Event Generators for LHC

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Abstract:
We give a survey of the event generators that may be used to predict *pp* collider physics at the LHC. The main program features are described, and also some of the known limitations are listed.

1 Introduction

The task of event generators 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 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.

To write a good event generator is an art, not an exact science. It is essential not to trust blindly the results of any single event generator, but always to have several cross-checks. Further, an event generator cannot be thought of as an all-powerful oracle, able to give intelligent answers 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 the LHC before the day when real data are available.

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, often one is only interested in the total energy and direction of a jet, rather than the detailed jet structure. Then a more crude event description, in terms of partons ($\approx$ jets) and leptons, may be enough.

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, and are generally better documented and supported than the smaller packages. It may be that they will dominate in the description below, although they need not be the best for all applications.

Programs still undergo 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 at LHC are likely to look rather different from those available today, which is why a too detailed study would be of limited use (unlike the e^+e^- event generators survey for LEP last year [1], on the eve of LEP startup). Further, it is not possible to view the event generators working group as separate from the seven other *pp* physics groups, which all have made extensive use of event generators as part of their specific physics studies. One may also find discussions of, and comparisons between, event generators in many of the recent studies on SSC physics, such as [2,3,4], and in the article [5].

The objective of the current report is not to repeat this work, but rather

- to give a survey of existing event generators, with an overview of what is included in them;
- to indicate known shortcomings, so that one may understand how seriously predictions should be taken; and
- to provide in-depth studies of a few specific topics, which serve to illustrate the status of programs.

In addition to the current report, the following papers appear as individual contributions to this working group.

- 'Structure Functions' by H. Plothow-Besch [6].
- 'Monte Carlo Simulation of Minimum Bias Events at the LHC Energy' by G. Ciapetti and A. Di Ciaccio [7].
- 'A Comparison of Bottom Production in Different Event Generators' by J.R. Cudell, O. Di Rosa, I. ten Have, A. Nisati, R. Odorico and T. Sjöstrand [8].
- 'Multi-jet Event Generators for LHC', by H. Kuijf, P. Lubrano and V. Vercesi [9].
- 'On the calculation of the exact $gg \rightarrow Zb\bar{b}$ cross section including Z decay and b quark mass effects' by R. Kleiss and B. van Eijk [10].
- 'Vector Boson Production in Association with Jets' by W.T. Giele [11].

2 Overview of Event Generators

The perfect event generator does not exist. This reflects the limited understanding of physics in many areas. Indeed, a perfect event generator could only be constructed if everything were already known, in which case experiments would be superfluous. One therefore has to be satisfied with programs which are in reasonable agreement with already accumulated experience, theoretical and experimental, and which 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 subdivision 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. Any partons in the final state may radiate. At high energies, this perturbative radiation is the main responsible for building up the structure of 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.

Of course, this separation is very crude and schematic. Thus, one and the same 2 → 3 process might be described either in terms of a basic 2 → 3 matrix element, or in terms of a 2 → 2 hard scattering followed by final state radiation, or in terms of a 2 → 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 nontrivial, 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' (PS) and 'matrix elements' (ME), respectively.

In the 'parton shower' approach, it is customary to implement only the lowest order matrix elements, i.e. as a rule, basic 2 → 2 processes. Initial and final state radiation is 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 produced in hadron colliders. 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 → 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. We are aware of the following programs:

- ISAJET, by Paige and Protopopescu, current version 6.36 [12].
- PYTHIA, by Bengtsson and Sjöstrand, current version 5.4 [13].
- HERWIG, by Marchesini and Webber, current version 5.0 [14].
- COJETS, by Odorico, current version 6.11 [15].
- DTUJET, by Ranft *et al.* [16].
- FIELDAJET, by Field *et al.* [17].
- The Fire-String program by Angelini *et al.* [18].
- FRITIOF, by Andersson *et al.*, current version 6.0 [19].

Without passing judgement on quality, the ordering above does reflect an element of quantity: ISAJET and PYTHIA clearly are more versatile than the others, while the latter four programs only cover QCD jets and minimum bias events.

