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HERWIG 5.1 – a Monte Carlo event generator for simulating hadron emission reactions with interfering gluons *

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

This article includes a brief review of the physics underlying HERWIG, followed by a description of the program itself. This includes details of the input and control parameters used by the program, and the output data provided by it. Sample output from a typical simulation is given and annotated.

PROGRAM SUMMARY

Title of program: HERWIG 5.1

Catalogue number: ACBY

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Computer for which the program is designed and others on which it has been tested: VAX. Only minor modifications are needed to run on any machine running standard FORTRAN 77

Operating systems: VAX-VMS, and any other system which supports FORTRAN 77

Programming language used: FORTRAN 77

Memory required to execute with typical data: 240 kwords

No. of bits in a word: 32

No. of lines in distributed program, including test data, etc.: 12534

Keywords: Monte Carlo, event generator, perturbative QCD, parton shower, coherent branching, fragmentation, hadronic final states

Nature of physical problem
Simulation of high energy particle collisions, especially those in which a high momentum transfer gives rise to the emission of jets of hadrons. The theoretical basis is the resummation of the perturbative QCD expansion including all asymptotic and some important subasymptotic contributions.

Method of solution
Monte Carlo simulation of a variety of primary collision processes, followed by parton shower generation using a coherent branching algorithm and hadron formation using a cluster fragmentation model.

Restriction on the complexity of the problem
To run at very high energy ($\sqrt{s} \gg 40$ TeV), the program would need recompiling with larger arrays to accommodate the high multiplicity expected.

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Typical running time
Depends crucially on the process modelled. Can range from 1000 LEP $q\bar{q}$ events in 10 min, to 1000 SSC QCD $2 \to 2$ events in 3 h. Both times are for a 1 VUP (i.e. approximately 1 MIP) machine.

Reference to other published version of this program
CERN Program Library long write-up W5037.

LONG WRITE-UP

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 hard lepton–lepton, lepton–hadron and hadron–hadron 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 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 initialisation 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 section 5 for beams and processes available.

All analysis of generated events (histogramming, etc.) should be performed by the user-provided routines `HWABEG` (to initialise), `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 'HERWIG51.INC'` Vax Fortran statements (see section 7 for contents of `HERWIG51.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.

2. Physics underlying HERWIG

The physics that underlies the original program was presented in detail in ref. [1]. More recent improvements are discussed in refs. [2–7]. Other relevant theoretical background may be found in refs.

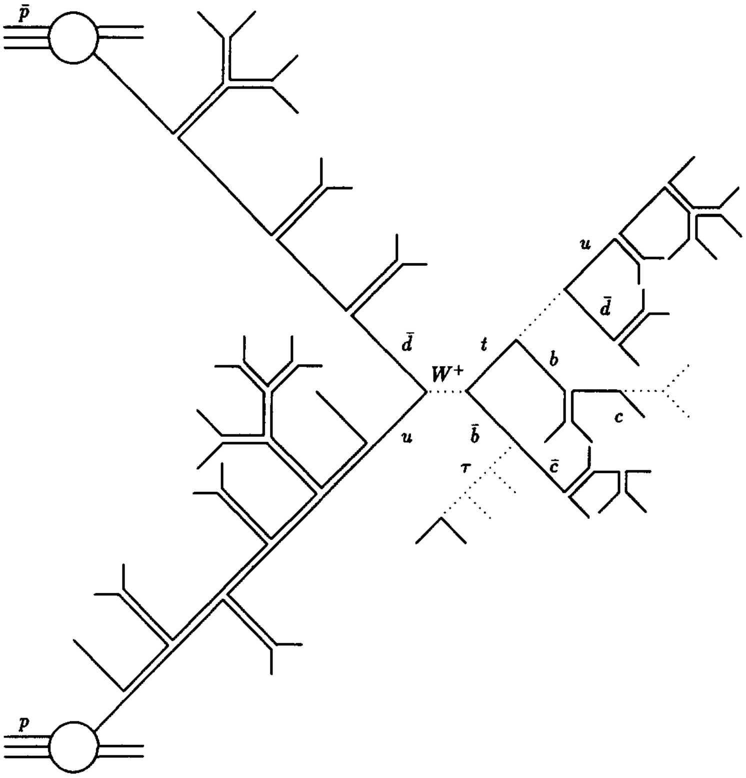

Fig. 1. Colour structure of a $\bar{p}p \to W^+ + X$, $W^+ \to t\bar{b}$ event.

[8–12]. 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 $p\bar{p} \to W^+ + X$, with $W^+ \to t\bar{b}$ *. 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.

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* This event was generated using an earlier version (2.2) of HERWIG. The decays of heavy quarks are handled slightly differently in version 5.1 – see section 12. In addition we now know that the top quark is too heavy for the W to decay to $t\bar{b}$. Nevertheless, fig. 1 illustrates the typical branching and colour structure of a simulated event.

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 $q\bar{q} \to W \to q\bar{q}$ 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 α_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 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 section 6, but we can take Q_0 here to represent the smallest cutoff.) As observed in some next-to-leading analyses [13], a transverse momentum cutoff corresponds to the $\overline{\text{MS}}$ 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 [1]; (b) for non-soft emission one finds azimuthal correlations due to spin effects. See refs. [2–4] for the method used to implement these correlations in full, to leading collinear logarithmic accuracy, in HERWIG.

5. In each branching the scale of α_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 [5,14,15] 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 [5].

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 intra-jet distributions such as the string effects in three-jet events [16].

The coherent branching correctly describes [17–19] 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 $\Lambda_{\overline{\mathrm{MS}}}$. 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 [20].

In the literature one can find different prescriptions for the branching subprocess (with different phase space and/or argument of α_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 [21], 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/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 θ_i between the incoming hadron and the emitted 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 terms 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 [21]. 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 [22].

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 $q_{\mathrm{t}i+1} > z_i q_{\mathrm{t}i}$, where $q_{\mathrm{t}i}$ is the transverse momentum of the ith emission. Therefore for $z_i \to 0$, the lower bound on $q_{\mathrm{t}i+1}$ 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 [23], 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 $z_i q_{\mathrm{t}i} < q_{\mathrm{t}i+1} < q_{\mathrm{t}i}$ 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 $q_{\mathrm{t}i} < q_{\mathrm{t}i+1}$ 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 [6] 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 $\Lambda_{\overline{\mathrm{MS}}}$. This is achieved by using the one-loop Altarelli–Parisi splitting functions and the two-loop expression for α_S with the following universal relation between the scale parameter Λ_{MC} used in the simulation and $\Lambda_{\overline{\mathrm{MS}}}$

$$\Lambda_{\mathrm{MC}} = \exp\left(\frac{67 - 3\pi^2 - 10N_\mathrm{f}/3}{2(33 - 2N_\mathrm{f})} \right) \Lambda_{\overline{\mathrm{MS}}} \approx 1.569 \Lambda_{\overline{\mathrm{MS}}} \quad \text{for} \quad N_\mathrm{f} = 5. \tag{2.1}$$

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

2.3. *Elementary hard subprocess*

In HERWIG version 5.1 there is a fairly large library of QCD and electroweak elementary subprocesses (see section 5).

From the point of view of QCD coherence, the elementary subprocess plays an important rôle 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 [1,17,24] 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 a number of contributions with different colour connections. The HERWIG library of elementary subprocesses includes the separate colour connection contributions. See ref. [1] for a discussion of the most complex case, namely the 2 → 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 [16].

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 (but not yet for W + jet production), using the approach of refs. [2–4] 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 types 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_s 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 convert the *emitted partons* into hadrons below the time-like cutoff scale Q_0. However, provided this mechanism does actually exist, perturbative QCD predicts [25,26] 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 [25] in perturbative QCD, as well as in the Monte Carlo simulations [9], 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 Leningrad group [26]. In this analysis the fragmentation functions for π, K and p production in e^+e^- annihilation at various high energies Q were compared with the fragmentations 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_π, 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 [1,10]. 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 suppress 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 "preconfinement" 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. From a cluster of flavour $\mathrm{f}_1\bar{\mathrm{f}}_2$, this specifies the flavours $\mathrm{f}_1\bar{\mathrm{f}}$ and $\mathrm{f}\bar{\mathrm{f}}_2$ of the decay products, which are then selected at random from tables of hadrons of those flavours. The hadrons can be $J^{\mathrm{P}} = 0^-$, $1^\pm$ or 2^+ mesons, or $\frac{1}{2}^+$ or $\frac{3}{2}^+$ baryons. For charmed hadrons, some of these states are just educated guesses. For b- and t-flavoured hadrons, only $J^{\mathrm{P}} = 0^-$ 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 $\mathrm{f}_1\bar{\mathrm{f}}$ and $\mathrm{f}\bar{\mathrm{f}}_2$ move in the directions of the original constituents f_1 and $\bar{\mathrm{f}}_2$ in their c.m. frame. Thus the fission mechanism is not unlike string fragmentation [27]. There are two fission parameters, `CLMAX` and `PSPLT`. The maximum cluster mass parameter `CLMAX` specifies the fission threshold M_{f} according to the formula

$$M_{\mathrm{f}}^2 = \mathtt{CLMAX}^2 + (Q_1 + Q_2)^2, \tag{2.2}$$

where Q_1 and Q_2 are the virtual mass cutoffs corresponding to flavours f_1 and f_2. The parameter `PSPLT` specifies the mass spectrum of the produced clusters, which is taken to be $M^{\mathtt{PSPLT}}$ within the allowed phase space. Provided the parameter `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. 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.

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 subsections 2.1 and 2.2 was analysed in ref. [12], 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 [28] 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 $p\bar{p}$ event generator of the UA5 Collaboration [29], modified to make use of our cluster fragmentation algorithm. The model starts from a parametrization of the $p\bar{p}$ 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 `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" $q_1\bar{q}_2$, $q_2\bar{q}_3, \ldots$, 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_i that define the flavour of the soft clusters are taken to be u or d only. The cluster masses are chosen from the distribution

$$P(M) \propto (M - M_0) \exp[-a(M - M_0)], \tag{2.3}$$

where $M_0 = 1$ GeV and $a = 2\ \text{GeV}^{-1}$. 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. [1,29].

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 `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, a model which could be unreliable for some distributions if the t mass is greater than about 130 GeV. After a b or t decay, secondary parton showers are produced by outgoing partons as discussed in ref. [5]; these are hadronized in the same way as primary jets.

3. New features of recent versions

We give here a summary of the main new features of HERWIG versions 4.1, 4.2, 4.3, 4.6, 5.0 and 5.1, all introduced since the preliminary program description [30].

For version 4.1, the program was largely rewritten to conform with the standards laid down by the Working Group on QCD Event Generators for LEP [31]. The standard event format, and any usages peculiar to HERWIG are discussed more fully later, especially in sections 9, 10, 16 and 18.

- All output event data appear in standard format in the LEP standard common block `/HEPEVT/`.
- Internal status codes and pointers in the program have been replaced by those in the standard common block. Status codes `ISTHEP` = 100–199 replace HERWIG codes `ISTK` = 0–99 of earlier

versions, and the tasks of the HERWIG pointers `IPTK` are now performed by the mother/daughter pointers `JMOHEP` and `JDAHEP`.

- All subroutine and non-standard common block names have been changed to the form `HW****`, to avoid conflicts with other programs to which HERWIG may be linked.
- The cluster formation and decay, and unstable particle and heavy flavour decay phases of event generation have been isolated in subroutines `HWCFOR`, `HWCDEC`, `HWDHAD` and `HWDHVY`, respectively, to enable any of these to be replaced by other packages if desired.

For version 4.2 the main new features were:

- Full azimuthal correlations due to gluon spin are now included in leading logarithmic approximation for *both initial and final state* parton showers, using the Knowles algorithms [2–4]. Azimuthal spin correlations between different jets are also included. In the case of heavy quark processes, correlations are treated in the massless approximation.
- Bugs in gluon splitting and Higgs cross-section have been fixed. The $gg \to H^0$ cross-section is now correctly included to lowest order for any combination of Higgs and top quark masses.
- Hard scattering and minimum-bias soft events can now be generated for any combination of pion, nucleon and/or antinucleon beams.
- The identifier and colour connection vectors `IDN` and `ICO` for hard subprocesses have been extended to dimension 10 for users who wish to use them in their own multijet subprocess routines.
- All variable types are now declared explicitly so that the program can be compiled with `IMPLICIT NONE` where this option is available.

