Vol. 38 (2007) *ACTA PHYSICA POLONICA B* No 7

LHC EVENT GENERATION WITH HERWIG++*

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(Received April 30, 2007)

We report on progress with the new Monte Carlo event generator Herwig++. The chain of event simulation is briefly outlined and details on current developments, particularly in the framework of Herwig++ are given.

PACS numbers: 12.38.–t, 13.85.Hd, 13.85.Fh

1. Introduction

The advent of the LHC poses new challenges towards Monte Carlo event generators. It was realised some time ago that it will become increasingly difficult to maintain the "workhorse" Monte Carlo programs like PYTHIA [1] and HERWIG [2] in their present state throughout the era of the LHC. Furthermore, the incorporation of new ideas to improve the event generation was understood to be difficult. Therefore, it was decided to completely rewrite the event generators [3, 4]. Besides, also new multi-purpose event generators, like SHERPA are being developed [5, 6]. In this report we focus on the present status of this rewrite for the case of the program HERWIG with its successor Herwig++.

In Fig. 1 we show a sketch of the event generation. The simulation usually begins with a hard signal process, in the figure this is chosen to be a pair of leptons (red). Then we have initial state parton showers followed by final state parton showers, these are the dark and light green gluon emissions in the figure. Gluons are split into non-perturbative light constituent quark pairs in the beginning of the hadronization phase. Then we form colourless clusters which carry flavour and momentum information. The latter ones

* Presented at the Cracow Epiphany Conference on Precision Physics and Monte Carlos for LHC, Cracow, Poland, 4–6 January 2007.

may eventually fission into lighter clusters, if necessary. Finally, clusters decay into pairs of hadrons according to some simple statistical weights. At the last stage of the simulation those hadrons that are unstable decay until we are left only with a handful of hadron species, electrons and photons — the particles that can be measured in an experiment. In the following we shall go through the different simulation stages and describe the recent status of the simulation in Herwig++.

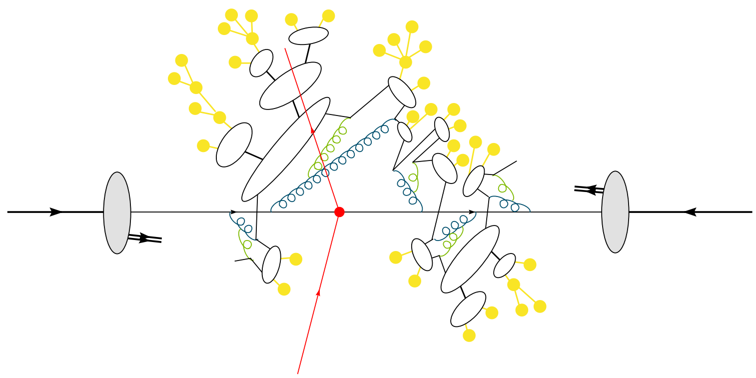

Fig. 1. Sketch of the simulation of a pp collision. There is no remnant handling in this figure.

2. Matrix elements

There is only a small number of built-in matrix elements available in Herwig++. The purpose of these is to have the possibility of testing all possible complications of the following simulation steps. First of all there is simple jet production in e^+e^- annihilation, $e^+e^- \to q\bar{q}$ and also the on-shell production of a vector boson, $e^+e^- \to Z^0$. For hadronic collisions we include the following Drell–Yan type processes with coloured particles only in the initial states,

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

as well as related processes with one additional hard jet in the final state

$$hh \to (\gamma, W^\pm, Z^0) + \mathrm{jet} \,, \qquad hh \to h^0 + \mathrm{jet} \,.$$

The latter ones play also a role for the hard matrix element corrections that are included. Furthermore, we have the QCD $2 \to 2$ processes including heavy quark pair production.

Unlike in the previous generation of Monte Carlo simulation programs this list is very short. However, we do have the possibility to easily extend this list as there is the possibility to read in event files in the common Les Houches file format [7]. Most of the tree-level processes of interest for the LHC are available from the commonly used, and well validated matrix element generator programs, *e.g.* MadGraph, AlpGen, CompHEP, Amegic++.

One exception to this approach is, however, the case of BSM physics simulation. We have the possibility to simulate spin correlations throughout the long decay chains, typically occurring the decay of supersymmetric particles, which may be abundantly produced at the LHC. As in this case the production and decay are closely linked together, one cannot factorise these two simulation steps and needs full control over both [8].