The 'matrix elements' 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 same 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 is 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 therefore 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:

- PAPAGENO, by Hinchliffe [20].
- EUROJET, by van Eijk *et al.* [21].

A few others will be mentioned in connection with the processes they simulate.

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 included 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 fulfill the requirements, a procedure which can often be very inefficient.

2.1 Hard scattering subprocesses

Lists of subprocesses included in Monte Carlos are found in Tables 1 and 2. These tables should be read as follows. For ISAJET, PYTHIA and PAPAGENO, a '•' indicates that the process is included and a '-' that it is not. In the column 'other PS' (PS = parton shower programs) a '•' indicates this is something found in most or all programs in this category, while a 'H' appears if only HERWIG includes it and a blank if no program does. In the column 'other ME' (ME = matrix element programs), an 'E' indicates a process included in EUROJET, and other letters indicate processes found in other programs, as explained further in the process-specific descriptions below.

The tables should be taken as indicative only, since there is a continuous evolution of many programs. For instance, the current EUROJET only contains a few processes, but a much expanded version is nearing completion and may be available by the time this appears in print; also, HERWIG has been expanded significantly since the beginning of this workshop. Furthermore, one and the same process may be treated differently in different programs. Below we will give some comments on a few of the processes, to illustrate the degrees of freedom open to Monte Carlo authors.

Table 1: Standard model physics processes included in the event generators studied. See text for program notation. 'f' stands for fermion, 'V' for W or Z, and 'Q' for heavy quark.

Process	ISAJET	PYTHIA	other PS	PAPA-GENO	other ME
QCD					
QCD jets	•	•	•	•	E, NJ
$q\overline{q}, gg \rightarrow t\overline{t}$	•	•	•	•	E
$qb \rightarrow q't$	-	•	H	-	
minimum bias	•	•	•	-	E
diffractive	•	•		-	
elastic	-	•		-	
Prompt photons					
$qg \rightarrow q\gamma, q\overline{q} \rightarrow g\gamma$	•	•	H	•	
$q\overline{q} \rightarrow \gamma\gamma$	•	•		•	
$gg \rightarrow \gamma\gamma$	-	•		•	
W/Z production					
$q\overline{q} \rightarrow V$	•	•	•	•	LD
$qg, q\overline{q} \rightarrow V(q,g)$	•	•	H	•	LD
$q\overline{q} \rightarrow VV, V\gamma$	•	•		•	BZ, BH
$q\overline{q}, qg \rightarrow VV(q,g)$	-	-		-	VV, BH
$gg \rightarrow VV, V\gamma$	-	-		-	GG
$q\overline{q} \rightarrow V^*V^*$	-	•		-	
$gg \rightarrow ZQ\overline{Q}$	-	•		•	LD
Standard model H^0 ($m_H \leq 800$ GeV)					
$q\overline{q} \rightarrow H^0$	•	•		-	
$gg \rightarrow H^0$	•	•	H	•	GG
$VV \rightarrow H^0$	•	•	H	•	BG
$q\overline{q} \rightarrow VH^0$	-	•		-	
$gg, qg, q\overline{q} \rightarrow H^0(q,g)$	-	•		-	HV
$H^0 \rightarrow VV$	•	•	H	•	BG, HV
$H^0 \rightarrow V^*V^*$	•	•	H	-	
$H^0 \rightarrow f\overline{f}$	•	•	H	-	
$H^0 \rightarrow gg$	•	•		-	
$H^0 \rightarrow \gamma\gamma$	•	•	H	-	
$H^0 \rightarrow \gamma Z^0$	-	•		-	
Standard model H^0 ($m_H \geq 700$ GeV)					
$VV \rightarrow VV$	•	•	H	-	BG
$gg \rightarrow VV$	-	-		-	GG

Table 2: Non-standard model physics processes included in the event generators studied. See text for program notation. In addition to notation for Table 1, 'V'' stands for W' or Z', 'R' for a horizontal boson, and 'L' for heavy lepton.

