- HERWIG56.FOR subroutine source code, 977 blocks
- HERWIG56.INC common blocks and type declarations, 10 blocks
- HERWIG56.SUD default Sudakov form factor file, 193 blocks
- HERWIG56.TST test job main program and BLOCK DATA, 47 blocks

For users who prefer a PATCHY version, this is available as

CBHEP::DISK$USER1:[THEORY.HERWIG.PATCHY]HERWIG56.*

To be added to the list of users who are kept in touch with new releases, bug fixes, etc., please email Bryan Webber at the address below. Every subroutine now has its principle author listed at the beginning, and bug reports will usually get a more rapid response if sent to the author concerned. When it is not clear exactly where the problem has occurred, reports should be sent to Bryan Webber or Mike Seymour in the first instance. The HERBV1 package can be obtained by emailing Bryan Webber or Mark Gibbs. The present email addresses of the authors are:

- Bryan Webber: webber@surya11.cern.ch
- Ian Knowles: knovles@anhep2.anl.gov
- Mike Seymour: mike@theplu.se
- Giovanni Abbiendi: abbiendi@vxdesy.decnet.cern.ch
- Luca Stanco: stanco@vxdesy.decnet.cern.ch
- Mark Gibbs: gibbs@cbhep.decnet.cern.ch

The correct reference for the HERWIG Monte Carlo event generator is

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