PYTHIA Status Report

Torbjörn Sjöstrand*

*Department of Theoretical Physics, Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

Abstract. Recent improvements in the PYTHIA event generator are summarized: new hard subprocesses, $\gamma^*\gamma^*$ physics, QCD final-state showers, and more.

Since 1997, the JETSET 7.4, PYTHIA 5.7 [1] and SPYTHIA [2] programs have been joined in the new PYTHIA 6.1 event generator [3]. The current version is 6.156, consisting of some 53,000 lines of Fortran 77 code. The code, update notes, the older long manual and sample main programs may be found at the webpage

`http://www.thep.lu.se/~torbjorn/Pythia.html`

while a new complete long manual is in preparation.

A general-purpose high-energy physics event generator, such as PYTHIA, need to contain a simulation of several physics aspects.

1. Hard subprocesses, such as $e^+e^- \to Z^0h^0$, which define the physics of interest.
2. Resonance decays, such as Z^0 and h^0 above, which attach closely to the hard process itself, and often need to be simulated with full angular correlations.
3. Final-state parton showers to add a realistic multi-jet and internal jet structure (the former alternatively possible with higher-order matrix elements).
4. Initial-state showers, in e^+e^- colliders mainly photon emission but for resolved-γ events also of the QCD type encountered in hadronic collisions.
5. Multiple parton–parton interactions, for hadrons and resolved photons.
6. Beam remnants, left behind when not the full CM energy is used in the hard process, again for hadrons or resolved photons.
7. Hadronization, whereby the coloured quarks and gluons, colour-connected into strings, are transformed into colour singlet hadrons.
8. Normal secondary decays of unstable hadrons and leptons.
9. Potentially: interconnection effects, such as colour rearrangement and Bose–Einstein effects, that complicate the hadronization/decay process.
10. The forgotten or unexpected, on the principle that a chain is never stronger than its weakest link.

Several of these areas have been improved in recent years.

PYTHIA contains well over 200 different hard subprocesses, in areas such as hard and soft QCD physics, heavy-flavour production, W/Z production, prompt-photon production, photon-induced processes, standard model Higgs production, both for a light and a heavy Higgs state, non-standard Higgs particle production, production of new gauge bosons, Technicolor production, compositeness effects, left–right symmetric models, leptoquark production and, last but not least, Supersymmetric particle production.

The area of $\gamma\gamma$ physics has been significantly expanded the last year, with the objective to present a 'complete' framework of $\gamma\gamma/\gamma^*\gamma/\gamma^*\gamma^*$ interactions spanning the whole range of photon virtualities Q^2, with special emphasis on the transition region when $Q^2 \sim m_\rho^2$ [4]. This is the topic of a separate talk in these proceedings [5].

The SUSY scenario contains a rather complete set of $2 \to 2$ processes in the MSSM, with R-parity conservation. News relative to SPYTHIA include an improved simulation of sbottom production, also including contributions from b's in the incoming hadrons, scenarios with the gravitino as the lightest SUSY particle, several 3-body decays of SUSY particles, and the possibility of processes with displaced decay vertices.

The Technicolor simulation has progressed away from the simple picture of ρ_{tc} resonance production with subsequent decay, to a more sophisticated one of $2 \to 2$ processes with full interference between ρ^0_{tc}, ω^0_{tc}, Z^0 and γ^* in the neutral s-channel and between $\rho^\pm_{\mathrm{tc}}$ and $W^\pm$ in the charged ones. The 2-body final states contain appropriate combinations of $\pi^\pm_{\mathrm{tc}}$, π^0_{tc}, ${\pi'}^0_{\mathrm{tc}}$, $W^\pm_{\mathrm{L}}$, Z^0_{L}, $W^\pm$, Z^0 and γ particles (where index L on $W^\pm$ and Z^0 denotes longitudinal states).

The Z'^0 can now have flavour-dependent couplings different between the first, second and third generations.

Higgs pair production, such as h^0A^0 and $h^0H^\pm$, is now included as explicit processes; previously only some of them could be accessed via $Z'^0/Z^0/\gamma^*$ production.