Process	ISAJET	PYTHIA	other PS	PAPA-GENO	other ME
Non-standard Higgs particles					
$q\overline{q}' \rightarrow H^+$	-	•		-	
$gb \rightarrow H^-t$	-	•		-	
$\gamma^*/Z^* \rightarrow H^+H^-$	-	•		-	
$t \rightarrow H^+b$	-	•		-	
$H^+ \rightarrow f\overline{f}'$	-	•		-	
Supersymmetry					
$q\overline{q}, gg \rightarrow \tilde{q}\tilde{\overline{q}}$	•	-		•	UA, BT
$q\overline{q}, gg \rightarrow \tilde{g}\tilde{g}$	•	-		•	UA, BT
$qg \rightarrow \tilde{q}\tilde{g}$	•	-		•	UA, BT
$q\overline{q} \rightarrow \tilde{g}\tilde{V}$	•	-		-	UA
$qg \rightarrow \tilde{q}\tilde{V}$	•	-		-	UA
$\tilde{q}, \tilde{g}, \tilde{V}$ decays	-	-		•	UA, BT
New Gauge Groups					
$q\overline{q} \rightarrow V'$	-	•		-	
$VV \rightarrow V'$	-	-		-	
$V' \rightarrow f\overline{f}$	-	•		-	
$V' \rightarrow VV$	-	•		-	
$q\overline{q}' \rightarrow R \rightarrow q''\overline{q}'''$	-	•		-	
Fourth Generation					
$q\overline{q}, gg \rightarrow Q\overline{Q}$	•	•		•	
$V/V' \rightarrow Q\overline{Q}, L\overline{L}$	-	•		-	
$qq' \rightarrow q''Q$	-	•		-	
Other Topics					
contact interactions	-	-		•	
axigluons	-	-		•	
leptoquarks	-	-		-	E
strongly interacting V	-	•		-	

2.1.1 QCD

Exact Born term cross-sections, for up to five jets in the final state, are available in the NJETS program of Kuijf and Berends ('NJ' of Table 1), see [9], which is the most advanced in this category. This program also contains approximate expressions for up to eight jets.

Complete loop calculations have been performed up to $\mathcal{O}(\alpha_S^3)$. These are implemented in the numerical integration programs of two groups [22], but no event generators exist.

Most programs only contain the lowest order Born term cross-sections for heavy flavour production. For top this may be sufficient, i.e. higher order contributions effectively contribute an overall K factor, but do not significantly change the production characteristics of top. However, at LHC energies, it is not correct to use only the Born term to estimate b or c production, since these quarks receive major higher order contributions, both by flavour excitation and by parton shower evolutions, see [8].

Minimum bias physics is discussed in section 2.4.

Even when diffractive and elastic scattering is included in programs, the treatment is fairly primitive, and likely to be insufficient for LHC physics. Several major features are missing, like high-$p_\perp$ jet production in diffractive events.

2.1.2 Prompt photons

Complete next-to-leading order programs for prompt photon production are available from two groups [23], but both are intended for cross-section calculation rather than event generation. Leading order formulae are contained in many event generators. Some parton shower algorithms also include the emission of photons as part of the evolution.

The $gg \to \gamma\gamma$ graph contains a quark box. The cross-section is reasonably compact in the limit of vanishing quark mass, but very complex if the correct quark mass dependence is included. Therefore often the massless formulae are used, with the number of flavours suitably chosen. PYTHIA contains the full formulae as an option, but these then are numerically unstable in some regions of phase space, and therefore not easy to use.

2.1.3 *W*/*Z* production

The most complete W/Z ME program is the 'Leiden-Durham W'/VECBOS program ('LD' of Table 1), which contains the production of a V, i.e. a W or a Z, plus 0, 1, 2, 3 or 4 jets, see [11]. No loop corrections are available in this program, but analytical formulae exist up to complete second order in α_S [24]. Programs for the production of $V + V$ and $V + \gamma$ are also available, in [25] ('BZ' of Table 1) with special emphasis on the possibility of testing for anomalous couplings in triple gauge boson vertices. The production of a VV pair plus one additional jet is found in two programs: in VVJET [26] ('VV' of Table 1) and in [27] ('BH' of Table 1); the latter also contains matrix elements for a VV pair plus two jets. In all the programs above, subsequent V decays are included, with full angular correlations.

