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1 Monte Carlo Event Generators and Beam Polarization

The use of numerical programs based on Monte Carlo (MC) techniques has become essential in performing any detailed experimental analysis in collider physics. In this section we will briefly recall the key features of these programs and discuss the inclusion of beam polarization effects. We will limit ourselves to the so-called event generators. These programs must be interfaced to both detector simulations and beam energy spectra to give a complete picture of the actual physics process.

In general the MC event generation process can be split into a number of phases.

- The hard process where the particles in the hard collision and their momenta are generated, usually according to the leading-order scattering matrix element (ME).
- The parton-shower (PS) phase where the coloured particles in the event are perturbatively evolved from the hard scale of the collision to the infrared cut-off. The emission of electromagnetic radiation from charged particles can be handled in a similar way.
- Those particles which decay before hadronization, *e.g.* the top quark, are decayed usually according to a calculated branching ratio with a ME to give the momenta of the decay products. Any coloured particles produced in these decays are then evolved by the PS algorithm.
- A hadronization phase in which the partons left after the perturbative evolution are formed into the observed hadrons.

Most MC event generators fall into one of two classes: *general-purpose (or multi-purpose) event generators* which aim to perform the full simulation of the event starting with the initial-state collider beams, proceeding through the hard scattering process and finishing with the final-state hadrons; the second class of programs (hereafter, *parton-level event generators*) typically performs the hard scattering part of the simulation only, perhaps including decays, and relies on one of the general-purpose generators for the rest of the simulation.

During the LEP-era the experiments relied on the general-purpose event generators for the description of hadronic final states together with more accurate parton-level programs interfaced to the former ones for specific processes, *e.g.* two- and four-fermion production. At a future linear collider (LC), as one wishes to study final states with higher multiplicities, for example six or even eight particles, this mixed approach will become more important as these final states cannot be described by the general-purpose event generators.

1.1 General-purpose Event Generators

Historically the main general-purpose event generators have been HERWIG [1], ISAJET [2] and PYTHIA [3]. While the general philosophy of these programs is similar, they use different phenomenological models and approximations. In general, at least for e^+e^- collisions, the range of hard scattering processes implemented is very similar. All these generators have a wide range of Standard Model (SM) processes available, reactions predicted by the Minimal Supersymmetric Standard Model (MSSM) as well as various selections of channels from other models too (*e.g.* extra gauge-bosons).

The major differences between the programs are in the approximations used in the PS evolution and the hadronization stage. While ISAJET still adopts the original PS algorithm which only re-sums collinear logarithms, both HERWIG and PYTHIA include the effects of soft logarithms via either an angular-ordered PS in the case of HERWIG, or an angular veto in the case of PYTHIA. For the hadronization process HERWIG uses the cluster model, ISAJET the independent fragmentation model and PYTHIA the Lund string model.

There are also major differences between the generators in the treatment of spin correlation and polarization effects. Both ISAJET and HERWIG include longitudinal polarization effects in both SM and Supersymmetric (SUSY) production processes, while PYTHIA includes both longitudinal and transverse polarizations in many processes. Another important difference is in the treatment of the subsequent decay of any heavy particle produced in the hard process. While HERWIG includes the full correlations in any subsequent decays using the method described in [4] both ISAJET and PYTHIA only include these effects in some processes, *e.g.* W pair production. To extend the method used in [4] to include transverse polarization also in the HERWIG production stage is certainly possible.

While these codes will continue to be used in the near future a major programme is underway to produce a new generation of general-purpose event generators in C++. The main aim of it is to provide the tools needed for the Large Hadron Collider (LHC). However, these tools will be used also for the next generation of LCs. The only program currently available in C++ which is capable of generating physics results is SHERPA (based on the APACIC++ [5] PS). Work is however underway to rewrite both PYTHIA [6] and HERWIG [7] in C++. These programs should be available in the next few years and we expect them to be the major tools for event generator at a future LC. Given the new design and structure of these programs the treatment of both spin correlation and polarization effects should be much better than in the current FORTRAN programs. For example HERWIG++, should include full polarization and correlation effects in the perturbative phase of the event using the method of [4].