For version 4.3 the main new features were:

- Default values of the parameters `QCDLAM` and `CLMAX` (see section 6) were changed to give better agreement with LEP data [32].
- Tau lepton decays are now generated from (simplified) particle data tables, like strong hadronic decays, instead of by secondary parton showering (which is still used for heavy quark decays). The decay tables used can been seen by setting print option `IPRINT` = 2.
- Clusters too light to decay into two hadrons are now treated more covariantly: the mass is shifted to an appropriate single-hadron mass by 4-momentum transfer to another cluster via rescaling the two-cluster centre-of-mass momentum, rather than via a lab energy transfer.
- "Remnant" clusters (i.e. those containing spectator partons from incoming hadrons) are now split if possible into two clusters like those produced in minimum-bias hadronic events. This change resulted from a study of remnant fragmentation in deep inelastic lepton scattering.

For version 4.6 the main new features were:

- QCD α_s was changed to the full 2-loop formula throughout, with matching at flavour thresholds as specified by the Working Group on QCD at LEP [33]. This means that the parameter `QCDLAM` must be interpreted differently from earlier versions, and can now be related to $\Lambda_{\overline{\mathrm{MS}}}$ *in the semi-inclusive region* (x or $z \to 1$) *only*. See ref. [6] for proof of this relation. (Since default parameter values were not changed from those in version 4.3, agreement with LEP data became less good.)
- The program was converted to double precision and array sizes were increased to facilitate running at LHC/SSC energies. The protection against even overflows (`NHEP>NMXHEP`) was also improved.
- Several hard processes were added:
  - New Higgs boson production and decay processes, including full matrix elements for Higgs production via WW fusion (`IPROC` = 1900, etc.),
  - Top production via W exchange, eg. $u + b \to d + t$ (`IPROC` = 2000, etc.),
  - W + jet production, eg. $q + g \to W + q$ (`IPROC` = 2100, etc.).
- `SAVE` statements were included to permit running in overlay mode.
- Bugs in heavy quark matrix elements were fixed.
- Default W and Z masses and widths were updated.

HERWIG version 5.0 was the first version to attempt seriously to simulate lepton–nucleon scattering at HERA, by including the heavy flavour generator HARHEA and other program developments by Abbiendi and Stanco [7], who have primary responsibility for this area of the program. The main new features compared with version 4.6 are:

- Neutral- and charged-current deep inelastic scattering of charged leptons were fully included with optionally polarized incident leptons.
- Neutral- and charged-current heavy flavour electroproduction were included.
- Several technical defects in the simulation of deep inelastic processes in earlier versions were corrected.
- Bugs in heavy quark plus spectator cluster fragmentation were corrected.
- `REAL*8` was changed to `DOUBLE PRECISION` for machine independence, and common blocks re-ordered to put `DOUBLE PRECISION` variables first.
- Parameter `QCDLAM` now equals the 5-flavour QCD scale $\Lambda^{(5)}{}_{\overline{\mathrm{MS}}}$ in the high-x region. (Printed values of $\Lambda_{\overline{\mathrm{MS}}}$ for $N_f = 3, 4, 5$ in version 4.6 were actually *not* $\Lambda_{\overline{\mathrm{MS}}}$ so they are now suppressed).
- Default parameter values were reset to those found to give a satisfactory fit to event shape data of the OPAL Collaboration at LEP [34].

The main further new features in the current version 5.1, are:

- New e^+e^- processes: WW pair production (`IPROC` = 200, programmed by Kunszt [35]) and standard model Higgs boson production via the Bjorken process and boson–boson fusion (`IPROC` = 300 and 400, etc.).
- All hard hadronic processes (1000 < `IPROC` < 8000) are available also for photon and lepton beams (and e^+e^-) via the hadronic component of the photon (Drees–Grassie structure functions [36], plus Weizsacker–Williams approximation for photon emission by leptons).
- The soft hadron remnant fragmentation model outlined in Subsect. 2.6 is used in lepton–hadron processes (`IPROC` = 9000, etc.). Set `IPROC` = 19000 etc. to suppress soft fragmentation (see section 5).
- Optional linking to the CERN nucleon structure function library PDFLIB [37]. For this option, remove the dummy subroutines `PDFSET` and `STRUCTF` and set the new HERWIG parameter `MODPDF` to the value of the PDFLIB parameter `MODE` for the structure function set required.
- W and Z boson decay modes are now controlled by new parameters `MODBOS`(i): see section 15.
- The running coupling `HWUALF` is now matched continuously at the top quark mass as well as at the b and c masses (but the input parameter `QCDLAM` still represents the *5-flavour* $\Lambda^{(5)}{}_{\overline{\mathrm{MS}}}$).
- The random number generator `HWRGEN` is now one of those recommended in ref. [38] (l'Ecuyer's algorithm).
- The reading and writing of the Sudakov form factor table also reads and writes the values of relevant parameters and checks for conflicts.
- The program prints more detailed information on cross-sections, and on Higgs boson branching ratios if relevant.

Note that the following features are *not* yet included in the program: polarization of heavy quarks and leptons; weak decays of heavy quarks before hadronization; treatment of coherence in the small-x region of incoming jets [21,23]; multiple-parton interactions and parton shadowing; diffractive processes; QED radiative corrections; $W/Z/\gamma$ gauge bosons as components of parton showers.

4. Program structure

The main program `HWIGPR` is listed at the end of this paper. Various phase of the simulation can be suppressed by deleting the corresponding subroutine calls, or different subroutines may be substituted.

For example, in studies at the parton level everything from `CALL HWCFOR` to `CALL HWMEVT` can be omitted.

The following is a full list of subroutines and functions, which are classified according to their initial letters. The starred sections may be omitted for certain event types provided the corresponding subroutine calls are suppressed in `HWIGPR` or `HWBGEN`. Brief subroutine descriptions may be found in sect. 19.

Main program and initialisation:

`HWIGPR  HWIGIN`

User-provided routines to initialise, terminate and perform user's analysis of event data:

`HWABEG  HWAEND  HWANAL`

Parton branching generation with interfering gluons:

`HWBAZF  HWBCON  HWBFIN  HWBGEN  HWBJCO  HWBMAS  HWBRAN  HWBSPA`
`HWBSPN  HWBSUD  HWBSUG  HWBSU1  HWBSU2  HWBTIM  HWBVMC`

Cluster hadronization model:

`HWCCUT  HWCDEC  HWCFLA  HWCFOR  HWCGSP  HWCHAD`

Decay of unstable particles and heavy flavours:

`HWDBOS  HWDBOZ  HWDHAD  HWDHIG  HWDHVY  HWDIDP  HWDPWT  HWDTHR`
`HWDTWO  HWDWWT`

Elementary subprocess generation:

`HWEFIN  HWEGAM  HWEINI  HWEONE  HWEPRO  HWETWO`

Individual hard subprocesses:

`HWHBGF  HWHBKI  HWHBRN  HWHBSG  HWHDIS  HWHDYP  HWHEPA  HWHEPG`
`HWHEWW  HWHEWO  HWHEW1  HWHEW2  HWHEW3  HWHEW4  HWHHVY  HWHIGC`
`HWHIGF  HWHIGM  HWHIGS  HWHIGT  HWHIGW  HWHIGY  HWHIGZ  HWHPHO`
`HWHQCD  HWHQCP  HWHWEX  HWHWPR  HWHW1J`

* Soft minimum-bias hadron–hadron collision or underlying event:

`HWMEVT  HWMLPS  HWMNBI  HWMULT`

Random number generators:

`HWRAZM  HWREXP  HWREXT  HWRGAU  HWRGEN  HWRINT  HWRLOG  HWRPOW`
`HWRUNG  HWRUNI`

* Spacelike branching of incoming partons:

`HWSBRN  HWSDGG  HWSDGQ  HWSFBR  HWSFUN  HWSGAM  HWSGEN  HWSGQQ`
`HWSSPC  HWSSUD  HWSTAB  HWSVAL`

Miscellaneous utilities:

`HWUALF  HWUBPR  HWUDAT  HWUEEC  HWUEEQ  HWUEPR  HWUGAU  HWUIDT`
`HWUINC  HWUINE  HWULDO  HWULOB  HWULOF  HWULOR  HWUMAS  HWUPCM`
`HWURAP  HWURES  HWUROB  HWUROF  HWUROT  HWUSOR  HWUSQR  HWUSTA`
`HWUTAB  HWUTIM`

Table 1
Variables which must be set in the main program

Name	Description	Default
`PART1`	type of particle in beam 1	`'P   '`
`PART2`	type of particle in beam 2	`'P   '`
`PBEAM1`	momentum of beam 1	20000.0
`PBEAM2`	momentum of beam 2	20000.0
`IPROC`	type of process to generate	1500
`MAXEV`	number of events to generate	100

Table 2
`NAME` values for beam particle types

Beam	Name	Beam	Name
e^+	`'E+  '`	$\bar{p}$	`'PBAR'`
e^-	`'E-  '`	n	`'N   '`
μ^+	`'MU+ '`	$\bar{n}$	`'NBAR'`
μ^-	`'MU- '`	π^+	`'PI+ '`
γ	`'GAMA'`	π^-	`'PI- '`
p	`'P   '`		

Vector manipulation:

`HWVDIF   HWVDOT   HWVEQU   HWVSCA   HWVSUM   HWVZRO`

Warning messages and error handling:

`HWWARN`

In addition there are dummy version of the CERN PDFLIB structure function routines PDFSET and STRUCTF, which should be deleted if the PDFLIB package is to be used.

5. Beams and processes

As indicated above, a number of variables must be set in the main program to specify what is to be simulated, see table 1.

Note that in HERWIG the beam momenta `PBEAM1` and `PBEAM2` *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 beam particle types `PART1`, `PART2` can take any of the values `NAME` listed in table 2.

The currently available processes `IPROC` are as follows:

100	$e^+e^- \to q\bar{q}$ (all flavours)
100 + `IQ`	$e^+e^- \to q\bar{q}$ (`IQ` = 1, 2, 3, 4, 5, 6 for q = d, u, s, c, b, t)
110	$e^+e^- \to q\bar{q}g$ (all flavours)
110 + `IQ`	$e^+e^- \to q\bar{q}g$ (`IQ` as above)
150 + `IL`	$e^+e^- \to \ell\bar{\ell}$ (`IL` = 2, 3 for $\ell = \mu, \tau$)

200	$e^+e^-\to W^+W^-$ (see Sect. 15 on control of W/Z decays)
300	$e^+e^-\to Z^0H^0\to Z^0q\bar{q}$ (all flavours)
300 + `IQ`	$e^+e^-\to Z^0H^0\to Z^0q\bar{q}$ (`IQ` as above)
306 + `IL`	$e^+e^-\to Z^0H^0\to Z^0\ell\bar{\ell}$ (`IL` = 1, 2, 3 for $\ell = e, \mu, \tau$)
310, 311	$e^+e^-\to Z^0H^0\to Z^0W^+W^-, Z^0Z^0Z^0$
312	$e^+e^-\to Z^0H^0\to Z^0\gamma\gamma$
399	$e^+e^-\to Z^0H^0\to Z^0$ anything
400 + `ID`	$e^+e^-\to\nu\bar{\nu}H^0+e^+e^-H^0$ (`ID` as in `IPROC` = 300 + `ID`)
1350	$q\bar{q}\to Z^0/\gamma\to\ell\bar{\ell}$ (all lepton species)
1350 + `IL`	$q\bar{q}\to Z^0/\gamma\to\ell\bar{\ell}$ (`IL` = 1, 2, 3 for $\ell = e, \mu, \tau$)
1400	$q\bar{q}\to W^{\pm}\to q'\bar{q}''$ (all flavours)
1400 + `IQ`	$q\bar{q}\to W^{\pm}\to q'\bar{q}''$ (q' or q'' as above)
1450	$q\bar{q}\to W^{\pm}\to\ell\nu_{\ell}$ (all lepton species)
1450 + `IL`	$q\bar{q}\to W^{\pm}\to\ell\nu_{\ell}$ (`IL` as above)
1499	$q\bar{q}\to W^{\pm}\to$ anything
1500	QCD 2 → 2 hard parton scattering. After generation, `IHPRO` is subprocess (see section 13)
1600 + `ID`	$gg\to H^0$ (`ID` as in `IPROC` = 300 + `ID`)
1700 + `IQ`	QCD heavy quark production (`IQ` as above). After generation, `IHPRO` is subprocess (see section 13)
1800	QCD direct photon + jet production. After generation, `IHPRO` is subprocess (see section 14)
1900 + `ID`	$W^+W^-\to H^0$ (`ID` as in `IPROC` = 300 + `ID`)
2000	t production via W exchange (sum of 2001–2008)
2001–4	$\overline{ub}\to\overline{dt}$, $d\bar{b}\to u\bar{t}$, $\overline{db}\to\overline{ut}$, $ub\to dt$
2005–8	$\overline{cb}\to\overline{st}$, $s\bar{b}\to c\bar{t}$, $cb\to st$
2100	$W^{\pm}$ + jet production
2110	$W^{\pm}$ + jet production (Compton only: $gq\to Wq$)
2120	$W^{\pm}$ + jet production (annihilation only: $q\bar{q}\to Wg$)
8000	Minimum bias soft hadron–hadron event
9000	deep inelastic lepton scattering (neutral current)
9000 + `IQ`	deep inelastic lepton scattering (NC on flavour `IQ`)
9010	deep inelastic lepton scattering (charged current)
9010 + `IQ`	deep inelastic lepton scattering (CC on flavour `IQ`) N.B. Charged incoming leptons only
9100 + `IP`	heavy quark production by boson–gluon fusion in charged lepton–nucleon NC processes. `IP`: 1 = $c\bar{c}$, 2 = $b\bar{b}$, 3 = $t\bar{t}$
9110 + `IP`	CC processes. `IP`: 1 = $s\bar{c}$, 2 = $b\bar{c}$, 3 = $s\bar{t}$, 4 = $b\bar{t}$ (+ch. conj.)
10000 + `IP`	as `IPROC` = `IP` but with soft underlying event (soft remnant fragmentation in lepton–hadron) suppressed