In order to utilise the spin correlation algorithm one needs access to the full helicity information of each process in the generation chain. This is achieved with the help of an implementation of the HELAS [9] helicity matrix element within Herwig++ — extended to include also Spin 3/2 and Spin 2 particles. Most matrix elements in Herwig++ are based on this code.

3. Parton shower and matrix element corrections

The parton shower in Herwig++ has been completely redeveloped. In [10] new evolution variables have been proposed. The advantages of the new variables are the smooth coverage of soft gluon phase space and the consistent treatment of radiation from heavy quarks in the quasi collinear limit. The implementations of the initial and final state parton showers in Herwig++ are based on this approach. The formulation of the initial state shower has been studied in greater detail also in [11].

The final state parton shower had been implemented and tested to a large extend against LEP data in the first release (version 1.0) of Herwig++ [12]. We have compared to data on jet production, event shapes, single particle distributions and the like. It was found that all relevant data can be described as well as with the FORTRAN program. One particular improvement that we would like to highlight is the description of the b quark fragmentation function, based on the parton showering off heavy quarks. In previous HERWIG one always had to include extra hadronization parameters in order to achieve a satisfactory description. In Fig. 2 we show a comparison of Herwig++ to SLD data [13].

Looking at the parton shower in the Drell–Yan process and comparing it to Tevatron data on Z^0 production it quickly becomes clear that a hard matrix element correction [14] is important for transverse momenta larger than the invariant mass of the produced vector boson. In Fig. 3 (left) the phase space for the partonic sub-process $q\bar{q} \to Z^0 g$ is shown. The light areas

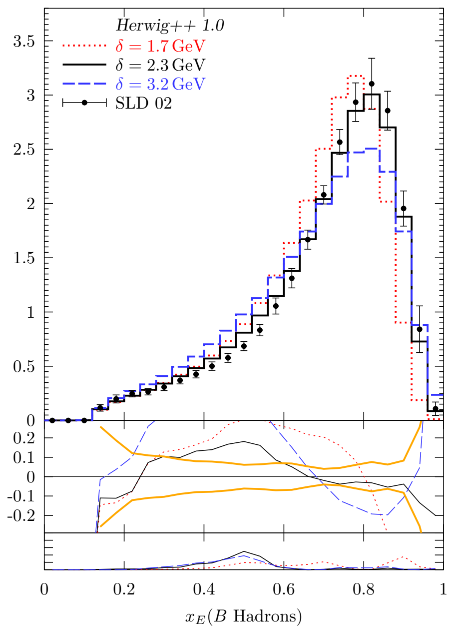

Fig. 2. Comparison of the b–quark fragmentation function from Herwig++ against SLD data [12, 13].

are filled by the Herwig++ parton shower whereas the dark grey area in the middle (dead region) is filled only by an additional hard matrix element correction. Clearly, when the emitted gluon is soft ($\hat{s} \to M^2$) the parton shower emissions have access to the whole phase space, also to large angles. The lack of emissions in the dead region becomes obvious when comparing to data. The transverse momentum of the vector boson as measured by

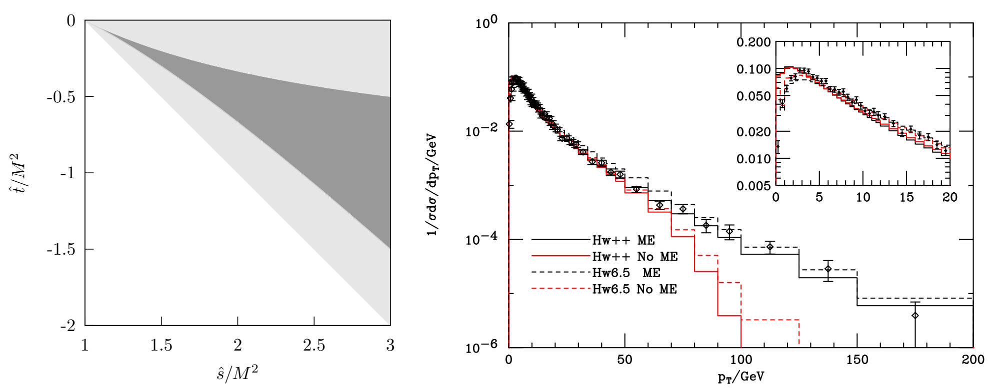

Fig. 3. Hard matrix element corrections in the Drell–Yan process. Phase space of parton shower emissions (left). Comparison to CDF data [15] (right).

