The Monte Carlos

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Abstract

The concept of an event generator is introduced, and its usefulness illustrated. The components needed to build up a complete event are listed, with some comments on ambiguities. A survey is given of the more frequently used existing programs, including which processes are implemented where. Finally, the description of SUSY Higgses in PYTHIA is covered in some detail. Some further topics are covered in the subsequent paper by F. Paige.

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1 Introduction

The events produced in high energy physics usually are high-multiplicity ones — today typical events contain 20–50 charged particles, tomorrow over 100. Normally it is in such events that signals for new physics have to be found. Since the new physics events are likely to be rare, they are also difficult to dig out from the background. Some of the events may contain spectacular features, such as energetic isolated leptons or photons, and here signal-to-background ratios usually are more promising. However, a good understanding of the full structure of both signal and background events is necessary in order to optimize the likelihood of discovery, and to ease the interpretation in terms of new physics.

It is here that event generators enter the stage. The task of an event generator is to describe, as accurately as possible, the experimental characteristics of physics processes of interest. The main applications are as follows:

- To give physicists a feeling for the kind of events that one may expect/hope to find, and at what rates.
- As a help in the planning of a new detector, so that detector performance is optimized, within other constraints, for the study of interesting physics scenarios.

- As a tool for devising the analysis strategies that should be used on real data, so that signal-to-background conditions are optimized.
- As a method for estimating detector acceptance corrections that have to be applied to raw data, in order to extract the 'true' physics signal.
- As a convenient framework within which to interpret the significance of observed phenomena in terms of a more fundamental underlying theory.

The necessary input for event generators comes from the calculated matrix elements for the different processes, from the measured and parametrized structure functions, from models for parton showers, underlying events and fragmentation, etc., which will be further discussed below.

As the name indicates, the output of an event generator should be in the form of 'events', with the same average behaviour and the same fluctuations as real data. In generators, Monte Carlo techniques are used to select all relevant variables according to the desired probability distributions. The Monte Carlo approach ensures that the proper amount of randomness is included. Normally an event is a list of all final-state observable particles, i.e. hadrons, leptons, and photons, together with their momenta. The event thus corresponds to what could actually be seen by an ideal detector. However, one often is only interested in the total energy and direction of a jet, rather than in the detailed jet structure. Then a cruder event description, in terms of partons ($\approx$ jets) and leptons, may be sufficient.

In principle, one must distinguish between an event generator and a numerical integration package for cross-sections: both can be used to evaluate the cross-section for a given process and for given cuts, but only the former gives the full multi-dimensional differential distribution of events within these cuts. In practice, this distinction is not always obvious for a large number of dedicated programs written to study one or a few specific processes: although the main application may be cross-section integration, only little additional effort is needed to generate simple events which consist of a small number of outgoing partons and leptons.

At the other end of the generator spectrum, there are large subroutine packages intended for general-purpose use, with many different processes included, and a full description of the production of all hadrons in an event. These packages contain many man-years of effort, 10–30 thousands of lines of Fortran code, and are generally better documented and supported than the smaller packages. Although they may not be the best for all applications, it is natural that we concentrate on them in the following.

Where does a generator fit into the overall analysis chain? In 'real life', the machine produces interactions. These events are observed by detectors, and interesting ones written to tape by the data acquisition system. Afterwards the events may be reconstructed. Based on this cleaned-up information one may proceed with the physics analysis. In the Monte Carlo world, the rôle of the machine, namely to produce events, is taken by the event generators described in this paper. The behaviour of the detectors is simulated in programs such as GEANT [1]. Ideally, the output of this simulation has exactly the same format as the real data registered by the detector; it can therefore be put through the same event reconstruction and physics analysis chain, except that here we know what the 'right answer' should be, and so can see how well we are doing.

Since the full chain of detector simulation and event reconstruction is very timeconsuming, one often does ‘quick and dirty’ studies in which these steps are skipped entirely, or at least replaced by very simplified procedures that only take into account the geometric acceptance of the detector and other trivial effects. One may then use the output of the event generator directly in the physics studies.