1.2 Parton-Level Event Generators

There are a large number of programs available which calculate an individual hard process, or some set of hard processes, and are interfaced to one of the general-purpose generators, most often PYTHIA, to perform the PS and hadronization. It is impossible to review all such programs here. As many of the two- [8] and four-fermion [9] generators were used by the LEP collaborations, we refer to the report of the LEP-II MC workshop for their detailed discussion. Some programs, *e.g.*, LUSIFER [10], SIXFAP [11], EETT6F [12] and SIXPHACT [13], have been written specifically for six fermion processes. Many of these codes use helicity amplitude techniques to calculate the MEs and therefore either already include polarization effects or could easily be modified to do so.

Given the vast physics programme of future LCs, it is likely that one will also regularly resort to programs which are capable of calculating and integrating the MEs for large numbers of final-state particles automatically. There are a number of such codes available.

– `AMEGIC++` [14] makes use of helicity amplitude techniques to evaluate the ME together with efficient multi-channel phase space integration to calculate the cross section. This package is part of SHERPA.

– `COMPHEP` [15] is an automatic program for calculation of cross sections for processes with up to eight external particles[1]. It uses the traditional trace techniques to evaluate the ME together with a modified adaptive integrator to compute the cross section, so it is at present not suitable for studies intended to investigate polarization/spin effects. However, the conversion to the use of helicity amplitudes techniques is currently planned.

– `GRACE` [16] (with the accompanying packages `BASES` and `SPRING`) combines the calculation of MEs via helicity amplitude techniques with adaptive integration.

– `HELAC/PHEGAS` uses the approach of [17] which is based on the Dyson-Schwinger equation together with multi-channel integration [18] to calculate the cross section.

– `MADGRAPH/MADEVENT` [19] uses helicity amplitude techniques for the ME together with an efficient multi-channel phase space integrator to compute the cross section. These packages are based on the `HELAS` [20] subroutines.

– `WHIZARD` [21] is a multi-channel integration package which can use either `COMPHEP, MADGRAPH` or `O'MEGA`[2] [23] to calculate the MEs.

All of these codes apart from `HELAC/PHEGAS`[3] are publicly available. In order to simulate events these programs need to be interfaced to the general-purpose event generators. Most use *ad hoc* interfaces to one of the major general-purpose event generators with the details varying from one package to another. Recently, generic (*i.e.*, program-independent) FORTRAN common blocks have been proposed for the transfer of event configurations from parton level programs to showering and hadronization event generators [24].

The implementation of polarization and correlation effects differs between these programs. In general, apart from `COMPHEP` (as noted), these programs are all based on helicity amplitude techniques at some point in the calculation and therefore the inclusion of both transverse and longitudinal beam polarization is possible even where it is not currently implemented.

1.3 SUSY

Polarization and spin correlation effects are particularly important in studying SUSY scenarios, in order to measure the fundamental parameters of the underlying model. Thus,

[1] `COMPHEP` can have up to six final-state particles for scattering processes and seven for decays.

[2] `O'MEGA` uses the approach of [22] to evaluate the ME but does not include yet any QCD processes.

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it is worth commenting in more detail on the inclusion of these effects in SUSY processes (hereafter, we assume the particle content of the MSSM).

HERWIG, PYTHIA and ISAJET all include longitudinal polarization effects in SUSY production processes. There is also a parton-level program SUSYGEN [25], interfaced to PYTHIA, which includes these effects.

All these programs also differ in the inclusion of the correlations in the subsequent decays of the particles. While SUSYGEN includes these correlations using helicity amplitude techniques and HERWIG uses the method of [4], these effects are generally not included in either PYTHIA or ISAJET.

Among the parton-level programs, at present only `COMPHEP` and `GRACE` include SUSY processes, although both `MADGRAPH` and `AMEGIC++` can be extended to add the additional interactions which are needed.

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References

[1] G. Corcella *et al.*, JHEP **0101** (2001) 010 [hep-ph/0011363]; G. Corcella *et al.*, hep-ph/0210213.

[2] H. Baer, F. E. Paige, S. D. Protopopescu and X. Tata, hep-ph/0001086.

