Appendix 4

Monte Carlo event generators*

General-purpose Monte Carlo event generators are designed for generating a wide variety of physics processes. There are literally hundreds of different Monte Carlo event generators; some of these are

- **ARIADNE** [1] is a programme for simulation of QCD cascades implementing the colour dipole model.
- **HERWIG** [2] (Hadron Emission Reactions With Interfering Gluons) is a package based on matrix elements providing parton showers including colour coherence and using a cluster model for hadronisation.
- **ISAJET** [3] is a programme for simulating pp, $p\overline{p}$ and e^+e^- interactions; it is based on perturbative QCD and phenomenological models for parton and beam jet fragmentation including the Fox–Wolfram final-state shower QCD radiation and Field–Feynman hadronisation.
- **JETSET** [4] is a programme for implementing the Lund string model for hadronisation of parton systems. Since 1998, JETSET has been combined with PYTHIA in a single package.
- **PYTHIA** [5] is a general-purpose programme with an emphasis on QCD cascades and hadronisation; it includes several extensions for modelling new physics (e.g. Technicolour).

There are also Monte Carlo event generators which are specifically designed to generate a number of interesting physics processes. They can be interfaced to one or more of the general-purpose event generators above or with other specialised generators.

* For a recent review see also Z. Nagy & D.E. Soper, *QCD and Monte Carlo Event Generators*, XIV Workshop on Deep Inelastic Scattering, hep-ph/0607046 (July 2006).

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- **AcerMC** [6] models Standard Model background processes in pp collisions at the LHC and works with either PYTHIA or HERWIG; it provides a library of massive matrix elements for selected processes and is designed to have an efficient phase-space sampling via self-optimising approaches.
- **CASCADE** [7] models full hadron-level processes for ep and pp scattering at small $x = 2p/\sqrt{s}$ according to the CCFM [8] evolution equation.
- **EXCALIBUR** [9] computes all four-fermion processes in e^+e^- annihilation which includes QED initial-state corrections and QCD contributions.
- **HIJING** [10] (Heavy Ion Jet INteraction Generator) models mini-jets in pp, pA and AA reactions.
- **HZHA** [11, 12] provides a wide coverage of the production and decay channels of Standard Model and Minimal Super Symmetric Model (MSSM) Higgs bosons in e^+e^- collisions and was heavily used in LEP2 Higgs-boson searches.
- **ISAWIG** [13] works with the ISAJET SUGRA package and general MSSM programs to describe SUSY particles which can be read in by the HERWIG event generator.
- **KK** [14] models two-fermion final-state processes in e^+e^- collisions including multiphoton initial-state radiation and a treatment of spin effects in τ decays.
- **KORALB** [15] provides a simulation of the τ-lepton production in e^+e^- collisions with centre-of-mass energies below 30 GeV including treatment of QED, Z exchange and spin effects; it makes use of the TAUOLA package.
- **KORALZ** [16] provides a simulation of the production and decay processes of τ leptons including spin effects and radiative corrections in e^+e^- collisions with centre-of-mass energies ranging from 20 GeV to 150 GeV.
- **KORALW** [17, 18] provides a simulation of all four-fermion final states in e^+e^- collisions and includes all non-double-resonant corrections to all double-resonant four-fermion processes; it uses the YFSWW package (see below) to include electroweak corrections to W-pair production.
- **LEPTO** [19] models deep inelastic lepton–nucleon scattering.

- **MC@NLO** [20] is a parton-shower package implementing schemes of next-to-leading order matrix-element calculations of rates for QCD processes and makes use of the HERWIG package; it includes the hadroproduction of single vector and Higgs bosons, vector-boson pairs, heavy-quark pairs and lepton pairs.
- **MUSTRAAL** [21] simulates radiative corrections to muon and quark-pair production in e^+e^- collisions near centre-of-mass energies of 91.2 GeV.
- **PANDORA** [22] is a general-purpose parton-level generator for linear collider physics which includes beamstrahlung, initial-state radiation and full treatment of polarisation effects including processes from the Standard Model and beyond; it is interfaced with PYTHIA and TAUOLA in the PANDORA–PYTHIA package.
- **PHOJET** [23] models hadronic multiparticle production for hadron–hadron, photon–hadron and photon–photon interactions using the Dual Parton Model (DPM).
- **PHOTOS** [24] simulates QED single-photon (bremsstrahlung) radiative corrections in decays; it is intended to be interfaced with another package generating decays.
- **RESBOS** (RESummed BOSon Production and Decay) [25] models hadronically produced lepton pairs via electroweak vector-boson production and decay by resumming large perturbative contributions from multiple soft-gluon emissions.
- **RacoonWW** [26] models four-fermion production at e^+e^- colliders including radiative corrections to four-fermion decays from W-pair production; it includes anomalous triple gauge-boson couplings as well as anomalous quartic gauge-boson couplings where applicable.
- **SUSYGEN** [12, 27] models the production and decay of MSSM sparticles (supersymmetric partners of particles) in e^+e^- collisions.
- **TAUOLA** [28] is a library of programs modelling the leptonic and semi-leptonic decays of τ leptons including full-final-state topologies with a complete treatment of spin structure; it can be used with any other package which produces τ leptons.
- **VECBOS** [29] models the leading-order inclusive production of electroweak vector bosons plus multiple jets.
- **YFSWW** [30] provides high-precision modelling of the $W^\pm$ mass and width using the YFS exponentiation technique.

