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## Herwig++ 2.1 Release Note

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## Abstract

A new release of the Monte Carlo program **Herwig++** (version 2.1) is now available. This version includes a number of significant improvements including: an eikonal multiple parton-parton scattering model of the underlying event; the inclusion of Beyond the Standard Model (BSM) physics; and a new hadronic decay model tuned to LEP data. This version of the program is now fully ready for the simulation of events in hadron-hadron collisions.

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## 1 Introduction

The last major public version (2.0) of **Herwig++**, described briefly in [1], was based on the original version (1.0) which was reported on in detail in [2]. There have however been significant changes since the original release (1.0) and therefore we intend to publish a full manual in the near future. This release note therefore only discusses the changes which have been made since the last release (2.0).

Please refer to [2] and the present paper if using version 2.1 of the program and the full manual once it is available.

The main new features of this version are an eikonal multiple parton-parton scattering model of the underlying event based on [3]; the simulation of BSM physics including the CP-conserving Minimal Supersymmetric Standard Model (MSSM), the minimal Universal Extra Dimensions (UED) model and the Randall-Sundrum model; a new model of meson and tau decays which has been tuned to LEP and B-factory data. In addition a number of other changes, such as the inclusion of intrinsic transverse momentum in hadron-hadron collisions, have been made and a number of bugs have been fixed.

### 1.1 Availability

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

<http://projects.hepforge.org/herwig/>

In order to improve our response to user queries, all problems and requests for user support should be reported via the bug tracker on our wiki. Requests for an account to submit tickets and modify the wiki should be sent to [herwig@projects.hepforge.org](mailto:herwig@projects.hepforge.org).

**Herwig++** is released under the GNU General Public License (GPL) version 2 and the MCnet guidelines for the distribution and usage of event generator software in an academic setting, which are distributed together with the source, and can also be obtained from

<http://www.montecarlonet.org/index.php?p=Publications/Guidelines>

## 2 Multiple Interactions

A dynamic model of the underlying event, in the form of an eikonal multiple parton-parton scattering model, is now included in **Herwig++**. It is intended to provide the same functionality as **FORTRAN HERWIG** [4, 5] running with **JIMMY** [3]. It is based on the same model [3] but implements the physics in a way that is somewhat closer to the eikonal approach than the original version.

The multiple interactions are generated as part of the parton-shower phase of the event. After the hard process has been produced and showered the number of additional scatters in this particular event is calculated. The calculated number of additional subprocesses are then created and successively processed by the parton shower. The initial partons from all subprocesses are extracted from the incoming beam particles, as long as there is enough energy available in the beams.

This means, of course, that several colour lines end on the beam particles and, furthermore, several quarks are possibly extracted from the beam particles. This and the prerequisite that the cluster hadronization model expects only (anti)quarks and (anti)diquarks to hadronize, makes it necessary to force the initial-state shower to end on a valence quark for the hard subprocess and to end on a gluon for the additional interactions. After extraction of all additional scatters the colour connections between them are set so that the initial partons of each scattering are connected to the next one. The last pair are connected to the hadron remnants, which are diquarks if the beam particles are baryons.

Predictions from the new model as well as **Herwig++** without multiple parton-parton scattering are shown in Fig 1. The predictions of the Monte Carlo simulations are compared to CDF data [6] for two observables, which are sensitive to underlying event activity.

A more detailed explanation of the model and the data comparison is available in [7].

## 3 BSM Physics

The simulation of physics Beyond the Standard Model (BSM) is now included in **Herwig++**. Rather than implement the matrix elements and decays for a specific model, as was done in the **FORTRAN** program, we have adopted a more general approach [8] which makes extensive use of the **Helicity** libraries in **ThePEG**.

The new framework has the matrix elements for the  $2 \rightarrow 2$  hard scattering processes and  $1 \rightarrow 2$  decays implemented for the different possible spins of the interacting particles. The diagrams are built from **Vertex** classes, each of which is based upon a certain Lorentz structure, which have the ability to calculate matrix elements and off-shell **WaveFunctions** for that combination of spins. The Feynman rules for a specific model are then implemented by inheriting from these general classes.

