SLAC-PUB-8289
October 1999

Event Generators for Linear Collider Physics

Michael E. Peskin[a]
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309 USA

ABSTRACT

I review the array of event generators which have been written to provide simulations of high-energy e^+e^- reactions.

presented at the International Workshop on Linear Colliders
Sitges, Barcelona, Spain, 28 April – 5 May 1999

[a] Work supported by the Department of Energy, contract DE–AC03–76SF00515.

EVENT GENERATORS FOR LINEAR COLLIDER PHYSICS

MICHAEL E. PESKIN
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309 USA

I review the array of event generators which have been written to provide simulations of high-energy e^+e^- reactions.

1 Introduction

In any simulation of an experimental analysis at an e^+e^- collider, we must begin with a sample of physics events to be analyzed. To produce these, we need an event generator. This program encodes our knowledge of Standard Model background processes and our expectations for signal processes. In this article, I will review the current variety of event generators available for simulations studies at future linear colliders.

There are a number of goals that an event generator might be expected to fulfill. It should realistically represent possible signal processes and Standard Model backgrounds. It should take care of the superposition of QCD and fragmentation effects onto electroweak cross sections. It should give high accuracy, for precision studies. And, it should have the flexibility to include new reactions of arbitrary and exotic form. These goals generally conflict with one another, or else are achieved only at the expense of a high level of complexity. So we needed different tools optimized for these various tasks.

In this report, I review the event generators which address these issues that were presented at Sitges. The major simulation programs described in this article are listed in Table 1. This table includes, for each program, a Web address where download information and documentation can be found.

2 Workhorses

Among event generators, first place must be given to the general purpose programs PYTHIA [1] and HERWIG.[2,3] Both programs were originally written to test ideas about QCD jet phenomena and hadronization. But both have now evolved into general-purpose codes incorporating all of the basic Standard Model processes in e^+e^- annihilation and a variety of nonstandard reactions.

The most important aspect of PYTHIA and HERWIG is that they fully simulate QCD final state state effects. Given a system of two or more partons with large invariant mass, these programs generate a QCD parton shower

Table 1: Event generators for e^+e^- linear collider physics

PYTHIA	`www.thep.lu.se/~torbjorn/Pythia.html`
HERWIG	`hepwww.rl.ac.uk/theory/seymour/herwig/`
CIRCE	`heplix.ikp.physik.tu-darmstadt.de/nlc/beam.html`
PHYSSIM	`www-jlc.kek.jp/subg/offl/physsim/`
PANDORA	`www.slac.stanford.edu/~mpeskin/LC/pandora.html`
ISAJET	`quark.phy.bnl.gov/~paige/`
SUSYGEN	`lyoinfo.in2p3.fr/susygen/susygen3.html`
EXCALIBUR	`home.cern.ch/charlton/excalibur/excalibur.html`
KORALW	`hpjmiady.ifj.edu.pl/programs/node9.html`
WPHACT	`www.to.infn.it/~ballestr`
KK	`home.cern.ch/~jadach/`
GRACE	`www-sc.kek.jp/minami/`
COMPHEP	`theory.npi.msu.su/~comphep/`

and then simulate the hadronization of the final array of partons. The shower algorithm is not exact at higher orders in α_s but does generate an approximately correct set of hard jets radiated from the original parton system. The hadronization step is carried out by different algorithms in the the two programs, but, in both cases, the description of hadronization has been tuned to fit the e^+e^- annihilation data. These features imply that QCD final-state interactions have been included in a way that extrapolates correctly to high energy.

PYTHIA allows any parton-level generator to be included as a hard subprocess. The generator must specific the color routing in the final state and the order in which parton showers are to be generated. One caution with this approach is that order α_s corrections can raise or lower the overall normalization of the cross section. This effect cannot be included in the hadronization but must be accounted for externally.

