

# Herwig++ Status Report\*

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## Abstract

Herwig++ is the successor of the event generator HERWIG. In its present version 2.2.1 it provides a program for full LHC event generation which is superior to the previous program in many respects. We briefly summarize its features and describe present work and some future plans.

## 1 Introduction

With the advent of the LHC era it was decided to completely rewrite the general purpose event generator HERWIG [1, 2] in C++ under the name Herwig++, based on the package ThePEG [3, 4]. The goal is not only to provide a simple replacement of HERWIG but to incorporate physics improvements as well [5]. From 2001 until now Herwig++ has been continuously developed and extended [6–10]. The current version is 2.2.1, cf. [11]. The physics simulation of the current version is more sophisticated than the one of Fortran HERWIG in many respects. In this report we will briefly summarize the status of the different aspects of the simulation. These are the hard matrix elements available, initial and final state parton showers, the hadronization, hadronic decays and the underlying event. We conclude with an outlook to planned future improvements.

## 2 Physics simulation steps

### 2.1 Matrix elements

The event generation begins with the hard scattering of incoming particles or partons in the case of hadronic collisions. We have included a relatively small number of hard matrix elements. These include  $e^+e^-$  annihilation to  $q\bar{q}$  pairs or simply to  $Z^0$  bosons and deep inelastic scattering. In addition there is the Higgsstrahlung process  $e^+e^- \rightarrow h^0 Z^0$ . For hadron–hadron collisions we have the QCD  $2 \rightarrow 2$  processes including heavy quark production. For colourless final states we have the following matrix elements,

$$hh \rightarrow (\gamma, Z^0) \rightarrow \ell^+ \ell^-, \quad hh \rightarrow W^\pm \rightarrow \ell^\pm \nu_\ell (\bar{\nu}_\ell), \quad hh \rightarrow h^0, \quad hh \rightarrow h^0 Z^0, \quad hh \rightarrow \gamma\gamma.$$

We also provide matrix elements for processes with additional jets in the final state, like

$$hh \rightarrow (\gamma, Z^0, W^\pm) + \text{jet}, \quad hh \rightarrow h^0 + \text{jet}.$$

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In addition, there are matrix elements for perturbative decays of the top quark, which will be simulated including spin correlations (see below). There will be some more matrix elements added in future versions, e.g. for  $hh \rightarrow qqh^0$ . Despite the rather small number of matrix elements, there is no real limitation to the processes that may be simulated with Herwig++. In practice, one may use any matrix element generator to generate a standard event file [12] which in turn can be read and processed by Herwig++.

For processes with many legs in the final state we follow a different strategy. When the number of legs becomes large — typically larger than 6–8 particles in the final state — it will be increasingly difficult to achieve an efficient event generation of the full matrix element. For these situations we have a generic framework to build up matrix elements for production and decays of particles in order to approximate any tree level matrix element as a simple production process with subsequent two or three body decays. This is a good approximation whenever the widths of the intermediate particles are small. The spin correlations among these particles can be restored with the algorithm described in [13]. Also finite width effects are taken into account [14]. The full simulation of several processes of many models for physics beyond the standard model (MSSM, UED, Randall–Sunrum model) is thus possible in Herwig++ [15]. Here, all necessary matrix elements for production and decay processes are constructed automatically from a model file.

## 2.2 Parton Showers and matching with matrix elements

After the hard process has been generated, typically at a large scale  $\sim 100 \text{ GeV} - 1 \text{ TeV}$ , the coloured particles in the process radiate a large number of additional partons, predominantly gluons. As long as these are resolved by a hard scale of  $\sim 1 \text{ GeV}$  this is simulated with a coherent branching algorithm, as outlined in [16] which generalizes the original algorithm [17–19] used in HERWIG. The main improvements with respect to the old algorithm are boost invariance along the jet axis, due to a covariant formulation, and the improved treatment of radiation off heavy quarks. We are using mass-dependent splitting functions and a description of the kinematics that allows us to dynamically generate the dead-cone effect. In addition to initial and final state parton showers there are also parton showers in the decay of heavy particles, the top quark in our case.