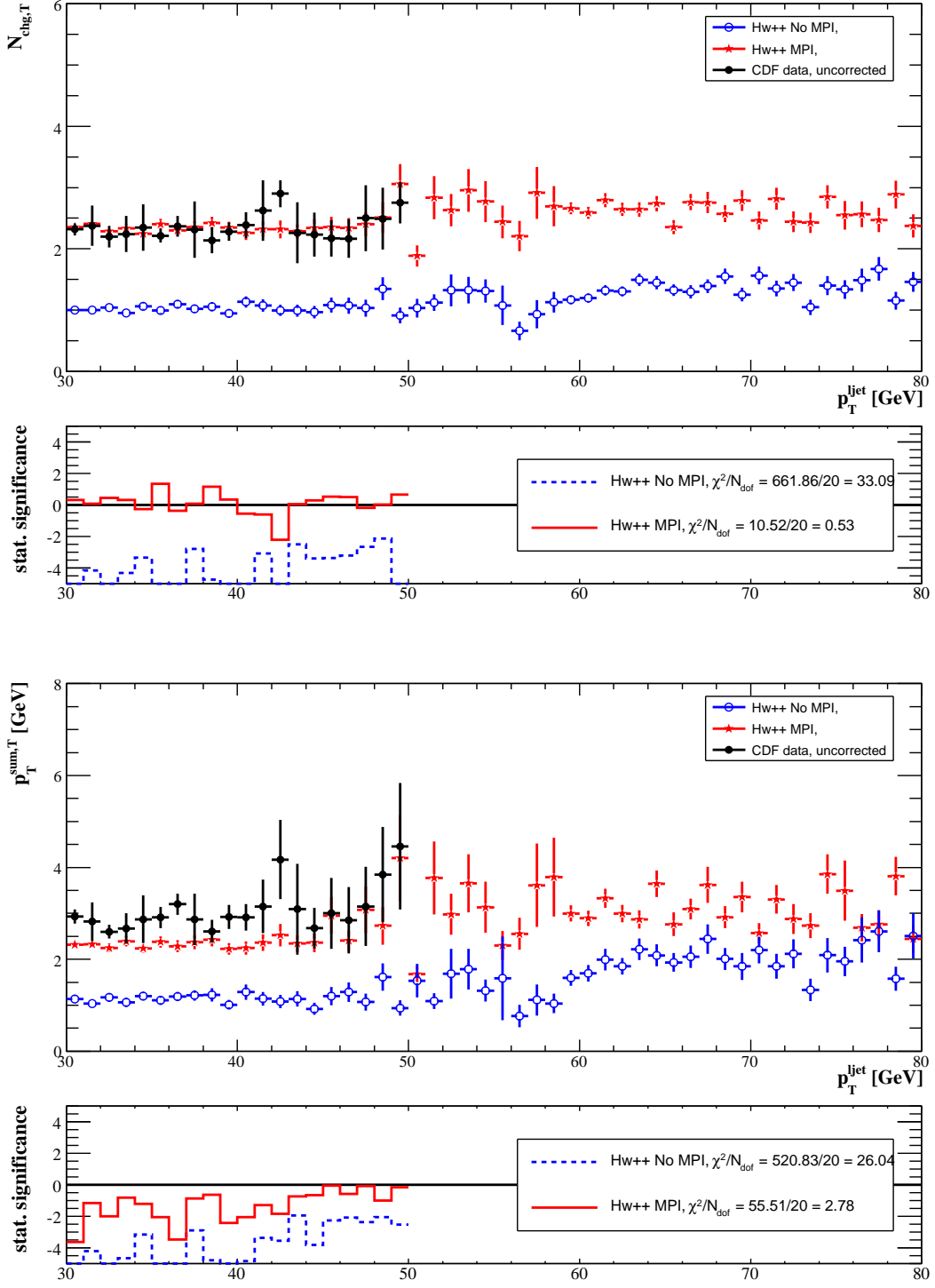


Figure 1: Average number and average scalar  $p_T$  sum of charged particles in the transverse region, as defined in [6]. The lower parts of the plots show the statistical significance of the disagreement between prediction and data. Black (full circles) indicates the data points, blue (open circles) shows Herwig++ without multiple parton interactions (MPI) and red (stars) shows Herwig++ with MPI.

The **Vertices** for the Minimal Supersymmetric Standard Model (MSSM), minimal Universal Extra Dimensions (UED) and Randall-Sundrum models are currently implemented. An interface to read files in the SUSY Les Houches Accord format [9] is included for the MSSM. Once the second version of the accord is finalised [10] we intend to include additional models, such as the Next to Minimal Supersymmetric Standard Model (NMSSM).

## 4 Hadronic Decays

A number of major improvements to the simulation of meson and tau decays have been made [11, 12]. Previously, in **Herwig++** 2.0, the particle properties and decay modes for all the particles were the same as those used in **FORTRAN HERWIG**. Furthermore, for the majority of the hadron decays, the momenta of the decay products were assumed to be uniformly distributed in phase space, or, in a limited number of cases, according to simple weak  $V - A$  matrix elements.

