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## Herwig++ 2.0 Release Note

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### Abstract

A new release of the Monte Carlo program Herwig++ (version 2.0) is now available. This is the first version of the program which can be used for hadron-hadron physics and includes the full simulation of both initial- and final-state QCD radiation.

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## 1 Introduction

The last major public version (1.0) of Herwig++ was reported in detail in [1], subsequently a release (2.0 $\beta$ ) with minimal hadron-hadron physics was made available for integration testing within experimental software frameworks, [2]. In this note we describe the main modifications and new features included in the latest public version, 2.0. We consider this to be the first version which can be used for realistic physics studies of hadron-hadron collisions.

Please refer to [1] and the present paper if using version 2.0 of the program. A full manual will be released in the near future.

The main new features of this version are that the limited functionality in the  $\beta$ -release for the simulation of hadron-hadron collisions has been extended to include: the simulation of processes other than Drell-Yan; final-state radiation of the time-like partons produced in the space-like shower; initial- and final-state showers in the decay of heavy particles (e.g. the top quark); the matrix element correction for Drell-Yan processes and top quark decays; the simulation of QED radiation in particle decays using the YFS formalism [3]; and simulation of the underlying event using the model of the UA5 collaboration [4].

### 1.1 Availability

The new program, together with other useful files and information, can be obtained from the following web site:

<http://hepforge.cedar.ac.uk/herwig/>

## 2 Hadron-Hadron Processes

A number of matrix elements have been added for important processes in hadron collisions including:<sup>1</sup>

- Direct photon pair production, i.e.  $q\bar{q}/gg \rightarrow \gamma\gamma$ ;

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<sup>1</sup>The charge conjugate processes while included in the code have been omitted in the list for brevity.

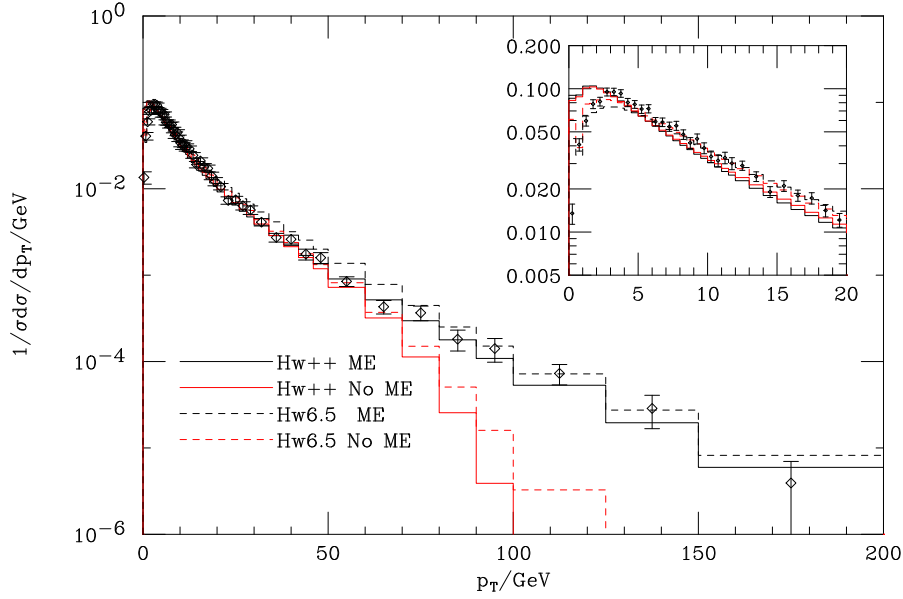


Figure 1: The transverse momentum of the  $Z^0$  boson at the Tevatron calculated by HERWIG6.5 and Herwig++ compared with run I CDF data taken from [7] with and without matrix element corrections.

- Photon plus jet production, i.e.  $q\bar{q} \rightarrow \gamma g$ ,  $qg \rightarrow \gamma q$ ;
- Higgs boson production, i.e.  $q\bar{q}/gg \rightarrow h^0$ ;
- Higgs boson plus jet production, i.e.  $gg \rightarrow gh^0$ ,  $qg \rightarrow qh^0$  and  $q\bar{q} \rightarrow gh^0$ ;
- Heavy quark pair production, i.e.  $q\bar{q}/gg \rightarrow Q\bar{Q}$ ;
- QCD  $2 \rightarrow 2$  scattering processes, i.e.  $gg \rightarrow gg$ ,  $gg \rightarrow q\bar{q}$ ,  $q\bar{q} \rightarrow gg$ ,  $qg \rightarrow qg$ ,  $qg \rightarrow qg$ ,  $q\bar{q} \rightarrow q\bar{q}$ ;

in addition the  $W$  and  $Z$  Drell-Yan processes which were included in the previous version have been extended to include the hadronic decays of the boson.