As in $\gamma\gamma$ pair production, VV pairs may also be produced from a gg initial state, via a quark box. The rates may be sizeable, thanks to the large value of the gluon structure functions at the small x values probed by LHC, and interference with the Higgs signal is of particular importance for Higgs searches. The program GGZZ simulates this process [28] ('GG' of Table 1).

The parton shower programs tend to give a fairly good description of V production at current energies. However, the rate of high-$p_\perp$ V production is not so well reproduced if the starting point is the $q\bar{q} \to V$ matrix element. One may instead use the $qg \to qV$ and $q\bar{q} \to Vg$ matrix elements, in which case at least one high-$p_\perp$ jet is assured from the start, and then include showering to generate additional jets. This gives a better description at high $p_{\perp V}$, but cannot be used to describe inclusive V production, since the $2 \to 2$ matrix elements are divergent for $p_\perp \to 0$. The choice between the two descriptions therefore has to depend on the application. In ISAJET a special option is available, in which the $2 \to 2$ matrix elements have been regularized (by hand) in the limit $p_\perp \to 0$, and so a good description is obtainable over the whole $p_\perp$ spectrum.

For intermediate mass Higgs background studies, the $Z + (Z^*/\gamma^*)$ (where * denotes that the interesting configurations are those with the particle far off mass-shell) and $Zb\bar{b}$ channels are of particular interest. The latter process is calculated in [10], and is now included in a few generators, although still with an inefficient selection of phase-space points.

2.1.4 Standard model H^0

A single unified description of Higgs production and decay characteristics, valid for all Higgs masses, would be very complex. In practice, two different descriptions are in use in programs. 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 Higgs is heavy, this is no longer possible but, in this region, mainly the $VV \to H \to VV$ graphs are of experimental interest, and so only full interference with the $VV \to VV$ background need be included.

A light or intermediate mass Higgs is predominantly produced by $gg \to H$. The process $VV \to H$, i.e. properly $qq' \to q''q'''H$, also contributes. This process is included with the full matrix elements in HERWIG and PAPAGENO, but in ISAJET and PYTHIA only in the effective W approximation, an approximation which is known to be good for $m_H \gg m_W$. For $m_H < 2m_W$ the channel is switched off in ISAJET, while it is still on in PYTHIA, and here gives about a factor two too high a rate compared to the correct treatment.

In the description of Higgs decays, two new aspects have played a particular rôle in the current workshop. One is the introduction of running quark masses for couplings $H \to q\bar{q}$; this typically leads to a reduction of the quark partial widths by a factor of around 2. At intermediate Higgs masses, where the $H \to b\bar{b}$ decays dominate, some other branching ratios are enhanced by the same factor 2, notably $H \to \gamma\gamma$. Running quark masses are included in PYTHIA and HERWIG, but not in ISAJET. The other new aspect is $H \to V^{(*)}V^*$ decays, i.e. where one or both final state gauge bosons are significantly off mass-shell. Particularly interesting is the $H \to ZZ^* \to 4\ell$ decay. These decays are now found in ISAJET, PYTHIA and HERWIG.

For the heavy Higgs scenario, both ISAJET and PYTHIA rely fully on the effective W approximation for $VV \to VV$ matrix elements. In both programs the incoming V bosons are assumed longitudinally polarized, as are the outgoing in PYTHIA, while ISAJET includes all polarization combinations in the final state.

A more detailed description, based on exact matrix elements with full interference between all graphs that can yield VV plus two jets in the final state, is found in [29] ('BG' of Table 1); full angular correlations in the V decays are also included.

Finally, just as for the description of high-$p_\perp$ V production, it may be convenient to have a description of a H recoiling against a jet; this is available in the program HVVJET [30] ('HV' of Table 1).

2.1.5 Non-standard Higgs particles

Very little effort has gone into scenarios with more Higgses than in the standard model — no event generators at all are available for an extended neutral Higgs sector. A charged Higgs, in the framework of the minimal supersymmetric extension to the standard model, is available in PYTHIA.