PYTHIA can run with a given initialization at a variety of e^+e^- center of mass energies. This allows the program to be linked to a generator of initial-state e^- and e^+ energy distributions, such as CIRCE [4] or PYBMS,[5] to simulation the effect of beamstrahlung. Initial state polarization is not included in the current version. Final state spin correlations are included for some but not all processes; notably, spin correlations are included for the very important process $e^+e^- \to W^+W^-$.

PYTHIA and HERWIG both include generators for the process $\gamma\gamma \to$ hadrons, including hard, soft, and 'resolved' components. The third of these

refers to processes in which partons in the photon undergo a hard scattering. The relative magnitudes of these three components are not understood from theory, but it is important to understand this problem to compute the high-rate 'minijet' background in which a $\gamma\gamma$ collision produces a low-mass hadronic system.[6,7] New data on high energy $\gamma\gamma$ processes from LEP 2 and on γp processes from HERA—which contain much of the same physics–should allow systematic tuning of these generators.

3 Polarization

To introduce the next sections of this report, I must digress on the subject of polarization. Polarization has a central role in the LC physics. On one hand, because the LC will operate in the energy region well above the Z^0 where it becomes manifest that left- and right-handed have completely different quantum numbers, all standard and non-standard cross sections will depend strongly on polarization. On the other hand, since it is difficult to measure polarization effects in the hadronic environment, polarization provides many new observables that cannot be studied at the LHC. Thus it is important that both initial- and final-state polarization be included properly in LC event generators.

How can polarization be included in physics simulations? The traditional approach is to generalize cross section formulae to include polarization asymmetries. However, this rapidly becomes cumbersome. Generators that take polarization seriously typically work at the amplitude level. Even if one does not include polarization, it is useful to work with amplitudes in any complex Feynman diagram computation, since if there are N terms in the expression for the amplitude, there are N^2 in the expression for the cross section. Any method that makes use of amplitudes to compute the cross section can be structured so that the polarization-dependence is available for free.

There are two common approaches for including polarization in the cross-section formulae used in event generators. The first approach is the *helicity-amplitude paradigm*. In this approach, one computes amplitudes for transitions between states of definite helicity.[8] These amplitudes are then linked together to provide the complete amplitude for a process that turns the initial e^+e^- state into the final decay products. Finally, the complete amplitude is squared to provide the event weight.

The second approach is the *CALKUL paradigm*. In this approach, one concentrates on amplitudes with massless particles in the inital and final states, the typical situation for e^+e^- annihilation when top quarks, W bosons, and other heavy particles have decayed to their final products. Then it is possible

to compactly represent the amplitude for the whole process of production and decay in terms of *spinor products*,[9,10]

$$\langle 12\rangle = \overline{u}_L(p_1)v_R(p_2)\ , \qquad [12] = \overline{u}_R(p_1)v_L(p_2)\ . \tag{1}$$

The spinor products can in turn be computed directly for the set of initial and final massless four-vectors in a given event.

It is important to note that there are no important polarization effects associated with hadronization, except that the τ decay depends strongly on τ polarization. This effect should be accounted explicitly by decaying τ's through the simulation program TAUOLA.[11]

The use of helicity amplitudes to systematically describe LC physics was pioneered by the JLC group, using the programs HELAS,[12] for automatic Feynman diagram computation, and BASES/SPRING,[13] to provide weight-1 events. The current version of their package is PHYSSIM in Table 1.

The need to build up systematically the full complexity of LC reactions—including beamstrahlung, initial-state radiation, initial- and final-state polarization effects, and hadronization—has led the authors of almost all the simulation programs to embrace object-oriented programming for their future versions. One relatively simple generator, pandora, already segregates the beam and e^+e^- reaction information into separate C++ classes which interact through a simple interface. Further details can be found in ref. [14].

4 Supersymmetry

The next few sections of this report will discuss generators devoted to specific problems of LC physics. The first of these is the coherent representation of supersymmetry processes.