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Finally, several packages exist which aid in the evaluation of Feynman diagrams and are able to provide source code for inclusion in a Monte Carlo event generator. Such packages include CompHEP [31], FeynArts/FeynCalc [32], GRACE [33], HELAS (HELicity Amplitude Subroutine for Feynman diagram evaluation) [34] and MADGRAPH [35].

In the field of cosmic rays and astroparticle physics the following Monte Carlo event generators are frequently used. A recent overview including the relevant references is published in [36]. For further references see Sect. 15.5.1.

- **VENUS** (Very Energetic NUclear Scattering) is designed for ultra-relativistic heavy-ion collisions including a detailed simulation of creation, interaction and fragmentation of colour strings. Diffractive and non-diffractive collisions are also treated. It covers cosmic-ray energies up to $2 \cdot 10^7$ GeV.
- **QGSJET** (Quark Gluon String model with Jets) is based on the Gribov–Regge model of strong interactions. It treats nucleus–nucleus interactions and semihard processes. At high energies the collision is described as a superposition of a number of elementary processes based on Pomeron exchange.
- **DPMJET** (Dual Parton Model with JET production) simulates particle production in hadron–nucleus and nucleus–nucleus interactions at high energies. The soft component is described by a supercritical Pomeron. For hard collisions also hard Pomerons are introduced.
- **HDPM** is a phenomenological generator inspired by the Dual Parton Model and adjusted to experimental data.
- **NEXUS** combines VENUS and QGSJET in the framework of a parton-based Gribov–Regge theory with unified soft and hard interactions. The shower development is based on cascade equations.
- **SIBYLL** is a minijet model using a critical Pomeron describing soft processes and strings originating from hard collisions with minijet production of high transverse momenta.

Extensive air showers are frequently generated with the CORSIKA programme [37] where different event generators can be built in. CORSIKA includes also packages for the modelling of the geometry of a special detector, like GEANT [38] and the description of low-energy interactions, e.g. with FLUKA [39].

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References

[1] L. Lönnblad, ARIADNE Version 4: A Program for Simulation of QCD Cascades Implementing the Color Dipole Model, *Comp. Phys. Comm.* **71** (1992) 15–31

[2] G. Marchesini *et al.*, HERWIG: A Monte Carlo Event Generator for Simulating Hadron Emission Reactions with Interfering Gluons. Version 5.1, *Comp. Phys. Comm.* **67** (1992) 465–508

[3] F.E. Paige, H. Baer, S.D. Protopopescu & X. Tata, *ISAJET 7.51 – A Monte Carlo Event Generator for pp,* $p\bar{p}$*, and* e^+e^- *Reactions*, www-cdf.fnal.gov/cdfsim/generators/isajet.html, ftp://ftp.phy.bnl.gov/pub/isajet/

[4] T. Sjöstrand, High-Energy Physics Event Generation with PYTHIA 5.7 and JETSET 7.4, *Comp. Phys. Comm.* **82** (1994) 74–90; *Lund University report* LU TP 95–20

[5] T. Sjöstrand, QCD Generators, in G. Altarelli, R.H.P. Kleiss & C. Verzegnassi (eds.), *Z physics at LEP 1 – Event Generators and Software*, CERN-89-08-V-3 (1989) 143–340

[6] B.P. Kersevan & E. Richter-Was, *The Monte Carlo Event Generator AcerMC 1.0 with Interfaces to PYTHIA 6.2 and HERWIG 6.3*, hep-ph/0201302