[3] T. Sjöstrand, P. Edén, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, Comput. Phys. Commun. **135** (2001) 238 [hep-ph/0010017]; T. Sjöstrand, L. Lönnblad and S. Mrenna, hep-ph/0108264.

[4] P. Richardson, JHEP **0111**, 029 (2001) [hep-ph/0110108].

[5] R. Kuhn, F. Krauss, B. Ivanyi and G. Soff, Comput. Phys. Commun. **134**, 223 (2001) [hep-ph/0004270]. `SHERPA` is available from: `http://www.physik.tu-dresden.de/~krauss/hep/`.

[6] M. Bertini, L. Lönnblad and T. Sjöstrand, Comput. Phys. Commun. **134**, 365 (2001) [hep-ph/0006152].

[7] S. Gieseke, hep-ph/0210294.

[8] M. Kobel *et al.*, hep-ph/0007180.

[9] M. W. Grunewald *et al.*, hep-ph/0005309.

[10] S. Dittmaier and M. Roth, Nucl. Phys. B **642**, 307 (2002) [hep-ph/0206070].

[11] G. Montagna, M. Moretti, O. Nicrosini and F. Piccinini, Eur. Phys. J. C **2**, 483 (1998) [hep-ph/9705333];
F. Gangemi *et al.*, Eur. Phys. J. C **9**, 31 (1999) [hep-ph/9811437] and Nucl. Phys. B **559**,

3 (1999) [hep-ph/9905271];
F. Gangemi, hep-ph/0002142.

[12] K. Kołodziej, Eur. Phys. J. C **23**, 471 (2002) [hep-ph/0110063] and Comput. Phys. Commun. **151**, 339 (2003) [hep-ph/0210199];
A. Biernacik and K. Kołodziej, Nucl. Phys. Proc. Suppl. **116** (2003) 33 [hep-ph/0210405].

[13] E. Accomando, A. Ballestrero and M. Pizzio, Nucl. Phys. B **547** (1999) 81 [hep-ph/9807515];
E. Accomando, A. Ballestrero and M. Pizzio, hep-ph/9709277.

[14] F. Krauss, R. Kuhn, and G. Soff, JHEP **02**, 044 (2002) [hep-ph/0109036].

[15] A. Pukhov *et al.*, hep-ph/9908288. `COMPHEP` is available from:
`http://theory.sinp.msu.ru/comphep/`.

[16] MINAMI-TATEYA group, T. Ishikawa *et al.*, KEK-92-19. `GRACE` is available from:
`http://minami-home.kek.jp/`.

[17] A. Kanaki and C. G. Papadopoulos, Comput. Phys. Commun. **132**, 306 (2000) [hep-ph/0002082].

[18] C. G. Papadopoulos, Comput. Phys. Commun. **137**, 247 (2001) [hep-ph/0007335].

[19] F. Maltoni and T. Stelzer, JHEP **02**, 027 (2003) [hep-ph/0208156];
T. Stelzer and W. F. Long, Comput. Phys. Commun. **81**, 357 (1994) [hep-ph/9401258].
`MADGRAPH/MADEVENT` is available from:
`http://madgraph.physics.uiuc.edu/`.

[20] H. Murayama, I. Watanabe and K. Hagiwara, KEK-91-11.

[21] T. Ohl, hep-ph/0011287;
W. Kilian, LC-TOOL-2001-039 *In '2nd ECFA/DESY Study 1998-2001', 1924-1980*.
`WHIZARD` is available from:
`http://www-ttp.physik.uni-karlsruhe.de/Progdata/whizard/`. For `O'MEGA`, see:
`http://heplix.ikp.physik.tu-darmstadt.de/~ohl/omega/`.

[22] F. Caravaglios and M. Moretti, Phys. Lett. **B358**, 332 (1995) [hep-ph/9507237].

[23] M. Moretti, T. Ohl, and J. Reuter, hep-ph/0102195.

[24] E. Boos *et al.*, hep-ph/0109068.

[25] N. Ghodbane, hep-ph/9909499;
S. Katsanevas and P. Morawitz, Comput. Phys. Commun. **112**, 227 (1998) [hep-ph/9711417]. `SUSYGEN` is available from:
`http://lyoinfo.in2p3.fr/susygen/susygen3.html`.