Programs are still undergoing rapid evolution: new processes are calculated and included; improved structure function parametrizations appear; aspects of parton showering, fragmentation and decay are gradually better modelled; and even the physics landscape changes, e.g. as a function of the currently favoured value for the top-quark mass. The programs that will be used ten years from now (at the LHC/SSC or at linear e^+e^- colliders) are likely to look rather different from those available today. However, many of the basic principles should remain more or less unchanged.

One may find discussions of, and comparisons between, event generators in a number of recent workshop proceedings: e^+e^- physics was covered in the LEP workshop [2], ep physics in the HERA one [3], and pp physics in several LHC and SSC ones [4, 5, 6, 7]. Part of the current report has been borrowed from [8].

2 Physics Overview

The perfect event generator does not exist. This reflects the limited understanding of physics in many areas. Indeed, a perfect generator can only be constructed once everything is already known, in which case experiments are superfluous. One therefore has to be satisfied with programs that are in reasonable agreement with already accumulated experience, theoretical and experimental, and provide sensible extrapolations to higher energies. Since the ultimate goal is to look for new physics, it is also necessary to include the simulation of different alternative scenarios.

Given the complexity of the problem, the Monte Carlo approach allows a convenient division into separate subtasks. Thus, to describe an event in full, one needs to consider the following components:

1. The hard scattering matrix elements. These define the process(es) under study, and are therefore at the core of the programs.
2. The structure functions. The differential cross-sections, which are to be simulated in the programs, are given as the products of structure functions and the hard scattering matrix elements above.
3. Final state radiation. Partons in the final state may radiate. At high energies, this perturbative radiation is the dominant mechanism for building up the structure of (high-$p_\perp$) jets, with broad jet profiles and subjets.
4. Initial state radiation. The incoming partons may also radiate before the hard interaction, thus giving rise to additional jets close to the directions of the incoming hadrons.
5. Beam jets. Only one parton from each incoming hadron is assumed to participate in the hard interaction, and in the initial state showering. All the other partons act to produce the beam jets found along the directions of the original incoming hadrons.
6. Fragmentation and decays. Partons are not directly observable. Instead, once sufficiently removed from each other, they are fragmented into a collection of hadrons.

Many of these hadrons are unstable, and subsequently decay. Also particles directly produced as part of the hard process may undergo long decay chains, which may additionally involve further parton shower evolution and fragmentation.

Some of the components may be absent in some cases, e.g. e^+e^- annihilation events do not contain beam remnants.

It is important to remember that, although the subdivision above may be found in all the major event generators, the implementations of the different components vary a lot. In part this reflects an uncertainty in our basic understanding. However, the different physics interests of the program authors also means that some programs may have an especially sophisticated description of some components.

Just to give some flavour, here are a few of the uncertainties that appear in the above components.

1. The matrix elements are usually calculated to lowest order, and therefore contain scale ambiguities. Some processes contain soft or collinear singularities, which have to be regularized by arbitrary cutoffs.
2. A plethora of structure function parametrizations exist on the market, most of them collected in [9]. Many are out of date, i.e. are known to disagree with more recent data. However, the spread among remaining ones is non-negligible. In particular, the gluon structure function is expected to saturate at small x due to dense-packing effects, but the details remain very uncertain.
3. Final state radiation is rather well understood from e^+e^- annihilation. As an example, coherence effects may be included by requiring parton branchings to be ordered in terms of decreasing angles. This should give a large predictive power for the internal structure of jets, also at hadron colliders. However, the maximum virtuality from which the cascade is to be started remains uncertain, and this is reflected in a less accurate description of the production of well separated jets.
4. The coherence issues are rather more complicated in the initial state radiation than in the final state one. Despite impressive progress [10] large uncertainties therefore remain, in particular when one enters the small-x region. This is in addition to the uncertainty in the production rate of well separated jets, which is of the same nature as already noted for final state radiation.
5. No standard theory exists for beam jets, not even a common framework or language within which to discuss the underlying physics. Therefore each program author has been forced to develop his own ideology, basically from scratch. Issues that appear in this game are for instance minijet rates, minijet unitarization and relations to total cross-sections, pedestal effects, forward–backward correlations, colour flow topologies, leading particles in the remnants, rapidity gaps, and so on.
6. Also fragmentation descriptions lack solid theoretical backing, although experience from e^+e^- annihilation at least provides strong experimental constraints. Currently the two main models are string fragmentation and cluster fragmentation. Also independent fragmentation is used in several programs, although this approach is known to be flawed. In decays, the treatment is often simplified by a neglect of spin effects, i.e. decays are assumed to be isotropic even when it is likely that they are not.