Table 3
Adjustable parameters

Name	Description	Default
QCDLAM	Λ_{QCD} (see below)	0.20
RMASS(1)	down quark mass	0.32
RMASS(2)	up quark mass	0.32
RMASS(3)	strange quark mass	0.50
RMASS(4)	charmed quark mass	1.80
RMASS(5)	bottom quark mass	5.20
RMASS(6)	top quark mass	100.0
RMASS(13)	gluon effective mass	0.75
VQCUT	quark virtuality cutoff (added to quark masses in parton showers)	0.48
VGCUT	gluon virtuality cutoff (added to effective mass in parton showers)	0.06
CLMAX	maximum cluster mass parameter	3.50
PSPLT	split cluster spectrum parameter	1.00
QDIQK	maximum scale for gluon → diquarks	0.00
PDIQK	gluon → diquarks rate parameter	5.00
QSPAC	cutoff for spacelike evolution	2.50
PTRMS	intrinsic p_{T} in incoming hadrons	0.00
ENSOF	enhancement of underlying event	1.00

6. Input parameters

The quantities that may be regarded as adjustable parameters are given in table 3. Notes on parameters:

- QCDLAM can be identified at high momentum fractions (x or z) with the fundamental 5-flavour QCD scale $\Lambda^{(5)}{}_{\overline{\mathrm{MS}}}$. 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 [6].
- 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

$$1/Q_i + 1/Q_j < 1/\mathtt{QCDL3} \tag{6.1}$$

for either i or j or both gluons, where $Q_i = \mathtt{RMASS}(i) + \mathtt{VQCUT}$ for quarks, $\mathtt{RMASS(13)} + \mathtt{VGCUT}$ for gluons, and QCDL3 is the equivalent $\Lambda^{(3)}$ computed from QCDLAM. In the notation of ref. [6] and section 2, QCDL3 is the 3-flavour equivalent of QCDL5 where

$$\mathtt{QCDL5} = \mathtt{QCDLAM} \times \exp\left(\frac{151 - 9\pi^2}{138}\right)/\sqrt{2} = 1.109 \times \mathtt{QCDLAM}. \tag{6.2}$$

We have approximately

$$\mathtt{QCDL3} \approx \mathtt{QCDL5} \times L_\mathrm{b}^{107/1725} L_\mathrm{c}^{107/2025} \exp\left(\frac{L_\mathrm{b} + L_\mathrm{c}}{27} \right), \tag{6.3}$$

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

- `CLMAX` determines the maximum allowed mass of a cluster made from quarks i and j as follows

$$M^2 < \mathtt{CLMAX}^2 + (\mathtt{RMASS}(i) + \mathtt{RMASS}(j))^2. \tag{6.4}$$

Since the cluster mass spectrum falls rapidly at high mass, results become insensitive to `CLMAX` at large values.

- `PSPLT` determines the mass distribution in the cluster splitting $\mathrm{Cl}_1 \to \mathrm{Cl}_2 + \mathrm{Cl}_3$ when Cl_1 is above the maximum allowed mass. The masses of Cl_2 and Cl_3 are generated uniformly in $M^{\mathtt{PSPLT}}$. As long as the number of split clusters is small, dependence on `PSPLT` is weak.
- `QDIQK` greater than twice the lightest diquark mass enables non-perturbative gluon splitting into diquarks as well as quarks. The probability of this is $\mathtt{PDIQK} \times \mathrm{d}Q/Q$ for scales W below `QDIQK`. The diquark masses are taken to be the sum of constituent quark masses. Thus the default value `QDIQK` = 0 suppresses gluon → 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 $\mathrm{p\bar{p}}$ collision at c.m. energy $\mathtt{ENSOF} \times \sqrt{s}$.

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 [32,34].

A number of further parameters are needed to control the program and to turn various options on or off, see table 4. Printout options are:

`IPRINT` = 0 print program title only
1 print selected input parameters
2 1 + table of particle codes and properties
3 2 + tables of Sudakov form factors

See section 8 on form factors for details of `LRSUD` and `LWSUD`.

If `BGSHAT` is `.FALSE.`, the scale used for heavy quark production via boson–gluon fusion in lepton–hadron collision will be

$$\mathrm{Q}^2 = \frac{2\hat{s}\hat{t}\hat{u}}{\hat{s}^2 + \hat{t}^2 + \hat{u}^2}. \tag{6.5}$$

The quantities from `PTMIN` onwards control the region of phase space in which events are generated and the importance sampling inside those regions. See section 11 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 section 15 for details.

Table 4
Control parameters

Name	Description	Default
`IPRINT`	printout option	1
`MAXPR`	number of events to print out	1
`MAXER`	maximum number of errors	10
`LWEVT`	unit for writing output events	0
`LRSUD`	unit for reading Sudakov table	0
`LWSUD`	unit for writing Sudakov table	7
`NRN(1)`	random number seed 1	17673
`NRN(2)`	random number seed 2	63565
`WGTMAX`	max weight (0 to search for it)	0.0
`NOWGT`	generate unweighted events	`.TRUE.`
`AZSOFT`	soft gluon azimuthal correlations	`.TRUE.`
`AZSPIN`	gluon spin azimuthal correlations	`.TRUE.`
`NCOLO`	number of colours	3
`NFLAV`	number of (producible) flavours	6
`MODPDF`	PDFLIB structure function set (if negative do not use PDFLIB)	−1
`NSTRU`	input structure function set (1, 2 = Duke–Owens1,2; 3,4 = EHLQ1,2)	1
`EPOLN`	electron beam polarization in DIS (± 1 for fully r.h./l.h. polarized)	0.0
`BGSHAT`	scale = $\hat{s}$ for boson–gluon fusion	`.TRUE.`
`PTMIN`	min p_{T} in hadronic jet production	10.0
`PTMAX`	max p_{T} in hadronic jet production	10^8
`PTPOW`	$1/p_{\mathrm{T}}^{\mathtt{PTPOW}}$ for jet sampling	4.0
`YJMIN`	min jet rapidity	−8.0
`YJMAX`	max jet rapidity	8.0
`EMMIN`	min dilepton mass in Drell–Yan	10.0
`EMMAX`	max dilepton mass in Drell–Yan	10^8
`EMPOW`	$1/m^{\mathtt{EMPOW}}$ for Drell–Yan sampling	4.0
`Q2MIN`	min Q^2 in deep inelastic	9999.5
`Q2MAX`	max Q^2 in deep inelastic	10000.5
`Q2POW`	$1/Q^{2\,\mathtt{Q2POW}}$ for sampling	2.5
`THMAX`	max thrust in 3-parton production	0.9

In addition there are options to give different weigths 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. Common block file

The common block file is listed at the end of this paper.

8. Form factor file

HERWIG uses look-up tables of Sudakov form factors for the evolution of initial- and final-state parton showers. These can be read from an input file rather than being recomputed each time. The reading, writing and computing of form factor tables is controlled by integer parameters `LRSUD` and `LWSUD`:

`LRSUD` $= $ `N` > 0	read form factors for this run from unit `N`
`LRSUD` $= 0$	compute new form factor tables for this run
`LRSUD` < 0	form factor tables are already loaded
`LWSUD` $= $ `N` > 0	write form factors on unit `N` for future use
`LWSUD` $= 0$	do not write new form factor tables

The option `LRSUD` < 0 allows the program to be initialized several times in the same run (e.g. to generate various event types) without recomputing or rereading form factors.

Note that the Sudakov form factors depend on the parameters `QCDLAM`, `VQCUT`, `VGCUT`, `NCOLO`, `NFLAV`, `RMASS(13)` and `RMASS(`i`)` for $i = 1, \ldots,$ `NFLAV`. Consequently form factor tables *must* be recomputed every time any of these parameters is changed. In version 5.1, these parameters are written/read with the form factor tables and checks are performed to ensure consistency.

9. Event data

`/HEPEVT/` is the LEP standard common block containing current event data:

`NEVHEP`	event number
`NHEP`	number of entries for this event
`ISTHEP(I)`	status of entry `I` (see blow)
`IDHEP(I)`	identity of entry `I` (Particle Data Group code)
`JMOHEP(1,I)`	pointer to first mother of entry `I` (see below)
`JMOHEP(2,I)`	pointer to second mother of entry `I` (see below)
`JDAHEP(1,I)`	pointer to first daughter of entry `I` (see below)
`JDAHEP(2,I)`	pointer to last daughter of entry `I` (see below)
`PHEP(*,I)`	(p_x, p_y, p_z, E, M) of entry `I`: $M = \mathrm{sign}(\sqrt{\mathrm{abs}(m^2)}\,, m^2)$
`VHEP(*,I)`	(x, y, z, t) of production vertex of entry `I` (not yet used)

All momenta are given in GeV/c in the laboratory frame, in which the input beam momenta are `PBEAM1` and `PBEAM2` as specified by the user and point along the $+z$ and $-z$ directions, respectively. Final state particles have `ISTHEP(I)` $= 1$. See section 10 for a complete list of the special status codes used by HERWIG.

The identity codes `IDHEP` are as recommended by the LEP Working Group [31], i.e. as defined by the Particle Data Group [39] plus `IDHEP` $= 91$ for clusters, 94 for jets, and 0 for others with no PDG code. HERWIG also has its own internal identity codes `IDHW(I)`, stored in `/HWEVNT/`. The utility subroutine `HWUIDT` translates between HERWIG and PDG identity codes. See section 16 for further details.

The mother/daughter pointers are standard, except that `JMOHEP(2,I)` and `JDAHEP(2,I)` for a *parton* are its *colour mother* and *colour daughter*, i.e. the partons to which its colour and anticolour are connected, respectively. For this purpose the primary partons from a hard subprocess are all regarded as outgoing (see examples in sections 13, 16 and 18). Since a quark has no anticolour, `JDAHEP(2,I)` is used to point to its *flavour* partner. Similarly for `JMOHEP(2,I)` in the case of an antiquark.

In addition to entries representing partons, particles, clusters, etc., `/HEPEVT/` contains purely informational entries representing the total centre-of-mass momentum, hard and soft subprocess momenta, etc. See section 10 for the corresponding status codes.

Information from all stages of event processing is retained in `/HEPEVT/` so the same particle may appear several times with different status codes. For example, an outgoing parton from a hard scattering (entered initially with status 113 or 114) will appear after processing as an on-mass-shell parton before QCD branching (status 123, 124), an off-mass-shell entry representing the flavour and momentum of the outgoing jet (status 143, 144), and a jet constituent (157). It might also appear again in other contexts, e.g. as a spectator in a heavy flavour decay (status 154, 160).

Incoming partons (entered with status 111, 112, changed to 121, 122 after branching) give rise to spacelike jets (status 141, 142), with $m^2 < 0$, indicated by `PHEP(5,IHEP)` < 0, due to the loss of momentum via initial state bremsstrahlung. The same applies in principle to incoming leptons, but QED radiative corrections are not yet included.