Currently the kinematic reconstruction of the parton showers in these processes does not use the original approach advocated in [5] but a simpler method where the centre-of-mass energy and rapidity of the hard process are preserved in the showering process. This is the procedure of [5] for  $s$ -channel colour-singlet systems. The time-like shower of the ongoing partons produced in the initial-state shower is generated using the same choice of basis vectors as for the space-like shower.

The matrix element correction for the production of an  $s$ -channel gauge boson, either  $W^\pm$  or  $Z^0$ , has been included using the approach of [6]. The comparison of Herwig++ with and without the matrix element correction is shown in Fig. 1. Herwig++ gives better agreement with the data for medium  $p_T$  but peaks about 2 GeV below data in the low  $p_T$  region. Herwig++ does not yet include a model of intrinsic- $k_T$  in the incoming hadrons which could be tuned to reproduce the data.

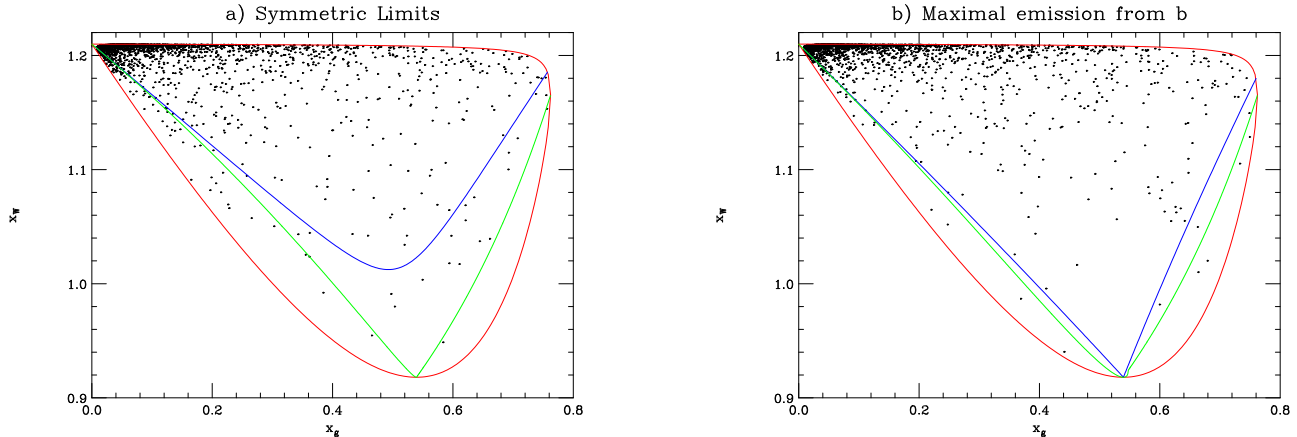


Figure 2: Dalitz plot for gluonic radiation in top decay. In both plots both the soft and hard matrix element corrections have been applied, but only one emission has been allowed. a) shows the radiation for the symmetric choice of [5] for emission from the top and bottom while b) shows the radiation with the scales chosen to give the maximum amount of radiation from the bottom quark. The blue (innermost) line gives the limit for radiation from the bottom, the green (middle) line from the top and the red (outer) line the boundary of the phase-space region.

### 3 Top Decay

One of the main features of the new shower formalism [5] was the treatment of the QCD radiation in the decay of heavy particles. This is now implemented and includes the initial-state forward shower of the heavy particle in its decay together with the traditional time-like shower of the decay products. This is essential in ensuring that the full phase-space for the emission of soft gluons is covered, in for example  $t \rightarrow bW$ .

In addition, in order to have the same level of simulation as in the **FORTRAN** program, and to correct for the over emission of soft radiation from the outgoing particles, the matrix element correction for  $t \rightarrow bW$  has been included using the method of [8]. This will be described in more detail in [9] and the forthcoming manual. The matrix element correction in **HERWIG** was not infrared safe and required an arbitrary cutoff on the gluon energy however as the new algorithm fills the whole region for soft emission such a cutoff is not required. Fig. 2 shows the distribution of the radiation for two different choices of the maximal scales for radiation from the top and bottom quark.

### 4 Underlying Event

The simulation of the underlying event currently uses the model of the UA5 collaboration [4] adapted as described in [10] to use the cluster model. This is the same as the **FORTRAN** implementation and is intended to give a simple model of the underlying event which will be replaced by a more sophisticated approach based on multiple scattering in the next major release.

Fig. 3 shows the number of charged particles and transverse momentum transverse to the direction of the leading jet at the Tevatron. In general there is good agreement between **Herwig++** and **HERWIG** for the distributions of particles from the soft underlying event with **Herwig++** producing more particles from the perturbative scattering.