2.1.6 Supersymmetry

SUSY is an important area to be explored at LHC. Several different particles should be searched for, in particular squarks, gluinos and a host of gauginos. In the current workshop, the two main programs in this area are ISAJET and UA2SUSY. As the name indicates, the latter ('UA' of Table 2) is an upgrade of a dedicated program written inside the UA2 collaboration [31], which is described in more detail in [32]. A further program is found in [33] ('BT' of Table 2). In the current workshop, both for ISAJET and UA2SUSY, special emphasis has been put on a flexible and detailed modelling of all sequential decay chains predicted for different parameter sets of the Minimal Supersymmetric Standard Model.

Comparisons between ISAJET and UA2SUSY have been performed by the SUSY working group [32]. In general, good agreement is found; where disagreements exist, their origin is understood, and the effect on experimental signatures is kept under control.

2.1.7 New gauge groups

A number of different scenarios can give rise to new gauge particles, here denoted V' ($= Z'^0$ or $W'^\pm$). In PYTHIA, vector and axial couplings of fermions to the V' have been left as free parameters; it is therefore possible to simulate most of the alternatives on the market by judicious choices. Couplings of a V' to the standard model gauge bosons can show a richer structure, and only a few of the possibilities are available here.

A specific model for a horizontal boson R, i.e. a boson which couples to generation number, has been included as a separate alternative in PYTHIA.

2.1.8 Fourth generation

With the current LEP limits on the number of light neutrino species, the prospects are slim for a standard fourth generation of fermions. Should there still be some interest in heavy standard quarks or leptons, the event generators are available, since only trivial extensions of the standard description of top are involved.

2.1.9 Other topics

The list of possible extensions to, or deviations from, the standard model is long, and only a few are found in Table 2. Among the most interesting ones are the prospects of a strongly interacting V sector, as could arise if the standard model Higgs were absent or, at least, much heavier than the 1 TeV mass scale directly probed. Some of the scenarios proposed in the literature have been implemented in PYTHIA.

2.2 Structure Functions

Knowledge of the proton structure functions is necessary for the calculation of any hard scattering cross-section. A community of people are involved in the analysis of data from current experiments, within the framework of perturbative QCD. The end result of these efforts is new structure function sets, with some region of validity in the (x, Q^2) plane. In the past, the number of sets available was fairly limited; for applications at the large Q^2 scales of LHC/SSC, only the EHLQ parametrizations [34] could be used, which is why these are still found as defaults in many programs.

More recently, the pace has picked up, and now new sets appear almost monthly. A review of, and comparison between, most of these is found in [6]. One conclusion is that many of the older sets do not do well when compared with current data, and therefore should no longer be used. Also some of the newer sets perform less well. In part, this is deliberate: given the large uncertainties involved, most authors do not provide one single 'best' set, but rather prefer to produce many different sets, which together are supposed to bracket the 'right' answer. The differences between these sets come from the correlation between the choice of Λ value (in α_S) and the choice of gluon structure function, from different assumptions about the behaviour of structure functions at low x, from different choices of s quark distributions at low Q^2, etc.

Since all sets of structure functions are limited in validity to given x and Q^2 ranges (in particular, $x > 10^{-5}$ to 10^{-4}, depending on the set), their use for applications at LHC/SSC energies should be taken with some caution. Total cross-section calculations or integrated differential distributions (e.g. for top, b or c quark production) would be affected. To overcome the problem Monte Carlo authors have to introduce further assumptions themselves.

An additional element of disparity comes from the choice of order and renormalization scheme. The three main alternatives are leading order, next-to-leading order in the $\overline{\mathrm{MS}}$ scheme, and next-to-leading order in the DIS scheme. For high precision measurements, it is essential to use the same conventions for matrix elements and structure functions, and here probably little confusion exists. The status may be less clear about the appropriate choice to use for parton shower based programs — while basically leading log, these programs do include some next-to-leading log contributions.

The main programming issue for structure functions is whether to use grids or parametrizations. In the former approach, the output of the evolution programs is stored directly as grids in the (x, Q^2) plane, and desired values can be obtained by interpolation in these grids. The drawback is that thousands of real numbers have to be transferred to each new computer as external files, which makes programs a little less easily transportable. The advantage is that interpolation usually is fast. In the parametrization approach, smooth functions are fitted to the grid values, and subsequent use is based on these fits. This way the number of real values that characterize a structure function is significantly reduced — the most spectacular example is the very compact parametrizations by Morfín and Tung [35]. Such parametrizations can easily be included in the code of an event generator, and thus there are no transport problems. Since the evaluation typically involves logarithms and exponents, it may be significantly slower than in the grid interpolation approach, however.