Each parton jet begins with a status 141–144 jet entry giving the total flavour and momentum of the jet. The first mother pointer of this entry gives the location of the parent hard parton, while the second gives that of the subprocess centre-of-mass momentum. If QCD branching has occurred, this is followed by a lightlike `CONE` entry, which fixes the angular extent of the jet and its azimuthal orientation relative to the parton with which it interferes. The interfering parton is listed as the second mother of the cone. Next come the actual constituents of the jet. If no branching has occurred, there is no cone and the single jet constituent is the same as the jet. However, the jet and constituent momenta may not coincide if some transfer of momentum has occurred during cluster hadronization. See the Test Run Output at the end of this paper and section 18 for illustration of these points.

10. Status codes

A complete list of currently used HERWIG status codes is given below. Many are used only in intermediate stages of event processing. The most important for users are probably 1 (final-state particle), 101–103 (initial state), 141–144 (jets), and 199 (decayed b- and t-flavoured hadrons).

The event status `ISTAT` in common `/HWEVNT/` is roughly `ISTHEP` $-$ 100 where `ISTHEP` is the status of entries being processes. For completed events, `ISTAT` $= 100$.

1	final state particle
2	gluon split to $q\bar{q}$
3	documentation line
100	cone limiting jet evolution
101	"beam" (beam 1)
102	"target" (beam 2)
103	overall centre of mass
110	unprocessed hard process c.m.
111	unprocessed beam parton
112	unprocessed target parton
113	unprocessed first outgoing parton
114	unprocessed other outgoing parton
115	unprocessed spectator parton
120–125	as 110–115, after processing

130	lepton in jet (unboosted)
131–134	as 141–144, unboosted to c.m.
135	spacelike parton (beam, unboosted)
136	spacelike parton (target, unboosted)
137	spectator (beam, unboosted)
138	spectator (target, unboosted)
139	parton from branching (unboosted)
140	parton from gluon splitting (unboosted)
141–144	jet from parton type 111–114
145–150	as 135–140 boosted, unclustered
151	as 159, not yet clustered
152	as 160, not yet clustered
153	heavy quark before decay
154	spectator before heavy decay
155	spectator from beam
156	spectator from target
157	parton from QCD branching
158	parton from gluon splitting
159	parton from cluster splitting
160	spectator after heavy decay
161	beam cluster before soft process
162	target cluster before soft process
163	other cluster before soft process
164	unhadronized beam cluster
165	unhadronized target cluster
170	soft process centre of mass
171	soft cluster (beam, unhadronized)
172	soft cluster (target, unhadronized)
173	soft cluster (other, unhadronized)
181	beam cluster (no soft process)
182	target cluster (no soft process)
183	hard process cluster (hadronized)
184	soft cluster (beam, hadronized)
185	soft cluster (target, hadronized)
186	soft cluster (other, hadronized)
190–193	as 195–198, before decays
195	direct unstable non-hadron
196	direct unstable hadron (1-body cluster)
197	direct unstable hadron (2-body cluster)
198	indirect unstable hadron or lepton
199	decayed heavy flavour hadron

11. Event weights

The default is to generate unweighted events (`EVWGT = AVWGT`). Then event distributions are generated by computing a weight proportional to the cross-section and comparing it with a random number times the maximum weight. Set `WGTMAX` to the maximum weight, or to zero for the program to compute it. If a weight greater than `WGTMAX` is generated during execution, a warning is printed and `WGTMAX` is reset. Similarly if the efficiency is too low (`WGTMAX` too large). If these errors occur too often, output event distributions could be distorted.

To generate weighted events, set `NOWGT = .FALSE.` in common `/HWEVNT/`.

In QCD hard scattering and heavy flavour, direct photon, and W + jet production (`IPROC` = 1500, 1700, 1800, 2100, etc.) the transverse energy distribution of weighted events (or the efficiency for unweighted events) can be varied using the parameters `PTMIN`, `PTMAX` and `PTPOW`.

Similarly in Drell–Yan processes (`IPROC = 1350`, etc.) the lepton pair mass distribution is controlled by the parameters `EMMIN`, `EMMAX` and `EMPOW`, and in deep inelastic scattering (`IPROC = 9000`, etc.) the Q^2 distribution depends on `Q2MIN`, `Q2MAX` and `Q2POW`.

Data on weights generated are output at the end of the run. The mean weight is an estimate of the cross-section (in nanobarns) integrated over the region used for event generation. Note that the mean weight is the sum of weights divided by the total number of *weights* generated, not the total number of *events*.

In version 5.1, the estimated cross-section (in picobarns) and its error are also printed.

12. Heavy flavour decays

Heavy quark decays (b, t and higher generations) are treated as secondary hard subprocesses. Heavy flavoured hadrons are split into collinear heavy quark and spectator and the former decays independently. After decay, parton showers may be generated from coloured decay products, in the usual way. See ref. [5] for details of the treatment of colour coherence in these showers.

As we discussed in section 2, for high values of the top quark mass, the t quark is expected to decay before it has time to form a hadron. At present this possibility is *not* taken into account in HERWIG.

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) (e, ν_e) (μ, ν_μ) (τ, ν_τ), 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 $\bar{b}$-hadrons, one would set `FBTM(J,1)` = 0 for `J` ≠ 5 and `FBTM(5,1)` = 1, without changing `FBTM(J,2)`. `FTOP` is the corresponding array for the top quark, while `FHVY` is for quarks heavier than top. All these quantities can be changed from event to event.

13. QCD hard subprocesses

At present only 2 → 2 subprocesses are implemented. They are classified as shown in table 5. "c/f conn." refers to the colour/flavour connections between the partons: "*i j k l*" means that the colour of parton 1 comes from parton *i*, that of 2 from *j*, etc. For antiquarks, which have no colour (only anticolour), the label shows instead to which parton the flavour is connected. For this colour/flavour labelling all partons are defined as outgoing. Thus, for example, process 10 has colour connections 3 1 4 2,

Table 5
QCD hard subprocesses

IHPRO	$1+2 \to 3+4$	c/f conn.
1	$q+q \to q+q$	3421
2	$q+q \to q+q$	4312
3	$q+q' \to q+q'$	3421
4	$q+\bar{q} \to q'+\bar{q}'$	2413
5	$q+\bar{q} \to q+\bar{q}$	3142
6	$q+\bar{q} \to q+\bar{q}$	2413
7	$q+\bar{q} \to g+g$	2413
8	$q+\bar{q} \to g+g$	2341
9	$q+\bar{q}' \to q+\bar{q}'$	3142
10	$q+g \to q+g$	3142
11	$q+g \to q+g$	3421
12	$\bar{q}+q \to \bar{q}'+q'$	3142
13	$\bar{q}+q \to \bar{q}+q$	2413
14	$\bar{q}+q \to \bar{q}+q$	3142
15	$\bar{q}+q \to g+g$	3142
16	$\bar{q}+q \to g+g$	4123
17	$\bar{q}+q' \to \bar{q}+q'$	2413
18	$\bar{q}+\bar{q} \to \bar{q}+\bar{q}$	4312
19	$\bar{q}+\bar{q} \to \bar{q}+\bar{q}$	3421
20	$\bar{q}+\bar{q}' \to \bar{q}+\bar{q}'$	4312
21	$\bar{q}+g \to \bar{q}+g$	2413
22	$\bar{q}+g \to \bar{q}+g$	4312
23	$g+q \to g+q$	2413
24	$g+q \to g+q$	3421
25	$g+\bar{q} \to g+\bar{q}$	3142
26	$g+\bar{q} \to g+\bar{q}$	4312
27	$g+g \to q+\bar{q}$	2413
28	$g+g \to q+\bar{q}$	4123
29	$g+g \to g+g$	4123
30	$g+g \to g+g$	4312
31	$g+g \to g+g$	2413

corresponding to the colour flow diagram in fig. 2. When different colour flows are possible, they are listed as separate subprocesses. This separation is not exact but is normally a good approximation [1,24]. The sum of the colour flows is the exact lowest-order cross-section.

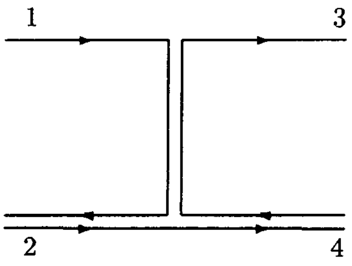

Fig. 2. Colour flow diagram of QCD hard subprocesses.

Table 6
QCD direct photon subprocesses

`IHPRO`	$1+2\to 3+4$	c/f conn.
41	$q+\bar{q}\to g+\gamma$	231
41	$q+g\to q+\gamma$	312
43	$\bar{q}+q\to g+\gamma$	312
44	$\bar{q}+g\to \bar{q}+\gamma$	231
45	$g+q\to q+\gamma$	231
46	$g+\bar{q}\to \bar{q}+\gamma$	312
47	$g+g\to g+\gamma$	231

14. QCD direct photon subprocesses

QCD direct photon subprocesses are listed in table 6. Note that at present the gluon fusion process 47, which proceeds via quark loops and is very small, is neglected.

15. Electroweak subprocesses

HERWIG generates Higgs bosons through gluon fusion and W fusion in hadron–hadron collisions (`IPROC=1600+ID` and `1900+ID`), and in lepton–lepton collisions through the Bjorken process (i.e. $Z^{(*)}\to Z^{(*)}H$ with one or both Z's off-shell) and W fusion (`IPROC=300+ID` and `400+ID`). Each process is generated according to the exact leading order matrix element in the s-channel approximation. This results in unitarity violation for $m_H \gg m_w$, $s \gtrsim$ a few m_H^2, (where $s=q_H^2$), so to regularize this, the $m_H\Gamma_H$ in the propagator can be replaced by $\sqrt{s}\,\Gamma_H(s)$. The variable `IOPHIG` controls this procedure, see table 7, where reweighting means weighting the distribution back to

$$\frac{\sqrt{s}\,\Gamma_H(s)}{\left(s-m_H^2\right)^2+\sqrt{s}\,\Gamma_H(s)}. \tag{15.1}$$

The default is `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 `HWHIGM`. In all cases, the distribution is restricted to the range $[m_H - \texttt{GAMMAX}\times\Gamma_H,\ m_H + \texttt{GAMMAX}\times\Gamma_H]$. `GAMMAX` 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 noticably for $m_H \lesssim 500$ GeV, and `GAMMAX` can safely be increased if necessary.

Table 7
Electroweak subprocesses

`IOPHIG`	Choose s according to	Reweight?
0	$s^2/((s-m_H^2)^2+m_H\Gamma_H)$	yes
1	$1/((s-m_H^2)^2+m_H\Gamma_H)$	yes
2	$s^2/((s-m_H^2)^2+m_H\Gamma_H)$	no
3	$1/((s-m_H^2)^2+m_H\Gamma_H)$	no

Table 8
Variable MODBOS(i)

MODBOS(i)	W decay	Z decay
0	all	all
1	$q\bar{q}$	$q\bar{q}$
2	$e\nu$	e^+e^-
3	$\mu\nu$	$\mu^+\mu^-$
4	$\tau\nu$	$\tau^+\tau^-$
5	$e\nu$ and $\mu\nu$	e^+e^- and $\mu^+\mu^-$
6	all	$\nu\nu$
> 6	all	all

For each process, ID controls the Higgs decay: ID = 1–6 for quarks, 7–9 for leptons, 10, 11 for WW/ZZ pairs, and 12 for photons. In addition ID = 0 gives quarks of all flavours, and ID = 99 gives all decays. For each process, the average event weight is the cross section in nanobarn times the branching fraction to the requested decay. The branching ratios to quarks use the next-to-leading logarithm corrections, those to WW/ZZ pairs allow for one or both bosons off-shell.

Gauge bosons formed by lepton–antilepton or quark–antiquark annihilation (IPROC = 100–199, 1300–1499) have their decay determined by the process code IPROC. Gauge bosons are also generated through the processes of W + 1 parton production in hadron–hadron collisions, and WW pair production in lepton–lepton collisions, as well as in the Higgs processes mentioned above. In these cases their decay is controlled by the variable MODBOS(i). This controls the decay of the ith gauge boson per event, see table 8.

All entries of MODBOS default to 0. Bosons which are produced in pairs (i.e. from WW pair production, or Higgs decay) are symmetrized in MODBOS(i) and 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 (ID = 10, 11) and not if ID = 99. The spin correlations in the decays are handled in one of two ways:

(a) the diagonal members of the spin density matrix are stored in RHOHEP(i,IHEP), where $i = 1, 2, 3$ for helicity $= i - 2$ in the centre-of-mass frame of their production, for processes where this matrix is diagonal (i.e. there is no interference between spin states),

(b) the correlations in the decay are handled directly by the production routine where (a) is not possible.