We have updated the properties of the leptons, quarks and mesons to agree with those in [13] together with some additional interpretation and assumptions where necessary. The particle properties now used in **Herwig++** can be obtained from

<http://www.ippp.dur.ac.uk/~richardn/particles>

More importantly, we now use matrix elements and include spin correlations for the decays including, where possible, a sophisticated treatment of off-shell effects. The new hadron decay model is described in more detail in [11, 12].

While the properties of the baryons are currently identical to those used in the previous version we have made some changes to ensure that excited  $\Xi_b$  baryons can decay. The masses and decay modes of the  $\Xi_b$ ,  $\Xi'_b$  and  $\Xi_b^*$  baryons have been adjusted so that there is only a radiative decay mode for the  $\Xi'_b$  and a pionic mode for the  $\Xi_b^*$ . The properties of the remaining baryons will be updated in the near future.

## 5 Other Changes

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

- The option of intrinsic transverse momentum has been added. Since this cannot be calculated perturbatively, we have to model this using a non-perturbative distribution. The distributions that can be used in **Herwig++** are a Gaussian, an inverse quadratic or a combination of both. The best fit obtained to Drell Yan  $Z$  and  $W$  boson production data at the Tevatron is a Gaussian distribution with a root-mean-square transverse momentum of 2.2 GeV. Assuming a logarithmic dependence on the beam energy, the corresponding value estimated for the LHC is 5.7 GeV.
- A number of features for CKKW [14] matching have been added. The structure is designed to be very flexible, allowing the straightforward implementation of different matching approaches following the general idea of the original proposal. Implementing a new merging prescription amounts to supplying the key ingredients of a CKKW-type algorithm, *i.e.* a jet measure to reconstruct a parton shower history and a jet resolution to separate regions of jet production and jet evolution. No approximation is performed in the Sudakov form

factors used for reweighting. Testing and development of an adaptation of the CKKW method to the improved angular ordered shower in **Herwig++** is currently underway.

- A major clean-up and restructuring of the hadronization module has been performed. As part of this process a number of hadronization parameters which either did not depend on the flavour of the partons forming a cluster, or only had different values for clusters which contained a bottom quark, are now different for clusters containing light, charm and bottom quarks. These include **CIMax**, **CIPow**, **PSplit**, **CIDir** and **CISmr**. In addition, the option for increasing the threshold for the single hadron decay of bottom clusters above the threshold for the production of two hadrons has been extended to charm clusters.
- The choice of the  $n$  reference vector for initial-state radiation where the colour partner of the incoming particle is in the final state has been changed. Previously a vector backwards to the direction of the radiating particle was chosen in the laboratory frame, whereas we now use the Breit frame [15].
- **ThePEG** has moved to a templated solution to ensure that the dimensions of all calculations are correct, by default this is switched off for faster compilation. As part of this change **ThePEG** now uses an internal library for vectors and Lorentz transformations. This means that **Herwig++** no longer explicitly depends on **CLHEP**. **CLHEP** is now only needed when interfacing to external packages, such as **KtJet**, which use **CLHEP**.
- The majority of the **Helicity** classes which were previously in **Herwig++** have been moved to the **ThePEG**. The classes for the calculation of the **WaveFunctions** and the general **Vertices** based on spin structures have been moved to **ThePEG**. The classes which implement the vertices for specific models remain in **Herwig++** but have been moved to the relevant model directory. The **Helicity** directory no longer exists.
- The shower and hadronization modules have been extended to handle the showering and hadronization of processes which violate baryon number conservation.
- Additional options for the non-perturbative behaviour of the strong coupling constant used in the shower have been added to the **ShowerAlphaQCD** class.
- The structure of the input files has been significantly modified. In addition a default version of the **Repository** file is now installed so that most users will only need to use the **read** and **run** stages of the **Herwig++** program. A number of changes to **Switches** have also been made to improve the consistency of the names and options. The name of all the classes in the **Repository** has been changed from **Herwig++::** to **Herwig::** for consistency as well.
- Changes have been made to ensure that no radiation harder than the scale of the hard process is emitted in the parton shower, as was the case in **FORTAN HERWIG**.
- The non-perturbative gluon splitting in the **PartonSplitter** class now decays the gluons to all the quark-antiquark pairs which are kinematically allowed, with the probability of producing a given quark-antiquark pair proportional to the available phase space. Previously  $u\bar{u}$  and  $d\bar{d}$  pairs were produced with equal probabilities, however there is no change in behaviour for the default values of the parameters.