CDF [15] is compared to the simulation with and without ME correction in the right panel of Fig. 3, taken from [16]. The transverse momentum falls off quickly above the Z^0-mass.

Hard and soft/collinear gluon emissions in top decays have been reconsidered in [17]. It was found that the choice of kinematics in [10] was not well-suited for this problem, particularly for the emission of soft gluons. The choice of the reference vectors in the kinematics reconstruction of the gluon emission has been modified instead. With this choice, a smooth coverage of the whole three body phase space has been achieved. As in the Drell–Yan case already, it is crucial that the hard matrix element correction is complemented with a soft matrix element correction in order to have a smooth population of phase space at the boundaries between soft/collinear emissions and the hard emission region.

The hard and soft matrix element corrections are implemented for the Drell–Yan process (*i.e.* W and Z production at hadron colliders), for $e^+e^- \to q\bar{q}$ and for the top quark decay. Further improvements of the parton shower and its matching to matrix elements will be described in Section 5.

4. Hadronization and hadronic decays

The hadronization model of Herwig++ has not changed much with respect to the model in the FORTRAN program. The same cluster hadronization model has been implemented. Only slight changes have been made in order to allow for a more universal production of baryons.

In the first version, the hadronic decays have essentially been recoded in order to mimic the behaviour of the FORTRAN program. These decayers still exist and can be used. Currently, in a major effort, the decays of unstable hadrons have been completely redeveloped. First, a MySQL database with the particle properties, including decay channels and their branching fractions has been set up. Most of the information in this database is independent of the program that will use it and basically reflects what is in the Particle Data Book [18]. On top of that, many `DecayHandler`s have been implemented that can actually handle all the decays within the framework of Herwig++. This structure works but has not been validated very extensively against data.

As already mentioned for the hard processes involving supersymmetric particles, a cascade of hadronic decays implies spin correlations that are not taken into account if all $1 \to n$ body decays are handled independently. In order to improve that situation, a spin correlation algorithm [19] has been implemented into Herwig++. The narrow width approximation is still utilised here but angular correlations can be taken into account on the basis of the spins of the particles involved. Apart from this specification the algorithm is universal.

As an example we consider the decays of a (pseudo-) scalar Higgs boson into a τ pair, followed by $\tau \to \pi\nu$ decays. In Fig. 4 we show the angle ϕ^* between the decay planes of the two τ leptons and the angle δ^* between the two pions in the H/A rest frame. Both distributions strongly depend on the spin correlations among the final state particles. The figures show that the spin correlation algorithm of Herwig++ gives the same answer as the program TAUOLA [20] which includes full matrix elements for the resulting four body decays.

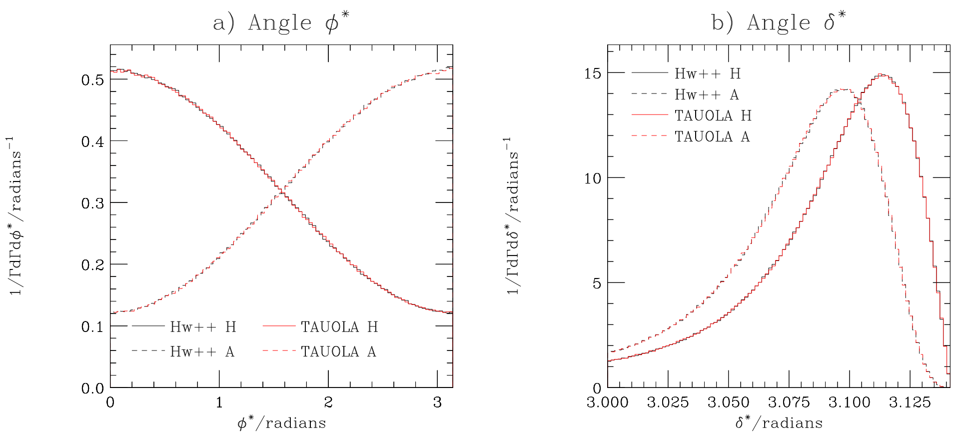

Fig. 4. Comparison of the distribution of ϕ^* and δ^* (see text) in (pseudo-) scalar Higgs decays into τ pairs between TAUOLA (full matrix elements) and Herwig++ (spin correlation algorithm).