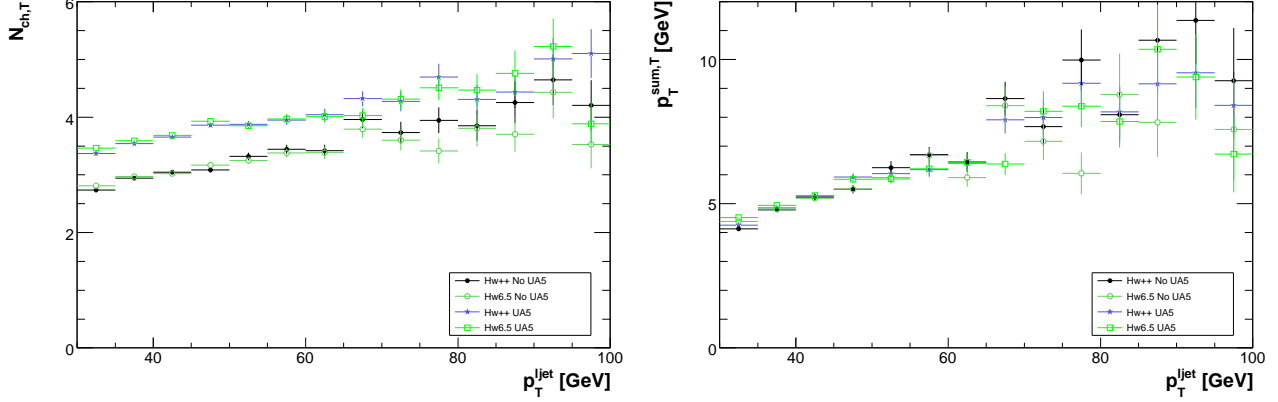


Figure 3: The number of charged particles and scalar sum of the transverse momentum in the transverse azimuthal direction with respect to the direction of the leading jet at the Tevatron as a function of the transverse momentum of the leading jet. The blue (upper) and black (lower) points are the results from Herwig++ with/without the soft underlying event. The light green (upper) and dark green (lower) points were generated with HERWIG with/without the soft underlying event. For both the number of charged particles and transverse the FORTRAN results lie slightly above those from Herwig++. The observables are defined in more detail in [11].

In addition, the simple model of the forced branching after the initial-state parton showers, to ensure that the evolution ends on the valence quarks in the incoming hadron, has been replaced with a more sophisticated approach based on that in the FORTRAN program [10]. This model allows the forced branchings to take place between a scale **QSpac** (Default 2.5 GeV) and a multiple **EmissionRange** (Default 1.1) of the minimum scale. The energy fractions are then determined using the perturbative result. This replaces the simple model in the beta release which generated the scale at the minimum value and used a flat distribution for the energy fraction which tended to give a large number of low mass soft collisions.

## 5 QED Radiation

The simulation of QED radiation using the approach of [3] has been included for both particle decays and unstable  $s$ -channel resonances produced in the hard process. This approach is based on the YFS formalism [12] which takes into account large soft photon logarithms to all orders. In addition, the leading collinear logarithms are included to  $\mathcal{O}(\alpha)$  by using the dipole splitting functions. A comparison of the results of Herwig++ and WINHAC [13] is shown in Figure 4 for leptonic W decays, more examples and a full description of the approach can be found in [3].

By default this is switched off for both decays and hard processes but can easily be switched on by including the **QEDRadiationHandler** as a **PostSubProcessHandler** for the hard process or using the **PhotonGenerator** interface of the relevant **Decayer**.

## 6 Other Changes

A number of other more minor changes have been made. The following changes have been made to improve the physics simulation:

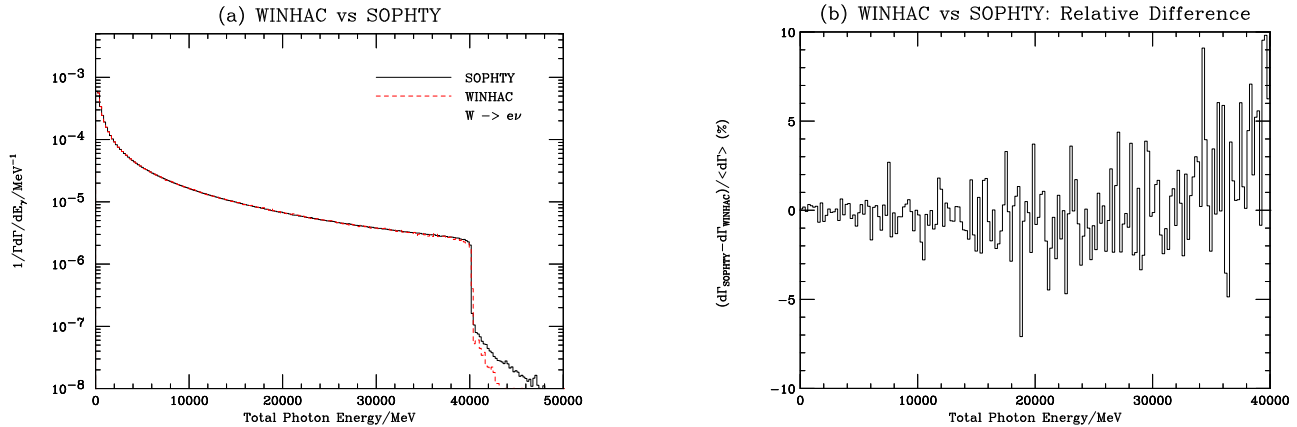


Figure 4: The total energy of the photons radiated in  $W^\pm \rightarrow e^\pm \nu_e / \bar{\nu}_e$  decays. In figure (a) the red (dashed) histogram was generated using the **WINHAC** [13] program, while the black (solid) line was generated using **Herwig++**. Figure (b) shows the difference between the spectra shown in (a) divided by the statistical error. The disagreement about 40 GeV is due to events with at least two hard photons which neither program is designed to model well.

- **Decayers** have been added for top and electroweak gauge boson decays which are switched on by default;
- The default mass of the Higgs boson has been increased and the appropriate decay modes added. In addition a number of **Decayers** have been added for the various Higgs decays.
- Some changes have been made to give a more reasonable physical description of the splitting of beam clusters.
- The default  $p_T$  cut for particles in the hard process has changed so that different cuts can be used for different types of particles. The default cut for photons and jets (gluons and quarks other than top) has been raised to 20 GeV. The cut for top quarks and leptons has been reduced to zero;
- A number of **AnalysisHandlers** for the showering from different processes have been added;
- The `cut` member of **ClusterFissioner** has been made virtual so that the model of [14] can be implemented as an external package;<sup>2</sup>
- An **AnalysisHandler** to print a tree history of the event using **Graphviz** has been added;
- A new set of input files to run top quark pair production in  $e^+e^-$  collisions at 500 GeV has been added;
- The **ShowerAlphaQCD** class implementing strong coupling used in the shower has been improved so that the same options as in **FORTRAN HERWIG** can be used, the default remains as in the previous version.
- The **AlphaEM** class implementing exactly the same running electromagnetic coupling as **FORTRAN HERWIG** has been included.

The following more technical changes to the code structure have been made:

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<sup>2</sup>This is available from <http://hepforge.cedar.ac.uk/herwig/>.

- The **Show**er module has undergone a significant redesign in order to include the new features in this version, to make implementing new matrix element corrections easier and in preparation for improvements such as the multi-scale shower and CKKW procedure which are foreseen in future versions;
- The **GlobalParameters** object has been removed. The effective gluon mass is now taken to be the constituent mass of the gluon from its **ParticleData** object. This should be set to zero if the Lund string model is used for the hadronization of the event.
- The splitting of the hadronic remnant has been moved to be part of the **Hadronization** module;
- The libraries of **AnalysisHandlers** supplied with the release have been restructured to separate those which depend on **KtJet** from those which do not;
- The original obsolete matrix elements have been deleted;
- The default number of events outputted to the log file has been reduced to 100 due to the larger files created when the UA5 underlying event model is switched on;
- Numerous improvements have been made to the **DOXYGEN** documentation;
- Several fixes have been made to correct memory leaks in the initialisation of the event generator;
- The **Amegic** interface which has not been used or tested in some time has been removed from the release;
- The structure of the default input files has been changed and cleaned up;
- Most classes have been cleaned up to remove unused member functions;
- Vector and Tensor meson decay base classes have been removed to speed up code as little functionality remained in them.

The following bugs have been fixed:

- A bug affecting the gluon splitting function for time-like radiation;
- A number of bugs affecting the backward evolution of antiquarks;
- A bug affecting the azimuthal distribution of the gauge boson in Drell-Yan processes;
- Corrections to particle data tables so that gauge and Higgs boson spins are correctly set;
- A bug in the **VSSVertex** where the off-shell scalar wavefunction was not correctly included;
- A bug to the multi-channel decay phase-space integrator which affected a vertex with two off-shell particles, which had not previously been encountered.

## 7 Summary

Herwig++2.0 is the first version of the Herwig++ program with a complete simulation of hadron-hadron physics. We look forward to feedback and input from users, especially from the Tevatron and LHC experiments.

Our next major milestone is the release of version 3.0 which will be at least as complete as HERWIG in all aspects of LHC and linear collider simulation. The major new features for this version will be the inclusion of Beyond the Standard Model physics, a multiple scattering model for the underlying event and the full inclusion of the new hadron decay module. In addition depending on the time scale for the release a number of improvements to the parton shower may also be included. Following the release of Herwig++3.0 we expect that support for the FORTRAN program will cease.

## Acknowledgements

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