There are also uncertainties that involve several of the above components. In particular, one and the same $2 \to 3$ process might be described either in terms of a basic $2 \to 3$ matrix element, or in terms of a $2 \to 2$ hard scattering followed by final state radiation, or in terms of a $2 \to 2$ hard scattering preceded by initial state radiation. It is therefore important to join the different descriptions in a consistent manner, e.g. to avoid double counting.

The double counting issue is non-trivial, and in practice it has led to a split of the Monte Carlo program activity into two different approaches, which we will refer to as 'parton showers' and 'matrix elements'.

3 Overview of Event Generators and Processes

In the parton shower approach, it is customary to implement only the lowest order matrix elements, i.e. as a rule, basic $2 \to 2$ processes. Initial and final state radiation are added on to the basic scattering in the shower approach proper. The showers are assumed to be universal, i.e. the shower evolution is not allowed to depend on the details of the hard scattering, but only on the gross features: energies and flavours of incoming and outgoing partons, and an overall Q^2 scale for the hard scattering. The approximate nature is reflected in a limited accuracy for the rate of production of additional well-separated jets, but the internal structure of jets should be well modelled. It is feasible to add fragmentation and beam jets, and thus to generate realistic representations of the events. In this category of programs, a large fraction of the total investment is in the common shower and fragmentation routines, while the effort needed to include yet another $2 \to 2$ process is modest, if only matrix elements are known and not too complex. Some of the programs of this kind therefore allow the simulation of many different processes.

The list of such event generators is fairly small. The three most commonly used are:

- HERWIG, by Marchesini and Webber [11].
- ISAJET, by Paige and Protopopescu [12].
- PYTHIA/JETSET, here PYTHIA for short, by the present author [13].

These three contain a multitude of processes (see below). HERWIG and PYTHIA can be used both for e^+e^-, ep and pp physics, while ISAJET is only for pp physics.

Several others may also be mentioned [2, 3, 8], for example:

- COJETS, by Odorico [14], can be used for QCD processes in e^+e^-, ep and pp.
- DTUJET, by Ranft et al. [15], is a pp QCD program.
- FIELDAJET, by Field et al. [16], is another pp QCD program.
- The Fire-String programs, by Angelini et al. [17], offers a non-standard-QCD approach.
- FRITIOF, by Andersson et al. [18], is mainly intended for heavy ion physics, but can also be used for pp QCD events.
- LEPTO, by Ingelman [19], is a program for deep inelastic scattering in ep.
- NLLjet, by Kato and Munehisa [20], is a program for QCD shower evolution in e^+e^- and ep.

The matrix element approach is represented by another class of programs. Here the emphasis is on the use of exact higher-order matrix elements. The analytic formulae in the programs are considerably more complicated, and the phase space generation machinery more advanced. The big investment here is in the matrix element calculation itself — usually these programs are written by the very people who calculated the matrix elements in the first place — and in selecting the kinematic variables in an efficient way. There is therefore less impetus for a common approach to many disparate processes. Since the precision aspect is important, it is not feasible to attach a simple, generic parton shower picture. Normally, therefore, only a fixed (small) number of partons are generated. Since most modern fragmentation models are tuned to be attached at the end of the parton shower evolution, fragmentation and beam jet treatments also become less interesting. These programs thus mainly generate parton configurations of 'pencil jets', rather than events as they may appear in a detector.