2.3 Initial and Final State Showers

In the parton shower approach, a hard 2 → 2 scattering is convoluted with initial and final state radiation to build up multiparton final states. Of the two showering types, final state radiation is theoretically and experimentally well under control, while initial state radiation remains less well understood.

Final state showers are timelike: the two outgoing partons of a 2 → 2 scattering each has $m^2 = E^2 - \overline{p}^2 \geq 0$. An off-mass-shell parton may successively branch into partons of lower virtuality, until the mass-shell is reached. In leading log, the structure of allowed branchings $q \to qg$, $g \to gg$, and $g \to q\overline{q}$ is described by the standard Altarelli-Parisi evolution equations. The naive leading log parton shower picture is modified by coherence effects, which can be taken into account by the inclusion of angular ordering [36], i.e. not only are virtualities successively degraded, but so are the opening angles of branchings. Further details on the theory of timelike showers may be found in several reviews, e.g. [37,38].

On the experimental front, final state showers have been much studied in e^+e^- annihilation; since no initial state QCD showers appear in e^+e^-, and since the production graph is s-channel only, the analysis is simpler than in hadron collisions. The recent LEP results underline how well existing showering programs do, see e.g. [39,40]. It is seldom that disagreements between data and programs like JETSET (which is the program used for showering in PYTHIA) or HERWIG reach the 10% level. Even more importantly, with parameters tuned at LEP, programs also do a good job of describing data at lower energies, at PEP, PETRA and TRISTAN. Confidence in extrapolations to higher energies is therefore high.

Anytime one has to consider the hadronic decay of a colour singlet particle in hadron colliders, such as W, Z, H, etc., the e^+e^- experience is directly applicable, and predictive power high. In principle, questions could be raised whether colour exchange might take place between the partons of the decaying singlet particle and the partons of the underlying event; such effects could modify event topologies, but probably not drastically. When the hard process does not go through a colour singlet intermediate state, on the other hand, there are significant ambiguities in how to begin the shower evolution at high virtualities, such that the proper amount of multijet activity is obtained. Once a choice is made here, the subsequent evolution is again well under control.

Initial state radiation is considerably more difficult to model. The shower is initiated by a parton selected from structure functions at small Q^2. This parton may now branch, but in the branching only one daughter is timelike, whereas the other is spacelike, i.e. $m^2 < 0$. The timelike parton may develop a shower, very much like the final state radiation case, although typically with less allowed phase space and therefore less extensive. The spacelike parton may branch once again, to a new pair of one timelike and one spacelike daughter, etc. The sequence of spacelike daughters is terminated at the hard interaction: a $2 \to 2$ (QCD) process consists of two incoming spacelike partons and two outgoing timelike ones. In leading log language, the virtuality $Q^2 = -m^2$ of the sequence of spacelike partons is required to increase monotonically, and is constrained from above by the Q^2 scale of the hard interaction. In recent years, theoretical progress has been made in including coherence corrections to this picture [41]. The complexity of these corrections is such that no program includes all effects in full, however. HERWIG is the program that contains the most advanced machinery. It has still not been clarified exactly how big the differences are compared to the more simpleminded approaches in other programs.

2.4 Beam Jets

The description of beam jets, i.e. the physics of underlying events and minimum bias events, remains the least well understood aspect of Monte Carlo modelling of hadronic events. It is therefore possible to choose many possible approaches. One is simply to use a longitudinal phase space parametrization, as in COJETS and HERWIG, with parameters fitted to describe data. Another is to allow a variable number of parton-parton interactions to take place within one and the same hadron-hadron collision. This is done in ISAJET, PYTHIA and DTUJET, but along quite different lines in each. If, in the end, programs agree reasonably well, it is mainly because they have been tuned to the same data. For further discussions see [7].