A further improvement is that running particle widths are taken into account for important resonances, resulting in different decay channels and branching fractions, depending on the actual mass that an instable particle has been assigned.

Whenever charged hadrons decay they may as well radiate a number of soft/collinear photons and even a hard photon. The simulation of this additional photon radiation, based on Yennie–Frautschi–Suura (YFS) exponentiation is incorporated into a package SOPHTY [21] which is now also part of Herwig++.

5. Current and future developments

In addition to the features that have been described in the previous sections we currently have implemented the parametrisation of UA5 data in order to have some underlying event simulation. It is well known that this is really just a parametrisation and needs to be adjusted. Furthermore, not all observables that are related to the underlying event can be described at the same time. One current development is the implementation of a multiple interaction model, like JIMMY [22] in Herwig++. Nevertheless, currently all physics models that are needed for a complete simulation of hadron collider events are implemented and we believe that Herwig++ can be used for some serious physics analysis already.

Needless to say, that the program is still not perfect. Recently, there has been a lot of conceptual development in the area of matching higher order matrix elements and parton showers. Some of these ideas will be included in future versions of Herwig++. In the following we want to discuss the status of these developments in greater detail.

5.1. CKKW matching

When asking for a more accurate description of exclusive jet observables it will become more and more important to take into account angular correlations from higher order matrix elements, which cannot be included in the parton showering algorithm alone. Particularly when some of the extra jets are required to be hard the parton shower cannot even access the regions of phase space that are important for these observables.

For some higher order observables, say involving n additional hard emissions, one would need access to the full n-loop matrix elements. Clearly, for most observables this is out of reach. One way out, somewhere in between the pure parton shower picture and the higher order computation is the Catani–Krauss–Kuhn–Webber (CKKW) approach to matching higher order matrix elements with parton showers [25,26]. In this approach one generates an exclusive sample of events with *up to* n additional hard emissions with respect to the leading order. In order to achieve this without the full n loop calculation one still utilises the same NLL approximation (*i.e.* collinear/soft logs) that one has in the parton shower alone, in order to describe proper jet rates. However, when it comes to describing the angular details of the phase space the full matrix element is used in place of the collinear information alone. In this way one still has a NLL description of the jet rates, which is believed to work fairly well but at the same time one has the possibility of improving the hard, wide-angle gluon emissions.

This approach has proven to be very successful in describing additional exclusive jets in vector boson production events at the Tevatron [27] as well as some four jet angular distributions [24] at LEP. All this has been implemented in the program package SHERPA [5]. Implementations for PYTHIA and HERWIG have also been studied [32].

For Herwig++ this approach has to be modified in order to account for the different parton shower evolution and the peculiarities of the angular ordered parton shower. As a first step, this algorithm has been implemented for $e^+e^- \to$ jets at LEP [23]. As one of the results we see the distributions of the Bengtsson–Zerwas and Nachtmann–Reiter angles in comparison to LEP data in Fig. 5.

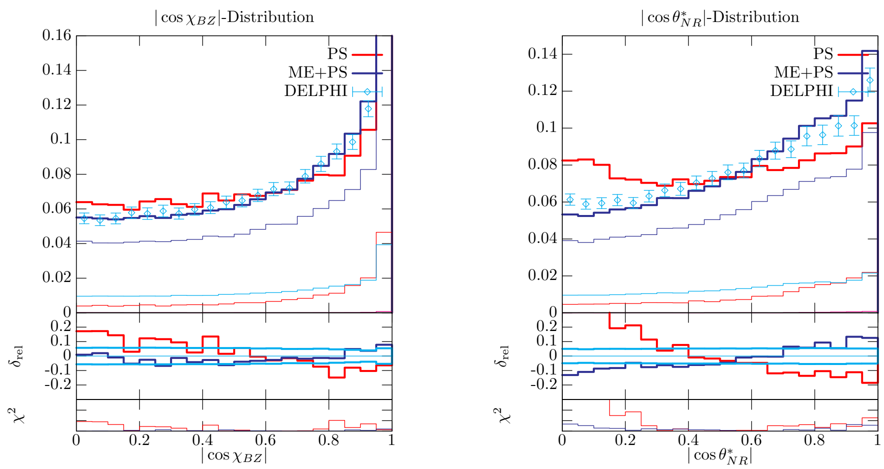

Fig. 5. The distributions of four jet angles with and without CKKW matching compared to DELPHI data [23, 24]. Thin lines show the contributions of different multiplicity matrix elements (blue: $e^+e^- \to 4$ jets).