The number of matrix element programs is considerably higher than the number of parton shower programs: once a matrix element has been calculated, the Monte Carlo approach is usually the most convenient way to obtain physical cross-sections. Therefore many calculations are directly turned into programs. It is not possible in this report to give a complete list of all programs of this kind, some of which are publicly maintained and others which are not. Two programs contain matrix elements for widely different purposes, although only intended for pp interactions:

- EUROJET, by van Eijk et al. [21].
- PAPAGENO, by Hinchliffe [22].

A few others will be mentioned below.

The parton shower and matrix element programs fill somewhat complementary functions. The former are convenient for exploratory work: it is fairly easy to simulate a new, postulated physics process in sufficient detail to establish experimental feasibility, and to try out the tools needed to separate signal from background. For high-precision measurements of an established process, on the other hand, one needs the higher order matrix elements. The matrix element programs are also more convenient for generating events within very specific phase space regions, since the cuts can be built in from the start. With parton shower based programs it is necessary to generate more inclusive event samples and afterwards discard those events that do not fulfil the requirements, a procedure that can often be very inefficient.

In Table 1, a survey is given of the kind of physics processes found in the main generation packages mentioned above. This should be taken as indicative only — a given physics area may still be sufficiently ill-defined to allow rather different implementations. Further, whereas W′ production only requires the introduction of a single process, the SUSY scenario involves a multitude of processes, so all areas are not equally large. In the following, we will comment on the SUSY and Higgs sectors, but clearly several of the other topics mentioned above are of interest: some may form backgrounds that need to be controlled, others may provide alternative explanations that need to be disproven, once potential SUSY signals are found.

The minimal supersymmetric extension to the standard model (MSSM) contains a complete setup of supersymmetric partners to the ordinary particles: squarks, sleptons, gluinos, photinos, other gauginos, and so on. A host of different hard scattering subprocesses can therefore be considered, in particular for pp/p$\bar{\text{p}}$ physics. In terms of past usage, the two main programs in this area are ISAJET and UA2SUSY. As the name indicates,

Table 1: Physics topics included in some event generators. A • indicates that at least some processes are included.

Process	HERWIG	ISAJET	PYTHIA	EURO-JET	PAPA-GENO
QCD jets	•	•	•	•	•
minimum bias	•	•	•	•	-
heavy flavours	•	•	•	•	•
prompt photons	•	•	•	-	•
single W/Z	•	•	•	•	•
W/Z pairs	•	•	•	-	•
standard model H	•	•	•	-	•
heavy H (VV→VV)	•	•	•	-	-
h^0, H^0, A^0, $H^\pm$	•	-	•	-	-
SUSY	-	•	-	-	•
W'/Z'	-	-	•	-	-
fourth generation	-	•	•	-	•
contact interactions	-	-	•	-	•
leptoquarks	-	-	•	-	-
strongly interacting W/Z	-	-	•	-	-
excited fermions	-	-	•	-	-
technicolour	-	-	•	-	-
axigluons	-	-	-	-	•
baryon number violation	•	-	-	-	-

the latter is an upgrade of a dedicated program written inside the UA2 collaboration [23]. It is not clear whether this program will be supported in the future.

A further program is found in [24]. Here special emphasis is put on a flexible and detailed modelling of all sequential decay chains predicted for different parameter sets of the MSSM. This is an especially important and complicated aspect, since different mass hierarchies are possible, which lead to distinct decay chains and search strategies. The traditional ISAJET program, on the other hand, contains various production processes, but leaves it to the user to provide the SUSY decay tables. Hence the ISASUSY project, which is described by Paige [25]. When finished, the ISASUSY program will take a few MSSM basic parameters and from those calculate masses and branching ratios for all the main MSSM particles, using routines developed from those of [24]. The data will be written to a table, which can then be read by ISAJET for event generation. The table will be sufficiently self-contained, however, that also programs such as HERWIG or PYTHIA could read it. The threshold for including SUSY to these programs would then be lowered significantly, and one could hope to have several generators available, which would differ in aspects such as parton showers, fragmentation and underlying events.