16. Including new subprocesses

It should not be difficult for users to include further subprocesses in this version of the program if required. The parton and hard subprocess 4-momenta, masses and identity codes need to be entered in COMMON/HEPEVT/ with the appropriate status codes ISTHEP(I) = 110–114 to tell the program which is which (see the table in section 10). The colour/flavour structure should be specified by the second mother and daughter pointers as explained in sect. 13 (see also the Test Run Output and section 18).

The HERWIG identity codes IDHW(I) in COMMON/HWEVNT/ also need to be set correctly. The IDHW codes can be listed in a run with IPRINT = 2: the most important are the quarks 1–6 (as IDHEP), antiquarks 7–12, gluon 13, overall centre-of-mass 14, hard centre-of-mass 15, soft centre-of-mass 16, photon 59, leptons 121–126, antileptons 127–132.

The utility subroutine HWUIDT(IOPT,IPDG,IHWG,NAME) is provided to translate between Particle Data Group code IPDG, HERWIG code IHWG, and HERWIG CHARACTER*4 NAME, with IOPT = 1, 2, 3 depending on which of IPDG, IHWG and NAME is the input argument.

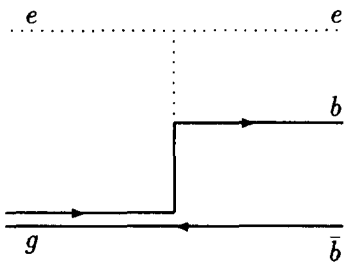

Fig. 3. Colour structure of the process of virtual photon–gluon fusion.

Consider for example the process of virtual photon–gluon fusion to make $b + \bar{b}$ in proton–electron collisions (in fact this process is now included as `IPROC` = 9102). We assume the user provides a subroutine to generate the momenta `PHEP` for the hard subprocess $e + g \to e b\bar{b}$. The colour structure is given in fig. 3. Thus the momenta generated, together with those of the initial beams and the overall centre of mass, could be entered in the sequence given in table 9. Note that if there are more than two outgoing partons, the first has status 113 and all the others 114. Each parton has `JMOHEP(1,I)` = 6 to indicate the location of the hard center of mass for this subprocess, while `JMOHEP(2,I)` gives the location of the colour mother (treating the incoming gluon as outgoing) or the connected electron. `JDAHEP(1,I)` will be set by the jet generator `HWBGEN`, while `JDAHEP(2,I)` points to the anticolour mother (or connected electron). Finally the HERWIG identifiers `IDHW(I)` could be set to the indicated values by means of the translation subroutine `HWUIDT` as follows:

```
      CHARACTER*4 NAME
      .....
      NHEP=9
      IDHEP(1)=11
      IDHEP(2)=2212
      .....
      IDHEP(9)=-5
      DO 10 I=1,NHEP
   10 CALL HWUIDT(1,IDHEP(I),IDHW(I),NAME)
      IDHW(6)=15
```

The last statement is needed because `IDPDG(I)` = 0 returns `IDHW(I)` = 14. If subroutine `HWBGEN` is

Table 9
`/HEPEVT/` entries for the process of fig. 3

IHEP	Entry	ISTHEP	IDHEP	JMOHEP	JDAHEP	IDHW
1	e beam	101	11	0 0	0 0	121
2	p beam	102	2212	0 0	0 0	73
3	ep c.m.	103	0	0 0	0 0	14
4	e in	111	11	6 7	0 7	121
5	gluon	112	21	6 9	0 8	13
6	hard cm	110	0	4 5	7 9	15
7	e out	113	11	6 4	0 4	121
8	b	114	5	6 5	0 9	5
9	$\bar{b}$	114	−5	6 8	0 5	11

now called, it will find the coloured partons and generate QCD jets from them. Subsequent calls to `HWCFOR` etc. can then be used to form clusters and hadronize them.

If the hard subprocess routine is called from `HWEPRO`, like those already provided, it should have two options controlled by the logical variable `GENEV` in `COMMON/HWHARD/`. For `GENEV=.FALSE.`, an event weight (normally the cross-section in nanobarns) is generated and stored as `EVWGT` in `COMMON /HWEVNT/`. If this weight is accepted by `HWEPRO`, the subroutine is called a second time with `GENEV=.TRUE.` and the corresponding event data should then be generated and stored as explained above. On certain computers it will be necessary to `SAVE` those variables that determine event characteristics between the two subroutine calls.

17. Error conditions

Certain combinations of input parameters may lead to problems in execution. HERWIG tries to detect these and print a warning. Errors during execution are dealt with by `HWWARN` which prints the calling subprogram and a code and takes appropriate action. In general, the larger the code the more serious the problem. Refer to the source program to find out why `HWWARN` was called. Events can be rerun by setting the random number seeds `NRN(1)` and `NRN(2)` to the values given in the error message or event dump. The contents of `/HEPEVT/` can by printed by calling `HWUEPR`, those of `/HWPART/` (the last parton shower) by calling `HWUBPR`.

Examples of error messages are:

```
HWWARN CALLED FROM SUBPROGRAM HWSBRN: CODE = 101
EVENT      31:   SEEDS =  422399901 &  771980111  WEIGHT = 0.3893E-08
EVENT KILLED.   EXECUTION CONTINUES
```

Spacelike (initial state) parton branching had no phase space. This can happen due to cutoffs which are slightly different in the hard subprocess and the parton shower. Action taken: program throws away this event and starts a new one.

```
HWWARN CALLED FROM SUBPROGRAM HWCHAD: CODE = 102
EVENT      51:   SEEDS = 1033784787 & 428957533  WEIGHT = 0.3893E-08
EVENT KILLED.   EXECUTION CONTINUES
```

A cluster has been formed with too low a mass to represent any hadron of the correct flavour, and there is no colour-connected cluster from which the necessary additional mass could be transferred. Action taken: program throws away this event and starts a new one.

```
HWWARN CALLED FROM SUBPROGRAM HWUINE: CODE= 200
EVENT SURVIVES.  RUN ENDS GRACEFULLY
```

CPU time limit liable to be reached before generating `MAXEV` events. Action taken: skips to terminal calculations using existing events.

```
HWWARN CALLED FROM SUBPROGRAM HWBSUD: CODE= 500
RUN CANNOT CONTINUE
```

The table of Sudakov form factors read on unit `LRSUD` does not extend to the maximum momentum scale `QLIM` specified for this run. Action taken: run aborted. The user must either reduce `QLIM` or set `LRSUD=0` to make a bigger table (set `LWSUD` nonzero to write it).

```
HWWARN CALLED FROM SUBPROGRAM HWBSUD: CODE= 515
RUN CANNOT CONTINUE
```

The table of Sudakov form factors read on unit `LRSUD` is for a different value of a relevant parameter (in this case the b quark mass). Action taken: run aborted. The user must make a new table (set `LWSUD` nonzero to write it).

18. Guide to Test Run Output

At the end of this paper we give a complete listing of output from the program, set up for $e^+e^- \to b\bar{b}g$ at a center-of-mass energy of 91.2 GeV. The main features of the output are discussed hereafter.

After listing the more important input parameter values, the program prints the message

```
PDFLIB STRUCT FUNCTIONS NOT USED
```

to tells us that the built-in structure functions have been selected, rather than the `PDFLIB` library (although of course they are not relevant for this process). The message

```
NO EVENTS WILL BE WRITTEN TO DISK
```

reminds the user that `LWEVT` = 0 for this run. Then a table of Sudakov form factors for parton branching is computed, since none has been provided on an input file (`LRSUD` = 0). The table is written on an output file (`LWSUD` = 7) for use in future runs:

```
WRITING SUDAKOV TABLE ON UNIT   7
```

The default particle data table is modified by calling `HWUSTA('PIO ')` to suppress π^0 decays:

```
PARTICLE TYPE 21=PIO  SET STABLE
```

Next the program searches for the maximum weight, i.e. the maximum cross-section in the available phase space, as implied by the default value `WGTMAX` = 0. The parameter

```
MAX THRUST FOR 2->3    =     0.9000
```

with

```
PROCESS CODE         =            115
```

means that $b\bar{b}g$ events with a thrust of less than 0.9 will be generated. After this search, the result

```
CROSS SECTION (PB) =    719.8381
ERROR IN C-S (PB)  =     17.2916
EFFICIENCY PERCENT =      7.9329
```

tells us that the initial estimate of the cross-section for this subprocess in this region is 720 ± 17 picobarns, and the fraction of weights accepted for event generation is likely to be about 8%.

Since the default is `MAXPR` = 1, the first generated event is printed. The heading

```
EVENT      1:       45.60 GEV/C E+    ON       45.60 GEV/C E-    PROCESS:   115
SEEDS:       17673 &       63565   STATUS: 100   ERROR:    0  WEIGHT: 0.7198E+00
```

tells us the beam and target, the random number seeds at the start of the event (so that it can be regenerated by setting `NRN(1&2)` to these values), and the process code `IPROC`. The status 100 means a complete event was generated and the zero error code means no problems were encountered. Since `NOWGT=.TRUE.` (unweighted event generation), each event has the mean weight computed earlier.

Table 10
Contents of COMMON /HEPEVT/

Entry	Description
1-3	initial state
4	hard subprocess: Z^0/γ production
5-7	Z^0/γ decay to $b\bar{b}g$
8-21	parton showers
22-33	gluon splitting
34-40	cluster formation
41-69	cluster and hadron decays
70-83	weak decays of $\overline{B^0}$ and B^+ mesons
84-124	hadronization of $B^+/\overline{B^0}$ decay products

Next come the content of COMMON/HEPEVT/ and related quantities. The various parts of this particular event are located as given in table 10. We discuss each part in turn.

INITIAL STATE (entries 1-3)

CMF represents the overall centre of mass of the initial state. The "mother" pointer MOi = JMOHEP(i, IHEP) and "daughter" pointer DAi = JDAHEP(i, IHEP) are set to zero for these entries.

HARD SUBPROCESS (entry 4)

and

H/W/Z BOSON DECAYS (entries 5-7)

Z0/G is the hard subprocess centre of mass (which is equal to the overall centre of mass because initial state QED radiation is not yet included). Its mother and daughter pointers give the locations of the incoming and outgoing partons. The status code 123 corresponds to the first outgoing parton, and 124 to all other outgoing partons in the hard subprocess. The first mother pointers show the location of the hard centre of mass, and the second mother of each parton is the "colour mother", as explained above. Thus the colours of partons 5, 6, 7 are connected to 6, 7, 5 respectively. Since antiquarks carry no colour MO2 for the $\bar{b}$ is used for the flavour connection to the b. Similarly, the first daughter points to the associated jet but the second daughter is the colour daughter, i.e. the parton to which this one's anticolour (or its flavour, in the case of the b) is connected. Thus the anticolour connections of 5, 6, 7 in this case are to 7, 5, 6. The colour flow diagram is given in fig. 4. Gluon radiation from the b and the $\bar{b}$ will be limited by interference with the gluon, and that from the gluon by the b or $\bar{b}$. The momenta and masses of the partons are the raw on-shell values generated before QCD radiative corrections.

If the incoming partons were coloured, then they would have status 121 and 122, and in specifying their colour connections, they would be regarded as outgoing.

PARTON SHOWERS (entries 8-21)

The QCD cascade from each hard parton is generated in sequence. First there is a jet entry (IDHEP = 94) giving the total jet momentum, flavour and mass. In the case of initial state jets the mass would represent $-|q^2|^{1/2}$. MO1 gives the parent hard parton and MO2 the hard centre of mass. DA1 and

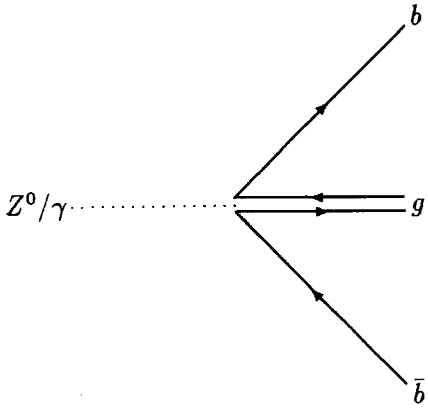

Fig. 4. Colour flow diagram of a Z boson decay.

DA2 point to the first and last parton in the jet after perturbative branching. If branching occurs, the next entry (CONE) is a lightlike 4-vector defining the radiation cone and the orientation of the radiation pattern.