An implementation of this algorithm for hadron–hadron collisions is underway and will be important for the accurate simulation of processes with one or more vector bosons and multiple jets. These in turn are important (irreducible) backgrounds for various searches at the LHC.

5.2. NLO matching

Another, somewhat complementary, path towards improving the accuracy of Monte Carlo event generators is the use of full higher order matrix elements. At the moment one only considers NLO corrections. The challenge is again, to avoid double counting of parton emissions that could both originate from real correction matrix elements and from the parton shower. The most prominent solution to this problem is MC@NLO [28–30]. The philosophy behind the development of this algorithm was to modify the existing parton shower Monte Carlo program, HERWIG in this case, as little as possible. The knowledge of how soft and/or collinear partons are generated in HERWIG is used in order to define subtraction terms that are specific to the parton shower program. With the help of these subtraction terms one can generate processes with zero or one extra emissions with some specific (positive or negative) weight. These events are generated such that, after parton showering and reexpansion in α_S the correct NLO behaviour is restored. Technically, MC@NLO generates these event files which are then simply read in by HERWIG, which then performs parton showering and hadronization.

The very same approach can in principle be utilised with any Monte Carlo event generator as long as the details of the parton showering are well understood. One needs to redefine the subtraction terms according to the specific kinematics used in the parton shower. This has been done now also for Herwig++ [31]. The first process in order to test these ideas was e^+e^- annihilation to hadrons. The results for event shapes differ not much from the results that are obtained with the default program with a matrix element correction applied, *cf.* Fig. 6 (left). The reason for this may be that the same subdivision into parton shower phase space and hard matrix element phase space is used. Of course, the overall normalisation is predicted more accurately from the MC@NLO implementation whereas for the comparison of the shape all histograms have been normalised to unity.

Another approach to the matching of parton showers and NLO matrix elements from Nason [33, 34] is based on the idea that the *hardest* emission should always be generated according to the full matrix element. This is not always clear in the parton shower. In order to achieve this, one has to formulate a modified Sudakov form factor for the hardest emission. Then, due to angular ordering one has to add in additional soft but wide angle gluon emissions before this hardest emission in order not to destroy the colour ordering of the process. This has been implemented into Herwig++, again for the case of e^+e^- collisions [35]. In the right panel of Fig. 6 we see that the description of the thrust distribution in e^+e^- collisions has been improved.

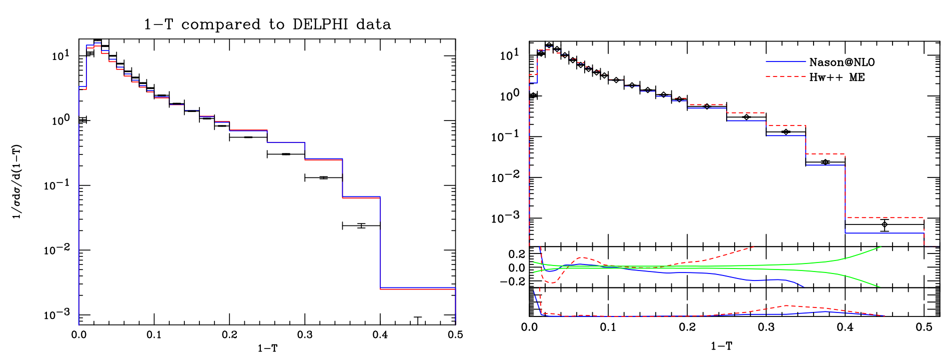

Fig. 6. Comparison of the thrust distribution, measured at LEP, with predictions from the MC@NLO (left) and Nason@NLO (right) implementations in Herwig++.

6. Conclusions

We have reported on various parts of the simulation in which a lot of progress has been made. The current status may be viewed as being sufficiently sophisticated to have full simulations of hadron–hadron collision events. Besides a handful of standard signals, also first processes of physics beyond the standard model (BSM) can be simulated now. Furthermore, the simulation of hadronic decays has been completely redeveloped.

In future versions the many developments that have been reported upon will be included in the releases of Herwig++. Major new developments will focus on more BSM physics and improved matching of higher order perturbative computations with parton showers. Furthermore, a multiple interaction model will significantly enhance the simulation of the underlying event.

I would like to thank the organisers for the invitation to this very pleasant and fruitful conference and all members of the Herwig++ team for their contributions to the results presented in this talk.

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