4 Higgses in PYTHIA

Higgs production is found in several generators, but the description in PYTHIA is probably the most extensive one, and it is on this one that we concentrate here. The two main alternatives covered in the program are (i) a single standard model Higgs particle and (ii) a two-Higgs-doublet scenario with five physical Higgs states. The latter is normally associated with the MSSM Higgs sector, although more general scenarios could also be simulated.

For the standard model Higgs, a single unified description of production and decay characteristics, valid at any Higgs mass, would be very complex. In practice, two different descriptions are used in PYTHIA. For a reasonably light Higgs, and thereby a reasonably narrow one, the 'signal' and the 'background' graphs do not interfere significantly, so that it is possible to separate the process into Higgs production and Higgs decay. If the standard model Higgs is heavy, this is no longer possible but, in this region, mainly the $V_L V_L \to \mathrm{H} \to V_L V_L$ (V_L = longitudinal W or Z) graphs are of experimental interest, and so only full interference with the $V_L V_L \to V_L V_L$ background need be included. In the MSSM scenario, the Higgs particles are sufficiently light and/or narrow that the latter situation does not occur. In the following we will therefore separate the production and decay aspects.

In the neutral MSSM Higgs sector, the following production graphs are included:

$X = \mathrm{h}^0$	$X = \mathrm{H}^0$	$X = \mathrm{A}^0$	
3	151	156	$\mathrm{f}_i\overline{\mathrm{f}}_i \to X$
102	152	157	$\mathrm{gg} \to X$
103	153	158	$\gamma\gamma \to X$
24	171	176	$\mathrm{f}_i\overline{\mathrm{f}}_i \to \mathrm{Z}^0 X$
26	172	177	$\mathrm{f}_i\overline{\mathrm{f}}_j \to \mathrm{W}^+ X$
123	173	178	$\mathrm{f}_i\mathrm{f}_j \to \mathrm{f}_i\mathrm{f}_j X$ (ZZ fusion)
124	174	179	$\mathrm{f}_i\mathrm{f}_j \to \mathrm{f}_k\mathrm{f}_l X$ ($\mathrm{W}^+\mathrm{W}^-$ fusion)
121	181	186	$\mathrm{gg} \to \mathrm{Q}_k\overline{\mathrm{Q}}_k X$
122	182	187	$\mathrm{q}_i\overline{\mathrm{q}}_i \to \mathrm{Q}_k\overline{\mathrm{Q}}_k X$

The first three columns contain PYTHIA process numbers, the last the basic processes. Notation is that f indicates a fermion in general and q a quark, while Q is a heavy quark (in practice t) with masses included in the kinematics. Thus a process such as 124 would be $\mathrm{e}^+\mathrm{e}^- \to \nu_\mathrm{e}\overline{\nu}_\mathrm{e}\mathrm{h}^0$ in an $\mathrm{e}^+\mathrm{e}^-$ collider, $\mathrm{eq} \to \nu_\mathrm{e}\mathrm{q}'\mathrm{h}^0$ in an ep one, and $\mathrm{q}_1\mathrm{q}_2 \to \mathrm{q}_1'\mathrm{q}_2'\mathrm{h}^0$ in a pp one, showing how the same matrix elements may be applied to different initial states. Note that the above classification scheme also contains a few entries that are not allowed in the MSSM, such as A^0 coupling to a pair of W or Z bosons. These processes are included for symmetry, but by default have vanishing cross-sections.

Charged Higgs production may be generated by process 161, $\mathrm{fg} \to \mathrm{f}'\mathrm{H}^\pm$, i.e. typically $\mathrm{bg} \to \mathrm{tH}^-$. Process 143, $\mathrm{f}\overline{\mathrm{f}}' \to \mathrm{H}^\pm$, may be seen as a simplified version, where the $\mathrm{g} \to \mathrm{f}'\overline{\mathrm{f}}'$ branching has been included as part of the structure function evolution. A charged Higgs may also be produced in top decay, $\mathrm{t} \to \mathrm{bH}^+$, independently of how the top itself was produced.