- The option of forbidding the production of specific hadrons during the hadronization has been added in order to forbid the production of  $\sigma$  and  $\kappa$  mesons, which are included to represent  $s$ -wave systems in some meson decays.
- The default parton distribution function (PDF) has been changed to the leading-order set of [16]. A change has been made so that, rather than the cubic interpolation previously used for the internal MRST PDFs, we now switch to linear interpolation above  $x = 0.8$  to give improved behaviour at high- $x$ .
- The Higgs boson running width is now calculated as described in [17]. The **SMHiggsMassGenerator** class has been added to generate the off-shell mass of the Higgs boson using the prescription of [17] and is used to give the mass distribution of the Higgs boson in  $gg, q\bar{q} \rightarrow h^0$  and Higgs boson plus jet processes. The Higgs boson branching ratios are now calculated for each decaying Higgs boson, based on its off-shell mass, and therefore the values in the data tables are not used. If modes are switched off the **SMHiggsMassGenerator** class correctly takes this into account when used as part of the cross-section calculation.
- An interface to ROOT [18] has been added so that it is easier to use ROOT in **AnalysisHandlers** if desired.
- A number of additional **AnalysisHandlers** have been added comparing the results of **Herwig++** to LEP and B-factory data. These were used to tune the shower and hadronization parameters in the current version of the program.
- The forced splitting required to ensure the correct valence content of the incoming hadrons, which was previously preformed as the first step of the hadronization, is now performed as the last step of the shower. This is part of the changes made to include multiple parton-parton scattering.
- The handling of partonic decays of bottom and charm hadrons has been changed. The **PartonicHadronizer** class, which was previously used to perform the hadronization of these decays, has been replaced by functionality in the **PartonicDecayerBase** class from which all classes implementing partonic decays now inherit.
- The shower module has been changed so that in the showering of particles which have already been decayed the off-shell mass of the particle is preserved, rather than the particle being given its on-shell mass at the end of the shower, in order to ensure the conservation of energy and momentum in the parton shower.
- An interface to the **EvtGen** [19] decay package has been added including spin correlation effects. This interface currently needs a modified version of **EvtGen** which is available on request but we hope these changes will be included in the LHC version of **EvtGen** in the near future.
- A new class, **MEQCD2to2Fast**, for QCD  $2 \rightarrow 2$  scattering processes which uses hard-coded expressions for the matrix elements rather than the helicity libraries of **ThePEG** has been added for use in the multiple parton-parton scattering model of the underlying event to increase the speed of the model.

- The `herwig-config` script has been added to the release to give information on the installed location of the program, etc., for use by other programs, such as `RivetGun` which use `Herwig++`.
- Options to handle the decay of a colour-singlet particle to three quarks or antiquarks, or the decay of a colour triplet particle to two antiquarks, have been added to the `MamboDecayer` class in order to test the showering and hadronization of systems which violate baryon number conservation.
- The implementation of the veto used to include the effects of the parton distribution functions (PDFs) in the backward evolution algorithm used to generate the initial-state parton shower has been modified to increase the efficiency of the veto, and hence the speed of the algorithm.
- A general interface for vetoing parton shower emissions has been added. Vetos on a single emission, a shower attempt or the whole event are possible. One implementation of this interface provides vetoing branchings depending on the  $p_{\perp}$  of the branching.
- A default rapidity cut of  $|y| < 3$  has been imposed for photons produced in the hard process to reduce the number of events at high rapidity and small- $x$  which could not be successfully showered.
- `Herwig++` now uses the GNU scientific library (GSL) [20] for some special mathematical functions.
- A number of improvements have been made to the `DOXYGEN` documentation.

The following bugs have been fixed:

- A bug in identifying which partons in clusters came from the perturbative stage of the event has been fixed. This meant that the wrong hadrons preserved the direction of their parton constituents when using the `[CIdir=1]` option.
- A bug affecting the calculation of the soft cluster masses for clusters containing a remnant of the beam particle has been fixed.
- A number of changes have been made to improve the identification of particles which have already been decayed but should be showered, for example in BSM physics processes or for processes supplied using the Les Houches accord.
- A bug affecting the generation of the phase space in the `MamboDecayer` class has been fixed.
- Several filenames have been changed to avoid problems with case-insensitive Mac OS X file systems.
- A bug preventing the use of the `NoPDF` parton distribution function in lepton-lepton collisions has been fixed.



## 6 Summary

Herwig++2.1 is the second version of the Herwig++ program with a complete simulation of hadron-hadron physics albeit with major improvements to the simulation of the underlying event and Beyond the Standard Model physics with respect to the previous version. The program has been extensively tested against a large number of observables from LEP, Tevatron and B factories. All the features needed for realistic studies for hadron-hadron collisions are now present and 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. Following the release of Herwig++3.0 we expect that support for the FORTRAN program will cease.

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