[7] H. Jung (Lund U.), G.P. Salam (CERN & Paris U., VI-VII), Hadronic Final State Predictions from CCFM: The Hadron Level Monte Carlo Generator CASCADE, *Eur. Phys. J.* **C19** (2001) 351–60

[8] L. Lönnblad & H. Jung (Lund U.), *Hadronic Final State Predictions from CCFM Generators*, 9th International Workshop on Deep Inelastic Scattering (DIS 2001), Bologna, Italy, 27 April–1 May 2001, Published in 'Bologna 2001, Deep inelastic scattering', 467–70

[9] F.A. Berends, R. Pittau & R. Kleiss, *EXCALIBUR – A Monte Carlo Program to Evaluate All Four Fermion Processes at LEP 200 and Beyond*, INLO-PUB-12/94 (1994) and hep-ph/9409326

[10] X.-N. Wang & M. Gyulassy, HIJING: A Monte Carlo Model for Multiple Jet Production pp, pA, and AA Collisions, *Phys. Rev.* **D44** (1991) 3501–16

[11] P. Janot, HZHA, (in part M.L. Mangano, G. Ridolfi (conveners), Event Generators for Discovery Physics), in G. Altarelli, T. Sjöstrand, F. Zwirner (eds.), *Physics at Lep2*, CERN-96-01-V-2 (1996) 309–11

[12] E. Accomando *et al.*, *Event Generators for Discovery Physics*, hep-ph/9602203

[13] H. Baer, F.E. Paige, S.D. Protopopescu & X. Tata, ISAJET 7.48: A Monte Carlo Event Generator for pp, $\bar{\mathrm{p}}$p, and $\mathrm{e}^+\mathrm{e}^-$ Reactions, preprint BNL-HET-99-43, FSU-HEP-991218, UH-511-952-00 (1999), hep-ph/0001086

[14] S. Jadach, Z. Was & B.F.L. Ward, *The Precision Monte Carlo Generator KK for Two-Fermion Final States in* e^+e^- *Collisions*, hep-ph/9912214

[15] S. Jadach & Z. Was, Monte Carlo Simulation of the Process $\mathrm{e}^+\mathrm{e}^- \to \tau^+\tau^-$, Including Radiative $O(\alpha^3)$ QED Corrections, Mass and Spin Effects, *Comp. Phys. Comm.* **36** (1985) 191–211, KORALB version 2.1. An Upgrade with the TAUOLA Library of τ Decays, *Comp. Phys. Comm.* **64** (1991) 267–74

[16] S. Jadach, B.F.L. Ward & Z. Was, The Monte Carlo Program KORALZ Version 4.0 for Lepton or Quark Pair Production at LEP/SLC Energies, *Comp. Phys. Comm.* **79** (1994) 503–22

[17] M. Skrzypek, S. Jadach, W. Placzek & Z. Was, Monte Carlo Program KORALW 1.02 for W-pair Production at LEP2/NLC Energies with Yennie-Frautschi-Suura Exponentiation, *Comp. Phys. Comm.* **94** (1996) 216–48; S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward & Z. Was, Monte Carlo Program KORALW 1.42 for All Four-Fermion Final States in e^+e^- Collisions, *Comp. Phys. Comm.* **119** (1999) 272–311

[18] S. Jadach, W. Placzek, M. Skrzypek & B.F.L. Ward, The Monte Carlo Program KoralW Version 1.51 and the Concurrent Monte Carlo KoralW&YFSWW3 with All Background Graphs and First-Order Corrections to W-pair Production, *Comp. Phys. Comm.* **140** (2001) 475–512

[19] G. Ingelman, A. Edin & J. Rathsman, LEPTO 6.5 – A Monte Carlo Generator for Deep Inelastic Lepton-Nucleon Scattering, *Comp. Phys. Comm.* **101** (1997) 108–34

[20] S. Frixione & B.R. Webber, *Matching NLO QCD Computations and Parton Shower Simulations*, JHEP **6** (2002) 29, 1–64; S. Frixione & B.R. Webber, *The MC@NLO 2.3 Event Generator*, Cavendish-HEP-04/09 (GEF-TH-2/2004)

[21] F.A. Berends, R. Kleiss & S. Jadach, Radiative Corrections to Muon Pair and Quark Pair Production in Electron-Positron Collisions in the Z0 Region, *Nucl. Phys.* **B202** (1982) 63–88