A further production channel of Higgs particles is provided by process 141,

$f\overline{f} \to \gamma/Z^0/Z'^0$, where the Z' part can be switched off if desired, and the mass range of the γ/Z^0 can be set freely. Among the allowed decay channels, one finds Z^0h^0, h^0A^0, H^0A^0 and H^+H^-. The first is the same as process 24 (when Z' is switched off), while the rest are genuinely new possibilities, of interest in particular for e^+e^- colliders.

The list of included decay modes reads as follows:

$$
\begin{array}{lllllllll}
h^0 \to & f\overline{f}, & gg, & \gamma\gamma, & \gamma Z^0, & Z^0Z^0, & W^+W^-; & & \\
H^0 \to & f\overline{f}, & gg, & \gamma\gamma, & \gamma Z^0, & Z^0Z^0, & W^+W^-, & Z^0h^0, & h^0h^0, \quad A^0A^0; \\
A^0 \to & f\overline{f}, & gg, & \gamma\gamma, & \gamma Z^0, & Z^0Z^0, & W^+W^-, & Z^0h^0; & \\
H^+ \to & f\overline{f}', & & & & & & W^+h^0. &
\end{array}
$$

As before, some channels have been included although they have a vanishing rate.

One major limitation exists in PYTHIA, and that is that the one-loop corrections to the MSSM have not been included so far. If one really wants to include such effects, masses and couplings must be provided by the user. This can be done in the appropriate common blocks, as described in the manual. For instance, the $h^0 \leftrightarrow q\overline{q}$ coupling for up-type quarks, with the Born level value $\cos\alpha/\sin\beta$, is stored in `PARU(162)`. Once introduced, the parameter values will be applied both to production and decay graphs, with appropriate mass factors, phase space factors, Breit-Wigner resonance shapes, etc., inserted as required. The program does include an option where the Born level couplings are automatically calculated from the two input parameters $\tan\beta$ and m_h; today this is maybe not of so much physics interest, but it can be useful for some cross-checks.

5 Summary

To write a good event generator is an art, not an exact science. It is essential not to blindly trust the results of any single event generator, but always to have several cross-checks. Further, an event generator is not an all-powerful oracle, able to give intelligent answers even to ill-posed questions; sound judgement and some understanding of the generator are necessary prerequisites for successful use. In spite of these limitations, the event generator approach is the most powerful tool at our disposal, if we wish to gain a detailed and realistic understanding of physics at future colliders before the day when real data are available. Further, it is a field which has reached some level of maturity, as exemplified by how well LEP physics was predicted. Considering how many years still remain before the turn-on of the next generation of colliders, the current status is not bad at all, in particular not if we compare with previous machine generations at a corresponding stage of planning.

Small programs intended for specific purposes have their applications, and will always be needed, but there are many gains from having access to large general-purpose packages, which are versatile and well maintained and documented. The three most widely used generators of this category are HERWIG, ISAJET and PYTHIA. Each of these have their limitations. ISAJET contains supersymmetric particle production, but is only intended for pp physics. HERWIG and PYTHIA can be used for e^+e^-, ep and pp alike, and contains Higgs production within a SUSY scenario, but not the production of sparticles.

These three programs are likely to evolve in the future, in particular with respect to the SUSY treatment. The planned ISASUSY program offers the possibility of calculating appropriate decay tables from a mimimal set of MSSM parameters. Such a program is distinct from the event generation activity itself, and will be debugged separately. Once available, it would immediately benefit the ISAJET program, where decay tables currently have to be provided by the user. Very likely ISASUSY tables could also be used by HERWIG and PYTHIA. The supersymmetric production processes could then gradually be introduced into these two programs. With a bit of luck we could therefore have three major SUSY generators available a few years from now. This should provide a healthy amount of cross-checks.

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