Theoretical work on the structure of minimum bias events has been carried out in particular by Levin and Ryskin [42]. Their approach is also based on a multiple parton-parton interaction scenario. Compared to the models above, particular emphasis is put on saturation effects at small x. Saturation can arise when the local density of partons becomes so large that not only parton branchings but also parton recombinations have to be taken into account. This saturation is predicted to set in sooner than given by naive estimates, since a large fraction of the partons inside a proton are assumed to be concentrated in a few 'hot spots'. If correct, naive extrapolations to LHC energies, as embodied in current event generators, may fail. Some first hints on the validity of the Levin-Ryskin model may come already with HERA. A more detailed description of the issues involved may be found in the report of the *ep* physics study group of this workshop [43].

2.5 Fragmentation and Decays

Fragmentation is a nonperturbative phenomenon, and as such is not yet understood from first principles. As with timelike parton showers, experience from e^+e^- annihilation helps constrain models significantly [39,40]. Three different main fragmentation schools exist: string (found in PYTHIA and FRITIOF), cluster (HERWIG) and independent (e.g. ISAJET, COJETS and EUROJET) fragmentation.

The former two are known to give good agreement with e^+e^- data over a wide range of energies, and are expected to work well also at higher energies, while the latter currently is not much used in e^+e^- (for a recent assessment of it see [44]). Differences between models are difficult to find in hadron collisions.

A majority of the particles produced in the fragmentation step are unstable and decay further. Almost all programs therefore include decay routines, more or less similar to each other. Decay data are taken from [45], where available, and according to the best understanding of the program author, where not. There are some differences in level of sophistication, with respect to inclusion of decay matrix elements and polarization information, but seldom does this give readily visible experimental consequences.

3 Concluding Remarks

3.1 Program Limitations

Already in the previous section, we have considered some of the uncertainties in our current understanding of physics at the LHC. Many more examples could certainly have been found.

Another class of uncertainties comes from the presence of bugs, i.e. programming errors, in event generators. Given the complexity of LHC simulation, almost all programs have bugs. Some of these simply are typographical errors, others are correct transcriptions of incorrect formulae in the literature (e.g., the $WZ \to WZ$ matrix elements in PYTHIA were incorrect for several years because the published formulae were not correct), others are programs that work at current energies but break down when run in single precision at LHC energies, and yet others are real mistakes by the programmer. Given the size of these generators, an error can lie dormant for a long time before being discovered. Even when discovered, errors need not be correctly corrected by the authors. Indeed, we saw three such examples during the workshop: the $gg \to \gamma\gamma$ matrix elements in PYTHIA, the $H \to \gamma\gamma$ partial width in ISAJET, and the $q\bar{q}, gg \to b\bar{b}$ matrix elements in HERWIG. In each of these cases, the first 'corrections' proposed by the authors did not solve the problem found by users, and repeated complaints were necessary to see some improvements in the situation. Errors that were more rapidly corrected are too numerous to be mentioned.

These examples do not imply a quality judgement on particular programs. Considering the size and complexity, there is no reason to say that event generators are any more error-prone than other comparable software. The message is rather that all critical studies should always be based on more than one event generator, and/or on analytical cross-checks of the generator results.

With the changing computer market, e.g. the emergence of RISC chips, one must also keep in mind that programs may need to be modified for maximum efficiency [9].

3.2 Summary

In this paper we have given an introduction to and overview of the LHC event generators currently available. As behooves a report of this kind, a heavy emphasis has been put on the unknown aspects. In particular, we have stressed the need for several independent cross-checks of crucial results.

However, one can also take another point of view: considering the number of years left before actual turn-on, the quantity and quality of LHC/SSC event generators are probably far superior to those available for any other major new accelerator at a corresponding stage of planning. We today have standard methods for turning the crank on any basic process (also including new hypothetical particles), to include initial and final state radiation, beam jets, fragmentation, etc., and to arrive at fairly realistic representations of what LHC events might look like. If the details may be a bit uncertain, the general picture of events at the LHC is still fairly clear. As experience from the Tevatron, LEP and HERA finds its way into programs, the quality should improve further. Needless to say, much continued work by event generator authors is necessary, not just to improve on the expected, but also to prepare for the unexpected.

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