When extrapolating to hard, wide-angle emissions, the parton shower description is not sufficiently accurate in situations where observables depend on large transverse momenta in the process. In these cases we supply so-called hard matrix element corrections that describe the hardest parton emission, usually a hard gluon, with the full matrix element for the process that includes that extra parton. In order to consistently describe the whole phase space one has to apply soft matrix element corrections. Matrix element corrections are available for Drell–Yan type processes, Higgs production in  $gg$  fusion and  $e^+e^-$  annihilation to  $q\bar{q}$ -pairs. In addition, we apply a matrix element correction in top-quark decays [20].

From the point of view of perturbation theory, the hard matrix element correction is only one part of the next-to-leading order (NLO) correction to the Born matrix element. The full NLO calculation also includes the virtual part with the same final state as the Born approximation. When trying to match NLO calculations and parton shower algorithms systematically, we have to avoid double counting of the real emission contributions. Two systematic approaches are being successfully discussed and applied in event generators: MC@NLO [21–23] and the POWHEG approach [24, 25]. In Herwig++ we have included working examples of matching in both approaches. The MC@NLO method, adopted to Herwig++ is described in [26]. Whereas the POWHEG method has already been applied for several processes in  $e^+e^-$  annihilation [27, 28] and also for Drell–Yan production [29]. Parts of these implementations will become available in future releases.

Another viable possibility to improve the description of QCD radiation in the event generation is the matching to multiple tree-level matrix elements, that describe the radiation of  $n$  additional jets with respect to the Born level. Theoretically most consistent is the CKKW approach [30] which has been studied in the context of an angular ordered parton shower in [31].

## 2.3 Hadronization and decays

The hadronization model in Herwig++ is the cluster hadronization model which has not been changed much from its predecessor in HERWIG. After the parton shower, all gluons are split nonperturbatively into  $q\bar{q}$  pairs. Then, following the colour history of the parton cascade, all colour triplet–antitriplet pairs are paired up in colourless clusters which still carry all flavour and momentum information of the original partons. While these are heavier than some threshold mass they will fission into lighter clusters until all clusters are sufficiently light. These light clusters will then decay into pairs of hadrons.

The hadrons thus obtained are often heavy resonances that will eventually decay on timescales that are still irrelevant for the experiment. These hadronic decays have been largely rewritten and are modeled in much greater detail in Herwig++. While in HERWIG they were often simply decayed according to the available phase space only, we now take into account more experimental information, like form factors, that allow for a realistic modeling of decay matrix elements [32,33]. In a major effort, a large fraction of the decay channels described in the particle data book [34] have been included into Herwig++.

## 2.4 Underlying event

The underlying event model of Herwig++ is a model for multiple hard partonic interactions, based on an eikonal model, similar to JIMMY [35]. In addition to the signal process there are a number of additional QCD scatters, including full parton showers, that contribute to the overall hadronic activity in the final state and eventually also give rise to a (relatively soft) jet substructure in the underlying event. The model has two important parameters, one parameter  $\mu$ , describing the spatial density of partonic matter in the colliding protons. Secondly, there is one cut off parameter  $p_{\perp,\min}$  that gives a lower bound on the differential cross section for QCD  $2 \rightarrow 2$  jet production. The model has been carefully tuned to Tevatron data [36]. Further possible bounds on the model parameters have been studied in [37]. An alternative modeling of the underlying event on the basis of the UA5 model [38] is also available for historic reasons.

Currently, the multiple partonic interaction model is limited to hard scattering while a soft component is simply not present. For a realistic simulation of minimum bias events a soft component is, however, very important. An extension into the soft region, allowing us the simulation of minimum bias events is currently being studied and is likely to be included in the next release of Herwig++.

## 3 Availability

The latest version of Herwig++ is always available from hepforge:

`http://projects.hepforge.org/herwig`

There one can also find wiki pages to help with questions concerning installation, changing particular parameters and other frequently asked questions. The installation process is straightforward on any modern variant of linux. The physics details of the program are now documented in great detail in our manual [33]. The pdf version of the manual contains additional links to the online documentation of the code. All important parameters have been carefully tuned to a wealth of available data and the code is shipped with default parameters that give the best overall description of the data that we have tuned to. Details of the tune can also be found in the manual [33].

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