The full set of processes in e^+e^- annnihilation to two supersymmetric particles is now available in three different programs, the supersymmetric extension of PYTHIA,[15] the latest release of ISAJET,[16] and the SUSYGEN program written for LEP 2 studies.[17] ISAJET was the first to include polarization-dependent cross sections. The new version also correctly includes the matrix elements for 3-body decays. SUSYGEN gives a complete treatment of initial and final polarization effects using the helicity-amplitude paradigm and even allows for nonzero phases in the A and gaugino mass parameters. ISAJET and SUSYGEN explicitly include parametrizations of beamstrahlung. All three programs allow input of a general set of supersymmetry parameters. Given the model-independent character of LC measurements, this is an important feature. PYTHIA and ISAJET also include facilities that compute the super-

symmetry spectrum from an underlying model; SUSYGEN includes an interface to spectrum calculations with SUSPECT.[18]

5 Precision Standard Model

For calculation of Standard Model background processes at a LC, it is not sufficient to consider e^+e^- annihilation to on-shell 2-body final states. Backgrounds to new physics typically come from higher-order corrections in which additional fermions are produced or from $e^+e^- \to W^+W^-$ processes in which one W boson fluctuations far off the mass shell. In fact, these reactions are not distinct and one must include all $e^+e^- \to 4$ fermion Feynman diagrams in order to obtain a gauge-invariant result.

This is already an issue at LEP 2 and a very serious effort has been made to provide 4-fermion event generators for the LEP 2 experiments. The status of generators for 4-fermion and W pair physics has recently been described by Bardin, *et al.*[19] These programs typically use the CALKUL paradigm. Though their implemetations are slightly different, they agree excellently among themselves and with the LEP 2 for configurations of four fermions all at large relative momenta. For brevity, I have included only three of these programs, EXCALIBUR,[20] KORALW,[21], and WPHACT,[22] in Table 1.

Two unresolved conceptual problems in the simulation of 4-fermion processes are the treatment of the W width for an off-shell W and the correct inclusion of transverse momentum for almost-collinear initial state radiation. In both cases, there is no simple prescription which is gauge-invariant. This leads to discrepancies among the various programs in certain specific kinematic regions. For example, for the process $e^+e^- \to e^+\nu d\overline{u}$ (very low mass single W^* production), the various generators give 10% differences in the predicted cross section when $m(d\overline{u})$ is as small as a few GeV.

Additional challenges can be found in higher-order processes. For the study of the standard process $e^+e^- \to t\bar{t}$ and also for many searches, one needs an event generator for $e^+e^- \to 6$ fermions. Accomando, Ballestrero, and Pizzio[23] have computed the relevant cross sections in a suitable form and are preparing a new generator, SIXPHACT. Alternatively, methods are now available to allow one to perform the computation automatically; I will describe these in the next section.

At the same time, it is necessary to reach for higher accuracy in the simulation of 2-fermion final states. KORALZ, by Jadach, Ward, and Was,[24] achieved an accuracy of 0.1% in the calculation of the small-angle Bhabha scattering cross section, and this was essential for the precision cross section normalization at LEP 1. At higher energies, it is necessary to treat multiple

photon emissions coherently, and the precision calculations must be extended to larger forward angles. Jadach and collaborators have just released a new program KK which addresses these issues.

6 Do it yourself

Eventually, workers in LC physics will have a need for event generators for processes that have not been included in the standard programs. The traditional recourse in this case has been to find a friendly theorist with time on his hands. Today, however, amother course is made available by the GRACE[25] and COMPHEP [26] programs. These encode the Feynman rules of the standard model and certain extensions, and allow encoding of arbitrary additional Lagrangian couplings, and then automatically generate the numerical sum of Feynman diagrams. The authors of GRACE have made available a supersymmetric extension which already includes all 239 $e^+e^- \to$ 3-body supersymmetry processes, and all 1424 $e^+e^- \to$ 3-body processes. A typical process might involve the summation of 100 tree diagrams. The calculations are done at the amplitude level, allowing the event generation to include full spin correlations using the helicity-amplitude paradigm. These programs can also compute one-loop corrections by evaluating diagrams in terms of the standard set of one-loop integrals defined by Passarino and Veltman.[27] A more complete discussion of these systems can be found in Perret-Gallix's contribution to this conference.[28]