The partons in the jet (ISTHEP = 157, plus 155, 156 for spectators, with gluons reset to 2 by gluon splitting subroutine HWCGSP) have their colour and anticolour connections specified by MO2 and DA2, respectively, as described above for the hard subprocess. The b jet is given in entries 8–11, the gluon jet in entries 12–17, and the $\bar{\mathrm{b}}$ jet in entries 18–21.

GLUON SPLITTING (entries 22–23)

As the first step in the cluster hadronization model, any gluons in the jets are split into light quark-antiquark pairs. The flavours of the pairs are chosen at random amongst those allowed by kinematics. The colour connections are remade accordingly.

CLUSTER FORMATION (entries 34–40)

Each quark (or antidiquark) is combined with its colour mother antiquark (or diquark) to make a cluster with the sum of their 4-momenta. Non-beam clusters with masses above the maximum specified by Eq. (2.2) would be split by creating new quark-antiquark pairs with ISTHEP = 159 (there are no such pairs in this event). In a hadron collision, the beam remnant clusters, i.e., those containing the spectator quarks from the incident hadrons (ISTHEP = 167, 168) would be split into 2 'soft' clusters each (see new features of version 4.3, above), making another two pairs. The clusters themselves are then listed.

CLUSTER DECAYS (entries 41–54)

The clusters, including the b-flavoured clusters 34 and 40, now decay isotropically into pairs of hadrons chosen according to density of states. Particles with ISTHEP = 1 are stable. ISTHEP = 199 indicates a heavy (b or t) hadron which will later decay weakly via a secondary hard subprocess.

`STRONG HADRON DECAYS` (entries 55–69)

Next come the decay products of unstable hadrons generated in the cluster decays. Remember that the π^0 was set stable in the initialization phase.

`HEAVY FLAVOUR DECAYS` (entries 70–83)

The $\overline{B^0}$ and B^+ are split into collinear heavy quarks and spectators (entries 70–73). Then the heavy quarks decay weakly, the spectators are copied and given the correct colour connection labels, and the leptons are copied and re-labelled as final state particles (entries 74–83).

`PARTON SHOWERS` (entries 84–91)

In the hadronization of the b decay products, the heavy flavour decays are treated as new hard processes, in which secondary parton showers may be generated. In this event, the phase space for branching is small and none of the decay quarks emits a gluon.

`CLUSTER FORMATION` (entries 92–94) and `CLUSTER DECAYS` (entries 95–100)

The weak decay products are thus the lepton pair already processed plus three clusters, which decay as in a primary hard process.

`STRONG HADRON DECAYS` (entries 101–124)

The subsequent charmed particle decays are generated according to the simplified particle data tables. In $t \to b \to c$ decays, the secondary b's would be hadronized, undergo strong decays and then weak decay in the same way as above.

Generation of this event is now complete. In the case of hadron collisions, this would be followed by the treatment of the soft underlying event. The undecayed beam clusters would undergo a soft collision with the remaining centre-of-mass energy in parallel with the hard subprocesses. This would produce soft clusters with a flat rapidity distribution and low transverse momenta, which would decay to provide the low-p_T hadrons of the soft underlying event.

After the 100 events requested have been generated, an analysis of the associated weight distribution is printed. The information

```
NUMBER OF WEIGHTS  =   1339
```

and

```
CROSS SECTION (PB) =     732.2993
ERROR IN C-S  (PB) =      73.8432
```

gives us a new, independent estimate of the cross-section (which is less accurate in this case since the number of weights is less than the 2000 generated in the initial search). Finally we are told that the Monte Carlo efficiency of elementary subprocess generation during the run was 8%, as was predicted in the initial search:

```
EFFICIENCY PERCENT =       8.0702
```

19. Subroutine descriptions

`HWIGPR`	main program
`HWIGIN`	default initializations

`HWABEG`	initializes user's analysis
`HWAEND`	terminates user's analysis
`HWANAL`	performs user's analysis on event

`HWBAZF`	computes azimuthal correlation functions
`HWBCON`	makes colour connections between jets
`HWBFIN`	transfers external lines of jet to `/HEPEVT/`
`HWBGEN`	finds unevolved partons and generates jets
`HWBJCO`	combines jets with correct kinematics
`HWBMAS`	computes masses and trans. momenta in jet
`HWBRAN`	generates a time-like parton branching
`HWBSPA`	computes momenta in space-like jet
`HWBSPN`	computes spin density/decay matrices
`HWBSUD`	computes (or reads) Sudakov form factors
`HWBSUG`	integrand in gluon Sudakov form factor
`HWBSU1`	first term in quark Sudakov form factor
`HWBSU2`	second term in quark Sudakov form factor
`HWBTIM`	computes momenta in time-like jet
`HWBVMC`	virtual mass cutoff for parton type `ID`

`HWCCUT`	cuts a massive cluster in two
`HWCDEC`	decays clusters into primary hadrons
`HWCFLA`	sets up flavours for `HWCHAD`
`HWCFOR`	forms clusters
`HWCGSP`	splits gluons
`HWCHAD`	decays a cluster into one or two hadrons

`HWDBOS`	finds and decays W and Z bosons
`HWDBOZ`	chooses decay mode of W and Z bosons
`HWDHAD`	generates decays of unstable hadrons
`HWDHIG`	finds and decays Higgs bosons
`HWDHVY`	finds and decays heavy flavours
`HWDIDP`	chooses a parton for `HWDHVY`
`HWDPWT`	phase space decay weight
`HWDTHR`	generates a three-body decay
`HWDTWO`	generates a two-body decay
`HWDWWT`	weak (V–A) decay weight

`HWEFIN`	final calculations on elementary subprocess
`HWEGAM`	generates Weizsacker–Williams photon
`HWEINI`	initializes elementary subprocess
`HWEONE`	sets up a 2 → 1 hard subprocess
`HWEPRO`	generates elementary subprocess

HWETWO	sets up a $2 \to 2$ hard subprocess

HWHBGF	hard subprocess: boson–gluon fusion (BGF)
HWHBKI	computes kinematics for BGF
HWHBRN	returns a phase-space point for BGF
HWHBSG	computes cross-section for BGF
HWHDIS	hard subprocess: deep inelastic e/μ quark
HWHDYP	hard subprocess: Drell–Yan Z^0/γ prodn
HWHEPA	hard subprocess: $e^+e^- \to q\bar{q}$
HWHEPG	hard subprocess: $e^+e^- \to q\bar{q}g$
HWHEWW	hard subprocess: $e^+e^- \to W^+W^-$
HWHEW0	$e^+e^- \to W^+W^-$ subroutine
HWHEW1	$e^+e^- \to W^+W^-$ subroutine
HWHEW2	$e^+e^- \to W^+W^-$ subroutine
HWHEW3	$e^+e^- \to W^+W^-$ subroutine
HWHEW4	$e^+e^- \to W^+W^-$ subroutine
HWHHVY	hard subprocess: heavy quark production
HWHIGC	Higgs $\to \gamma\gamma$ decay
HWHIGF	Higgs $\to W^+W^-$ decay
HWHIGM	choose Higgs mass for production routines
HWHIGS	hard subprocess: $gg \to$ Higgs
HWHIGT	computes $gg \to$ Higgs cross-section
HWHIGW	$W^+W^- \to$ Higgs cross-section
HWHIGY	computes $e^+e^- \to Z^0 \to Z^0H^0$ cross section
HWHIGZ	hard subprocess: $e^+e^- \to Z^0 \to Z^0H^0$
HWHPHO	hard subprocess: direct photon production
HWHQCD	hard subprocess: QCD $2 \to 2$
HWHQCP	identifies QCD $2 \to 2$ hard subprocess.
HWHWEX	top production by W exchange
HWHWPR	hard subprocess: W production
HWHW1J	hard subprocess: W + jet production

HWMEVT	generates min. bias or soft underlying event
HWMLPS	generates longitudinal phase space
HWMNBI	computes negative binomial probability
HWMULT	chooses min. bias charged multiplicity

HWRAZM	randomly rotated azimuth
HWREXP	random number: exponential distribution
HWREXT	random number: exponential transverse mass
HWRGAU	random number: Gaussian
HWRGEN	random number generator (l'Ecuyer's method)
HWRINT	random integer
HWRLOG	random logical
HWRPOW	random number: power distribution
HWRUNG	random number: uniform + Gaussian tails
HWRUNI	random number: uniform

HWSBRN	generates space-like parton branching
HWSDGG	Drees–Grassie gluon distribution in photon
HWSDGQ	Drees–Grassie quark distribution in photon
HWSFBR	chooses a space-like branching
HWSFUN	hadron structure functions
HWSGAM	gamma function (for structure functions)
HWSGEN	generates x values for spacelike parton
HWSGQQ	inserts $g \rightarrow q\bar{q}$ part of gluon form factor
HWSSPC	replaces spacelike partons by spectators
HWSSUD	Sudakov form factor/structure function
HWSTAB	interpolates in function table (for HWSSUD)
HWSVAL	checks for valence parton

HWUALF	two-loop QCD running coupling constant
HWUBPR	prints branching data for last parton shower
HWUDAT	particle properties (N.B. BLOCK DATA)
HWUEEC	computes e^+e^- cross-section and asymmetry
HWUEEQ	e^+e^- cross-section and asymmetry (given q)
HWUEPR	prints event data
HWUGAU	adaptive Gaussian integration
HWUIDT	translates particle identity codes
HWUINC	initial parameter-dependent calculations
HWUINE	initializes an event
HWULDO	Lorentz 4-vector dot product
HWULOB	Lorentz transformation: rest frame → lab
HWULOF	Lorentz transformation: lab → rest frame
HWULOR	multiplies by Lorentz matrix
HWUMAS	puts mass in 5th component of vector
HWUPCM	centre-of-mass momentum
HWURAP	rapidity
HWURES	computes/prints resonance data
HWUROB	rotation by inverse of matrix R
HWUROF	rotation by matrix R
HWUROT	computes rotation R from vector to z-axis
HWUSOR	sorts an array in ascending order
HWUSQR	square root with sign retention
HWUSTA	makes a particle type stable
HWUTAB	interpolates in a table
HWUTIM	checks time remaining (N.B. VAX Fortran)

HWVDIF	vector difference
HWVDOT	vector dot product
HWVEQU	vector equality
HWVSCA	vector times scalar
HWVSUM	vector sum
HWVZRO	vector zero

HWWARN	issues warnings and deals with errors

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PROGRAM LISTING

```
      PROGRAM HWIGPR
C---COMMON BLOCKS ARE INCLUDED AS FILE HERWIG51.INC
      INCLUDE 'HERWIG51.INC'
      INTEGER N
C---MAX NUMBER OF EVENTS THIS RUN
      MAXEV=100
C---BEAM PARTICLES
      PART1='P   '
      PART2='P   '
C---BEAM MOMENTA
      PBEAM1=20000.
      PBEAM2=20000.
C---PROCESS
      IPROC=1500
C---INITIALISE OTHER COMMON BLOCKS
      CALL HWIGIN
C---USER CAN RESET PARAMETERS AT THIS POINT,
C   OTHERWISE DEFAULT VALUES IN HWIGIN WILL BE USED.
      PTMIN=1000.
C---COMPUTE PARAMETER-DEPENDENT CONSTANTS
      CALL HWUINC
C---CALL HWUSTA TO MAKE ANY PARTICLE STABLE
      CALL HWUSTA('PIO ')
C---USER'S INITIAL CALCULATIONS
      CALL HWABEG
C---INITIALISE ELEMENTARY PROCESS
      CALL HWEINI
C---LOOP OVER EVENTS
      DO 100 N=1,MAXEV
C---INITIALISE EVENT
      CALL HWUINE
C---GENERATE HARD SUBPROCESS
      CALL HWEPRO
C---GENERATE PARTON CASCADES
      CALL HWBGEN
C---DO CLUSTER FORMATION
      CALL HWCFOR
C---DO CLUSTER DECAYS
      CALL HWCDEC
C---DO UNSTABLE PARTICLE DECAYS
      CALL HWDHAD
```

```
C---DO HEAVY FLAVOUR DECAYS
      CALL HWDHVY
C---ADD SOFT UNDERLYING EVENT IF NEEDED
      CALL HWMEVT
C---USER'S EVENT ANALYSIS
      CALL HWANAL
  100 CONTINUE
C---TERMINATE ELEMENTARY PROCESS
      CALL HWEFIN
C---USER'S TERMINAL CALCULATIONS
      CALL HWAEND
      STOP
      END
```