[22] M. Iwasaki & M.E. Peskin, *Pandora and Pandora-Pythia: Event Generation for Linear Collider Physics*, on-line: ftp://ftp.slac.stanford.edu/groups/lcd/Generators/PANDORA/ppythia.pdf

[23] R. Engel & J. Ranft, Hadronic Photon-Photon Collisions at High Energies, *Phys. Rev.* **D54** (1996) 4244–62

[24] E. Barberio, B. van Eijk & Z. Was, Photos – A Universal Monte Carlo for QED Radiative Corrections in Decays, *Comp. Phys. Comm.* **66** (1991) 115–28; E. Barberio & Z. Was, PHOTOS – A Universal Monte Carlo for QED Radiative Corrections: Version 2.0, *Comp. Phys. Comm.* **79** (1994) 291–308

[25] C. Balazs & C.P. Yuan, Soft Gluon Effects on Lepton Pairs at Hadron Colliders, *Phys. Rev.* **D56** (1997) 5558–83

[26] A. Denner, S. Dittmaier, M. Roth & D. Wackeroth, RacoonWW1.3: A Monte Carlo Program for Four-Fermion Production at e^+e^- Colliders, *Comp. Phys. Comm.* **153** (2003) 462–507

[27] St. Katsanevas & P. Morawitz, SUSYGEN 2.2 – A Monte Carlo Event Generator for MSSM Particle Production at e^+e^- Colliders, *Comp. Phys. Comm.* **112** (1998) 227–69, on-line: lpscwww.in2p3.fr/d0/generateurs/

[28] S. Jadach, J.H. Kühn & Z. Was, TAUOLA – A Library of Monte Carlo Programs to Simulate Decays of Polarised tau Leptons, *Comp. Phys. Comm.* **64** (1991) 275–99; S. Jadach, M. Jeżabek, J.H. Kühn & Z. Wąs, The τ Decay Library TAUOLA, update with exact $\mathcal{O}(\alpha)$ QED corrections in $\tau \to \mu(e)\nu\bar{\nu}$ decay modes, *Comp. Phys. Comm.* **70** (1992) 69–76; S. Jadach,

Z. Was, R. Decker & J.H. Kühn, The tau Decay Library TAUOLA: Version 2.4, *Comp. Phys. Comm.* **76** (1993) 361–80

[29] F.A. Berends, H. Kuijf, B. Tausk & W.T. Giele, On the Production of a W and Jets at Hadron Colliders, *Nucl. Phys.* **B357** (1991) 32–64

[30] S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward & Z. Was, The Monte Carlo Event Generator YFSWW3 VERSION 1.16 for W Pair Production and Decay at LEP-2/LC Energies, *Comp. Phys. Comm.* **140** (2001) 432–74

[31] A. Pukhov *et al.*, *CompHEP – A Package for Evaluation of Feynman Diagrams and Integration over Multi-particle Phase Space. User's Manual for Version 33* hep-ph/9908288

[32] J. Küblbeck, M. Böhm & A. Denner, Feyn Arts – Computer-Algebraic Generation of Feynman Graphs and Amplitudes, *Comp. Phys. Comm.* **60** (1990) 165–80

[33] Tl. Tanaka, T. Kaneko & Y. Shimizu, Numerical Calculation of Feynman Amplitudes for Electroweak Theories and an Application to $e^+e^- \to W^+W^-\gamma$ *Comp. Phys. Comm.* **64** (1991) 149–66

[34] H. Murayama, I. Wantanabe & K. Hagiwara, *HELAS: HELicity Amplitude Subroutines for Feynman Diagram Evaluations*, KEK Report 91-11 (1992)

[35] T. Stelzer & W.F. Long, Automatic Generation of Tree Level Helicity Amplitudes, *Comp. Phys. Comm.* **81** (1998) 357–71

[36] S. Ostapchenko, *Hadronic Interactions at Cosmic Ray Energies*, hep-ph/0612175 (December 2006)

[37] D. Heck *et al.*, Forschungszentrum Karlsruhe, Report FZKA 6019 (1998); D. Heck *et al.*, Comparison of Hadronic Interaction Models at Auger Energies, *Nucl. Phys. B Proc. Suppl.* **122** (2002) 364–7

[38] R. Brun, F. Bruyant, M. Maire, A.C. McPherson & P. Zanarini, GEANT3 CERN-DD/EE/84-1 (1987); wwwasdoc.web.cern.ch/wwwasdoc/geant_html3/geantall.html

[39] www.fluka.org/ (2005)