7 Conclusions

In this report, I have tried to summarize the array of programs that are now available to perform event generation for LC physics. These range from the general-purpose generators PYTHIA and HERWIG, to specific tools for supersymmetry and multi-fermion simulations, to tools for automatic generation of events for arbitrary physics processes. For the future, we expect to see trends toward object-oriented and modular programs, toward detailed high-accuracy computation of standard background processes, and toward further automation of complex calculations. We are well on the way to the level of accuracy and generality that will be needed for the LC physics program.

Acknowledgments

I am grateful to the authors of the programs described above for their help in organizing this review. This work was supported by the US Department of Energy under contract DE–AC03–76SF00515.

References

1. T. Sjostrand, Comp. Phys. Comm. **82**, 74 (1994), hep-ph/9508391.
2. G. Marchesini, *et al.*, Comp. Phys. Comm. **67**, 465 (1992).
3. T. Sjostrand and M. H. Seymour, these proceedings, hep-ph/9909346.
4. T. Ohl, Comp. Phys. Comm. **101**, 269 (1997), hep-ph/9607454.
5. T. Barklow, program available at `www.slac.stanford.edu/~masako/LC/generators.html`.
6. M. Drees and R.M. Godbole, Phys. Rev. Lett. **67**, 1189 (1991).
7. P. Chen, *et al.*, Phys. Rev. **D49**, 3209 (1994), hep-ph/9305247.
8. M. Jacob and G. C. Wick, Ann. Phys. **7**, 404 (1959).
9. R. Kleiss and W. J. Stirling, Nucl. Phys. **B262**, 235 (1985).
10. M.L. Mangano and S.J. Parke, Phys. Rept. **200**, 301 (1991).
11. S. Jadach, Z. Was, R. Decker and J. H. Kuhn, Comp. Phys. Comm. **76**, 361 (1993).
12. H. Murayama, I. Watanabe and K. Hagiwara, KEK report KEK-91-11.
13. S. Kawabata, Comp. Phys. Comm. **41**, 127 (1986), Comp. Phys. Comm. **88**, 309 (1995).
14. M. E. Peskin, these proceedings, hep-ph/9910519.
15. S. Mrenna, Comp. Phys. Comm. **101**, 232 (1997), hep-ph/9609360.
16. F. Paige, these proceedings, hep-ph/9909216.
17. N. Ghodbane, these proceedings, hep-ph/9909499.
18. A. Djouadi, J.-L. Kneur, and G. Moultaka, program available at `www.lpm.univ-montp2.fr:7082/~djouadi/GDR/mssm4.html`.
19. D. Bardin *et al.*, CERN–9601–A, hep-ph/9709270.
20. F. A. Berends, R. Pittau and R. Kleiss, Comp. Phys. Comm. **85**, 437 (1995), hep-ph/9409326.
21. S. Jadach, W. Placzek, M. Skrzypek, B.F. Ward and Z. Was, Comp. Phys. Comm. **119**, 272 (1999), hep-ph/9906277.
22. E. Accomando and A. Ballestrero, Comp. Phys. Comm. **99**, 270 (1997), hep-ph/9607317.
23. E. Accomando, these proceedings; E. Accomando, A. Ballestrero and M. Pizzio, Nucl. Phys. **B512**, 19 (1998), hep-ph/9706201.
24. S. Jadach, B.F. Ward and Z. Was, Comp. Phys. Comm. **79**, 503 (1994), hep-ph/9905205.
25. T. Ishikawa, *et al.*, KEK-92-19; H. Tanaka, *et al.*, NIM **A389** (1997) 295.
26. A. Pukhov, *et al.*, hep-ph/9908288.
27. G. Passarino and M. Veltman, Nucl. Phys. **B160**, 151 (1979).
28. D. Perret-Gallix, these proceedings.