COMMON BLOCK FILE

```
C          ****COMMON BLOCK FILE FOR HERWIG VERSION 5.1****
C ALTERATIONS:DOUBLED NQEV
C              DOUBLED NMXHEP
C              CONVERTED TO DOUBLE PRECISION
C              INTRODUCED NMXSUD (MAX NUMBER OF ENTRIES IN LOOKUP
C                TABLES OF SUDAKOV FORM FACTORS)
C              ADDED NEW VARIABLE RHOHEP: LIKE RHOPAR BUT WITH 3 CMPTS
C  25/7/90     CHANGED TREATMENT OF ALPHA-S
C  3/11/90     CHANGED ORDER (DOUBLE PRECISION FIRST), ADDED EPOLN
C  29/3/91     ADDED NEW COMMON /HWBOSC/, MADE NRN,IBRN ARRAYS(2)
C
      IMPLICIT NONE
C
      DOUBLE PRECISION PHEP,VHEP,PBEAM1,
     & PBEAM2,QCDLAM,VGCUT,VQCUT,BETAF,CAFAC,
     & CFFAC,CLMAX,PSPLT,QSPAC,PTRMS,PXRMS,QG,QV,SWEIN,SCABI,PDIQK,
     & QDIQK,ENSOF,TMTOP,ZBINM,GAMW,GAMZ,GAMH,PGSMX,PGSPL,PPAR,VPAR,
     & PHIPAR,DECPAR,RHOPAR,RHOHEP,XFACT,PTINT,EVWGT,AVWGT,WGTMAX,
     & WGTSUM,WSQSUM,WBIGST,TLOUT,YJMIN,YJMAX,PTMIN,PTMAX,PTPOW,EMMIN,
     & EMMAX,EMPOW,Q2MIN,Q2MAX,Q2POW,THMAX,QLIM,REQT,XXMIN,XLMIN,EMCMF,
     & EMLST,COSTH,GPOLN,GCOEF,XX,REQ,AEQ,DISF,RESN,RMIN,CTMAX,FBTM,
     & FTOP,FHVY,RMASS,BFRAC,CMMOM,ACCUR,QEV,SUD,VECWT,TENWT,DECWT,
     & QWT,PWT,SWT,SWTEF,RESWT,PIFAC,QCDL3,QCDL5,EPOLN,BRHIG,GAMMAX
      INTEGER NMXHEP,NEVHEP,NHEP,ISTHEP,IDHEP,JMOHEP,JDAHEP,
     & IPROC,MAXEV,IPRINT,LRSUD,LWSUD,NCOLO,NFLAV,MODPDF,NSTRU,
     & NZBIN,NBTRY,NCTRY,NDTRY,NETRY,NSTRY,NGSPL,NMXPAR,NEVPAR,
     & NPAR,ISTPAR,IDPAR,JMOPAR,JDAPAR,JCOPAR,INHAD,NSPAC,NRN,
     & MAXER,MAXPR,LWEVT,ISTAT,IERROR,NWGTS,IDHW,IBSH,IBRN,IPRO,
     & MAXFL,IDCMF,IHPRO,IDN,ICO,IDEQ,LOCN,NRES,IDPDG,ICHRG,MADDR,
     & MODES,MODEF,IDPRO,INTER,NQEV,NSUD,NMXSUD,MODBOS,IOPHIG
      LOGICAL AZSOFT,AZSPIN,FROST,GENEV,BGSHAT,NOWGT,TMPAR
      CHARACTER*4 PART1,PART2,RNAME
C
C---NEW STANDARD EVENT COMMON
      PARAMETER (NMXHEP=2000)
      COMMON/HEPEVT/NEVHEP,NHEP,ISTHEP(NMXHEP),IDHEP(NMXHEP),
     & JMOHEP(2,NMXHEP),JDAHEP(2,NMXHEP),PHEP(5,NMXHEP),VHEP(4,NMXHEP)
C
C---BEAMS, PROCESS AND NUMBER OF EVENTS
      COMMON/HWBEAM/PART1,PART2
      COMMON/HWPROC/PBEAM1,PBEAM2,IPROC,MAXEV
```

```
C---PARAMETERS (AND QUANTITIES DERIVED FROM THEM)
      COMMON/HWPRAM/QCDLAM,VGCUT,VQCUT,PIFAC,BETAF,CAFAC,CFFAC,CLMAX,
     & PSPLT,QSPAC,PTRMS,PXRMS,QG,QV,SWEIN,SCABI,PDIQK,QDIQK,ENSOF,
     & TMTOP,ZBINM,GAMW,GAMZ,GAMH,QCDL3,QCDL5,PGSMX,PGSPL(4),
     & IPRINT,LRSUD,LWSUD,NCOLO,NFLAV,MODPDF,NSTRU,NZBIN,NBTRY,
     & NCTRY,NDTRY,NETRY,NSTRY,NGSPL,AZSOFT,AZSPIN
C
C---PARTON SHOWER COMMON (SAME FORMAT AS /HEPEVT/)
      PARAMETER (NMXPAR=500)
      COMMON/HWPART/NEVPAR,NPAR,ISTPAR(NMXPAR),IDPAR(NMXPAR),
     & JMOPAR(2,NMXPAR),JDAPAR(2,NMXPAR),PPAR(5,NMXPAR),VPAR(4,NMXPAR)
C---PARTON POLARIZATION COMMON
      COMMON/HWPARP/PHIPAR(2,NMXPAR),DECPAR(2,NMXPAR),RHOPAR(2,NMXPAR),
     & TMPAR(NMXPAR)
C---ELECTROWEAK BOSON COMMON
      COMMON/HWBOSC/BRHIG(12),RHOHEP(3,NMXHEP),MODBOS(5),IOPHIG,GAMMAX
C---PARTON COLOUR COMMON:
C   JCOPAR(1,*) = COLOUR MOTHER
C   JCOPAR(2,*) = ANTICOLOUR MOTHER
C   JCOPAR(3,*) = COLOUR DAUGHTER
C   JCOPAR(4,*) = ANTICOLOUR DAUGHTER
      COMMON/HWPARC/JCOPAR(4,NMXPAR)
C
C---OTHER HERWIG BRANCHING, EVENT AND HARD SUBPROCESS COMMON
      COMMON/HWBRCH/XFACT,PTINT(3,2),NSPAC(7),INHAD,FROST
      COMMON/HWEVNT/EVWGT,AVWGT,WGTMAX,WGTSUM,WSQSUM,WBIGST,TLOUT,
     & NRN(2),MAXER,MAXPR,LWEVT,ISTAT,IERROR,NOWGT,NWGTS,IDHW(NMXHEP)
      COMMON/HWHARD/YJMIN,YJMAX,PTMIN,PTMAX,PTPOW,EMMIN,EMMAX,EMPOW,
     & Q2MIN,Q2MAX,Q2POW,THMAX,QLIM,REQT,XXMIN,XLMIN,EMCMF,EMLST,
     & COSTH,CTMAX,EPOLN,GPOLN,GCOEF(7),XX(2),REQ(6),AEQ(6),DISF(13,2),
     & IBSH,IBRN(2),IPRO,MAXFL,IDCMF,IHPRO,IDN(10),ICO(10),IDEQ(6),
     & GENEV,BGSHAT
C---UTILITIES COMMON
      COMMON/HWUCLU/RESN(12,12),RMIN(12,12),LOCN(12,12)
      COMMON/HWUFHV/FBTM(6,2),FTOP(6,2),FHVY(6,2)
      COMMON/HWUNAM/RNAME(264)
      COMMON/HWUPDT/RMASS(264),BFRAC(460),CMMOM(460),IDPDG(264),
     & ICHRG(264),MADDR(264),MODES(264),MODEF(264),IDPRO(3,460),NRES
C---MAX NUMBER OF ENTRIES IN LOOKUP TABLES OF SUDAKOV FORM FACTORS
      PARAMETER (NMXSUD=1024)
      COMMON/HWUSUD/ACCUR,QEV(NMXSUD,6),SUD(NMXSUD,6),INTER,NQEV,NSUD
      COMMON/HWUWTS/VECWT,TENWT,DECWT,QWT(3),PWT(12),SWT(264),
     & SWTEF(264),RESWT(264)
```

TEST RUN OUTPUT

```
HERWIG 5.1      APRIL   1991

INPUT CONDITIONS FOR THIS RUN

BEAM 1 (E+  ) MOMENTUM =     45.60
BEAM 2 (E-  ) MOMENTUM =     45.60
PROCESS CODE (IPROC)   =     115
NUMBER OF FLAVOURS     =    6
STRUCTURE FUNCTION SET =    1
AZIM SPIN CORRELATIONS =    T
AZIM SOFT CORRELATIONS =    T
QCD LAMBDA (GEV)       =    0.2000
DOWN     QUARK  MASS   =    0.3200
UP       QUARK  MASS   =    0.3200
STRANGE  QUARK  MASS   =    0.5000
CHARMED  QUARK  MASS   =    1.8000
BOTTOM   QUARK  MASS   =    5.2000
TOP      QUARK  MASS   =  100.0000
GLUON EFFECTIVE MASS   =    0.7500
EXTRA SHOWER CUTOFF (Q)=    0.4800
EXTRA SHOWER CUTOFF (G)=    0.0600
CLUSTER MASS PARAMETER =    3.5000
SPACELIKE EVOLN CUTOFF =    2.5000
INTRINSIC P-TRAN (RMS) =    0.0000
MAX THRUST FOR 2->3    =    0.9000

PDFLIB STRUCT FUNCTIONS NOT USED

NO EVENTS WILL BE WRITTEN TO DISK
WRITING SUDAKOV TABLE ON UNIT   7
PARTICLE TYPE  21=PI0  SET STABLE

INITIAL SEARCH FOR MAX WEIGHT

PROCESS CODE IPROC =        115
RANDOM NO. SEED 1  =     1246579
           SEED 2  =     8447766
NUMBER OF SHOTS    =        2000
NEW MAXIMUM WEIGHT =  0.4792E+01
NEW MAXIMUM WEIGHT =  0.6094E+01
NEW MAXIMUM WEIGHT =  0.9074E+01
```

```
        INITIAL SEARCH FINISHED

        OUTPUT ON ELEMENTARY PROCESS

        NUMBER OF EVENTS    =          0
        NUMBER OF WEIGHTS   =       2000
        MEAN VALUE OF WGT   =  0.7198E+00
        RMS SPREAD IN WGT   =  0.7733E+00
        ACTUAL MAX WEIGHT   =  0.8249E+01
        ASSUMED MAX WEIGHT  =  0.9074E+01

        PROCESS CODE IPROC  =        115
        CROSS SECTION (PB)  =    719.8381
        ERROR IN C-S  (PB)  =     17.2916
        EFFICIENCY PERCENT  =      7.9329



EVENT      1:      45.60 GEV/C E+   ON      45.60 GEV/C E-    PROCESS:  115

SEEDS:      17673 &      63565   STATUS: 100  ERROR:   0  WEIGHT: 0.7198E+00

                              ---INITIAL STATE---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y       P-Z     ENERGY     MASS
  1 E+      -11 101   0   0   0   0   0.00     0.00     45.60     45.60     0.00
  2 E-       11 102   0   0   0   0   0.00     0.00    -45.60     45.60     0.00
  3 CMF       0 103   0   0   0   0   0.00     0.00      0.00     91.20    91.20

                             ---HARD SUBPROCESS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y       P-Z     ENERGY     MASS
  4 Z0/G     23 120   1   2   5   7   0.00     0.00      0.00     91.20    91.20

                            ---H/W/Z BOSON DECAYS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y       P-Z     ENERGY     MASS
  5 BOTM      5 123   4   6   8   7  35.40    12.90     -8.32     38.94     5.20
  6 GLUE     21 124   4   7  12   5   3.67   -11.51      2.89     12.45     0.75
  7 BBAR     -5 124   4   5  18   6 -39.07    -1.39      5.43     39.81     5.20
```

```
                          ---PARTON SHOWERS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z    ENERGY   MASS
  8 BOTM    94 143   5   4  10  11   33.41    12.18    -7.85    37.11    7.17
  9 CONE     0 100   5   6   0   0    0.85    -0.73     0.10     1.13    0.00
 10 BOTM     5 157   8  22  34  21   31.72    12.16    -6.97    35.07    5.20
 11 GLUE    21   2   8  14  22  23    1.69     0.02    -0.88     2.05    0.75
 12 GLUE    94 144   6   4  14  17    3.46   -10.87     2.73    15.86   10.67
 13 CONE     0 100   6   7   0   0   -1.11     0.26     0.07     1.14    0.00
 14 GLUE    21   2  12  15  24  25    0.79     0.81     0.03     1.36    0.75
 15 GLUE    21   2  12  16  26  27   -0.08    -1.17     2.80     3.12    0.75
 16 GLUE    21   2  12  17  28  29    0.74    -1.59     0.96     2.13    0.75
 17 GLUE    21   2  12  20  30  31    2.01    -8.92    -1.06     9.24    0.75
 18 BBAR    94 144   7   4  20  21  -36.87    -1.31     5.12    38.23    8.63
 19 CONE     0 100   7   6   0   0   -0.40    -0.98     0.34     1.11    0.00
 20 GLUE    21   2  18  21  32  33   -1.42    -0.26     1.49     2.21    0.75
 21 BBAR    -5 157  18  10  40  33  -35.45    -1.05     3.63    36.02    5.20

                          ---GLUON SPLITTING---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z    ENERGY   MASS
 22 UBAR    -2 158   8  23  34  10    1.01    -0.02    -0.31     1.11    0.32
 23 UP       2 158   8  24  35  22    0.67     0.04    -0.57     0.94    0.32
 24 UBAR    -2 158  12  25  35  23    0.20     0.45    -0.07     0.59    0.32
 25 UP       2 158  12  26  36  24    0.59     0.36     0.10     0.77    0.32
 26 UBAR    -2 158  12  27  36  25   -0.10    -0.66     1.11     1.33    0.32
 27 UP       2 158  12  28  37  26    0.02    -0.51     1.69     1.79    0.32
 28 UBAR    -2 158  12  29  37  27    0.44    -1.02     0.78     1.39    0.32
 29 UP       2 158  12  30  38  28    0.30    -0.57     0.18     0.74    0.32
 30 UBAR    -2 158  12  31  38  29    1.14    -5.22    -0.80     5.42    0.32
 31 UP       2 158  12  32  39  30    0.87    -3.70    -0.26     3.82    0.32
 32 DBAR    -1 158  18  33  39  31   -0.59    -0.16     0.89     1.13    0.32
 33 DOWN     1 158  18  21  40  32   -0.84    -0.10     0.60     1.08    0.32

                         ---CLUSTER FORMATION---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z    ENERGY   MASS
 34 CLUS    91 183  10  22  41  42   32.73    12.14    -7.28    36.17    6.06
 35 CLUS    91 183  23  24  43  44    0.87     0.49    -0.63     1.53    0.97
 36 CLUS    91 183  25  26  45  46    0.49    -0.29     1.21     2.10    1.62
 37 CLUS    91 183  27  28  47  48    0.46    -1.53     2.47     3.18    1.23
 38 CLUS    91 183  29  30  49  50    1.44    -5.79    -0.62     6.15    1.37
 39 CLUS    91 183  31  32  51  52    0.29    -3.86     0.64     4.95    3.03
 40 CLUS    91 183  33  21  53  54  -36.28    -1.15     4.23    37.10    6.41
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                              ---CLUSTER DECAYS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y       P-Z    ENERGY     MASS
 41 B0BR   -511 199  34   8  70  71   27.90    10.32     -5.49    30.71     5.28
 42 PI-    -211   1  34   8   0   0    4.84     1.81     -1.79     5.47     0.14
 43 PI+     211   1  35   8   0   0    0.02     0.09     -0.12     0.21     0.14
 44 RH0-   -213 197  35   8  55  56    0.86     0.40     -0.51     1.32     0.77
 45 K+      321   1  36  12   0   0    0.53     0.11      0.62     0.96     0.49
 46 K*-    -323 197  36  12  57  58   -0.04    -0.40      0.58     1.14     0.89
 47 RH0+    213 197  37  12  59  60    0.50    -1.39      2.47     2.98     0.77
 48 PI-    -211   1  37  12   0   0   -0.04    -0.15     -0.01     0.21     0.14
 49 RH0+    213 197  38  12  61  62    0.50    -2.55      0.06     2.71     0.77
 50 PI-    -211   1  38  12   0   0    0.93    -3.24     -0.67     3.44     0.14
 51 DL++   2224 197  39  12  63  64    0.23    -1.25     -0.52     1.84     1.23
 52 DLB-  -2214 197  39  12  65  66    0.05    -2.61      1.15     3.11     1.23
 53 RH0-   -213 197  40  18  67  68   -4.61    -0.57     -0.05     4.71     0.77
 54 B+      521 199  40  18  72  73  -31.67    -0.59      4.27    32.40     5.27

                          ---STRONG HADRON DECAYS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y       P-Z    ENERGY     MASS
 55 PI0     111   1  44   8   0   0    0.15     0.29     -0.47     0.59     0.13
 56 PI-    -211   1  44   8   0   0    0.71     0.10     -0.04     0.73     0.14
 57 PI-    -211   1  46  12   0   0   -0.23    -0.09      0.40     0.50     0.14
 58 KBAR   -311 198  46  12  69  69    0.20    -0.31      0.18     0.64     0.50
 59 PI0     111   1  47  12   0   0    0.48    -1.32      1.80     2.29     0.13
 60 PI+     211   1  47  12   0   0    0.02    -0.06      0.67     0.69     0.14
 61 PI0     111   1  49  12   0   0    0.08    -1.80     -0.16     1.81     0.13
 62 PI+     211   1  49  12   0   0    0.42    -0.75      0.21     0.90     0.14
 63 PI+     211   1  51  12   0   0    0.22    -0.40     -0.29     0.56     0.14
 64 P      2212   1  51  12   0   0    0.02    -0.85     -0.22     1.29     0.94
 65 PI0     111   1  52  12   0   0    0.18    -0.46      0.38     0.64     0.13
 66 PBAR  -2212   1  52  12   0   0   -0.13    -2.14      0.78     2.47     0.94
 67 PI0     111   1  53  18   0   0   -0.52    -0.07      0.20     0.58     0.13
 68 PI-    -211   1  53  18   0   0   -4.09    -0.50     -0.25     4.13     0.14
 69 K0L     130   1  58  12   0   0    0.20    -0.31      0.18     0.64     0.50

                          ---HEAVY FLAVOUR DECAYS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y       P-Z    ENERGY     MASS
 70 BOTM      5 153  41  71  74  76   26.21     9.70     -5.16    28.84     4.95
 71 DBAR     -1 125  41  76  80  76    1.69     0.63     -0.33     1.86     0.32
 72 UP        2 125  54  79  81  79   -1.92    -0.04      0.26     1.97     0.32
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  73 BBAR     -5 153  54  72  77  79  -29.75   -0.55     4.01    30.43    4.95
  74 NUEB    -12 123  70  75  82  75    7.41    2.16    -2.02     7.98    0.00
  75 E-       11 124  70  74  83  74    2.86   -0.01     0.04     2.86    0.00
  76 CHRM      4 124  70  70  84  70   15.94    7.54    -3.18    18.01    1.80
  77 UP        2 123  73  78  86  78  -18.31   -0.94     2.49    18.51    0.32
  78 DBAR     -1 124  73  77  88  77   -5.82    0.17     0.02     5.83    0.32
  79 CBAR     -4 124  73  73  90  73   -5.62    0.22     1.50     6.09    1.80
  80 DBAR     -1 160  71  85  93  85    1.69    0.63    -0.33     1.86    0.32
  81 UP        2 160  72  91  92  91   -1.92   -0.04     0.26     1.97    0.32
  82 NUEB    -12   1  74  70   0   0    7.41    2.16    -2.02     7.98    0.00
  83 E-       11   1  75  70   0   0    2.86   -0.01     0.04     2.86    0.00

                          ---PARTON SHOWERS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2     P-X     P-Y      P-Z   ENERGY    MASS
  84 CHRM     94 144  76  70  85  85   15.94    7.54    -3.18    18.01    1.80
  85 CHRM      4 157  84  80  93  80   15.94    7.54    -3.18    18.01    1.80
  86 UP       94 143  77  73  87  87  -18.31   -0.94     2.49    18.51    0.32
  87 UP        2 157  86  89  94  89  -18.31   -0.94     2.49    18.51    0.32
  88 DBAR     94 144  78  73  89  89   -5.82    0.17     0.02     5.83    0.32
  89 DBAR     -1 157  88  87  94  87   -5.82    0.17     0.02     5.83    0.32
  90 CBAR     94 144  79  73  91  91   -5.62    0.22     1.50     6.09    1.80
  91 CBAR     -4 157  90  81  92  81   -5.62    0.22     1.50     6.09    1.80

                         ---CLUSTER FORMATION---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2     P-X     P-Y      P-Z   ENERGY    MASS
  92 CLUS     91 183  81  91  95  96   -7.54    0.18     1.76     8.06    2.22
  93 CLUS     91 183  85  80  97  98   17.63    8.17    -3.51    19.87    2.22
  94 CLUS     91 183  87  89  99 100  -24.13   -0.77     2.51    24.34    1.76

                          ---CLUSTER DECAYS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2     P-X     P-Y      P-Z   ENERGY    MASS
  95 PI+     211   1  92  72   0   0   -0.62   -0.11     0.22     0.68    0.14
  96 DC*-   -413 197  92  72 101 102   -6.92    0.30     1.54     7.38    2.01
  97 DC*+    413 197  93  84 103 104   15.59    7.08    -3.15    17.53    2.01
  98 PI0     111   1  93  84   0   0    2.04    1.09    -0.36     2.34    0.13
  99 PI+     211   1  94  86   0   0  -10.09   -0.29     0.92    10.14    0.14
 100 A20     115 197  94  86 105 106  -14.04   -0.48     1.58    14.20    1.32
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                    ---STRONG HADRON DECAYS---

IHEP ID   IDPDG IST MO1 MO2 DA1 DA2    P-X     P-Y      P-Z    ENERGY    MASS
101 DCBR   -421 198  96  72 107 108   -6.37    0.29     1.45     6.80    1.86
102 PI-    -211   1  96  72   0   0   -0.56    0.01     0.09     0.58    0.14
103 DCO     421 198  97  84 109 111   14.66    6.68    -2.94    16.48    1.86
104 PI+     211   1  97  84   0   0    0.93    0.41    -0.21     1.04    0.14
105 PI+     211   1 100  86   0   0   -5.59   -0.12     0.22     5.60    0.14
106 RHO-   -213 198 100  86 112 113   -8.45   -0.36     1.36     8.60    0.77
107 KO      311 198 101  72 114 114   -2.67    0.52     1.02     2.95    0.50
108 ETPR    331 198 101  72 115 116   -3.69   -0.23     0.43     3.85    0.96
109 KBAR   -311 198 103  84 117 117    4.99    2.37    -0.95     5.62    0.50
110 RHOO    113 198 103  84 118 119    5.11    2.33    -1.00     5.76    0.77
111 ETA     221 198 103  84 120 122    4.57    1.98    -0.99     5.11    0.55
112 PIO     111   1 106  86   0   0   -3.45    0.20     0.61     3.51    0.13
113 PI-    -211   1 106  86   0   0   -5.00   -0.56     0.76     5.09    0.14
114 KOL     130   1 107  72   0   0   -2.67    0.52     1.02     2.95    0.50
115 GAMA     22   1 108  72   0   0   -0.82    0.04    -0.05     0.82    0.00
116 RHOO    113 198 108  72 123 124   -2.88   -0.27     0.48     3.03    0.77
117 KOL     130   1 109  84   0   0    4.99    2.37    -0.95     5.62    0.50
118 PI-    -211   1 110  84   0   0    0.57    0.40     0.05     0.71    0.14
119 PI+     211   1 110  84   0   0    4.54    1.94    -1.05     5.04    0.14
120 PIO     111   1 111  84   0   0    1.22    0.53    -0.25     1.36    0.13
121 PI-    -211   1 111  84   0   0    1.57    0.53    -0.40     1.71    0.14
122 PI+     211   1 111  84   0   0    1.79    0.92    -0.33     2.04    0.14
123 PI-    -211   1 116  72   0   0   -2.39   -0.25     0.65     2.49    0.14
124 PI+     211   1 116  72   0   0   -0.49   -0.02    -0.17     0.54    0.14

        OUTPUT ON ELEMENTARY PROCESS

        NUMBER OF EVENTS    =        100
        NUMBER OF WEIGHTS   =       1339
        MEAN VALUE OF WGT   =  0.7323E+00
        RMS SPREAD IN WGT   =  0.8725E+00
        ACTUAL MAX WEIGHT   =  0.7355E+01
        ASSUMED MAX WEIGHT  =  0.9074E+01

        PROCESS CODE IPROC  =        115
        CROSS SECTION (PB)  =   732.2993
        ERROR IN C-S  (PB)  =    23.8432
        EFFICIENCY PERCENT  =     8.0702
```