In the context of a left–right symmetric scenario, i.e. with an extra $\mathbf{SU(2)}_R$ symmetry group, doubly-charged Higgs states appear, one set for each of the two $\mathbf{SU(2)}$ groups. $H^{\pm\pm}$ production singly or in pairs is complemented by decays to like-sign leptons or W_L's or W_R's, where the latter can decay further either to ordinary quarks or a lepton in association with a right-handed neutrino.

In compositeness scenarios, a few new processes have been added for e^* and q^* production.

The area of extra dimensions is still fairly new, with many new scenarios appearing. Currently the program only contains a narrow graviton resonance G^* in the context of the Randall–Sundrum model [6]. It is produced by $q\overline{q}$ or gg fusion (with separate access to the high-$p_\perp$ tail by $q\overline{q} \to G^*g$, $qg \to G^*q$ and $gg \to G^*g$ in preparation), and can decay to a pair of fermions or gauge bosons.

Moving away from the topic of hard/primary processes, the major upgrade of the generator has been in the area of final-state showers [7]. This is further described in a separate talk in these proceedings [8]. The starting point is the calculation of the matrix elements for gluon emission in two-body decays. Using the standard model and the minimal supersymmetric extension thereof as templates, a wide selection of colour and spin structures have been addressed, exemplified by $Z^0 \to q\overline{q}$, $t \to bW^+$, $H^0 \to q\overline{q}$, $t \to bH^+$, $Z^0 \to \tilde{q}\overline{\tilde{q}}$, $\tilde{q} \to \tilde{q}'W^+$, $H^0 \to \tilde{q}\overline{\tilde{q}}$, $\tilde{q} \to \tilde{q}'H^+$, $\tilde{\chi} \to q\overline{\tilde{q}}$, $\tilde{q} \to q\tilde{\chi}$, $t \to \tilde{t}\tilde{\chi}$, $\tilde{g} \to q\overline{\tilde{q}}$, $\tilde{q} \to q\tilde{g}$, and $t \to \tilde{t}\tilde{g}$. The mass ratios $r_1 = m_b/m_a$ and $r_2 = m_c/m_a$ have been kept as free parameters. These matrix elements are then used to correct the gluon emission rate in showers. A modified choice of shower variables simplifies this operation. By applying the matrix element corrections to all gluons emitted from the two primary decay products, in suitably modified form, the process- and mass-dependent emission rate should be well modelled also in the collinear region. With the modified algorithm, a good description is obtained of mass effects in the gluon emission rate at LEP1, i.e. of the difference between b-tagged and light quark jets. Predictions include a roughly 10% higher three-jet rate in Higgs decays to $b\overline{b}$ than for a γ^*/Z^0 of the same mass and in the same decay channel. In top decays, the amount of radiation in the W hemisphere is reduced relative to the older algorithm.

In the area of hadronization, the Lund string model [9] remains essentially unchanged. Improvements have been introduced in the low-mass region, however [10]. Such strings can be produced by parton-shower branchings $g \to q\overline{q}$ and, of course, in $\gamma\gamma$ events. The low-mass strings can only produce one or two hadrons. The relative rate of these two possibilities, as a function of string mass, has been modified. When two hadrons are chosen to be produced, their relative orientation remains isotropic just at threshold, but is now matched to fragmentation along the string direction further above threshold. If instead a collapse occurs to a single hadron, the necessary shuffling of energy and momentum is relative to other nearby string pieces.

A number of other changes and improvements have been made [3]. They include

- many improved resonance decays,
- newer parton distribution sets,
- QED radiation also off an incoming muon,
- an energy-dependent $p_{\perp\mathrm{min}}$ in multiple interactions,
- the colour rearrangement options for W^+W^- and Z^0Z^0 events included in the standard code,
- the Bose–Einstein algorithm has been expanded with new options,
- a new baryon production scheme is allowed as an option,
- simple routines for one-dimensional histogramming, and
- standard interfaces to 2-, 4- and 6-fermion electroweak generators and to 4-parton QCD generators, for performing subsequent showers and hadronization.

In the near future, Pythia 6 will continue to develop, e.g. by the inclusion of new processes and by further improvements of the showering algorithms, and of course by bug fixes. In the longer future, a radically new version of the program is required. Given the decisions by the big laboratories and collaborations to discontinue Fortran and instead adopt C++, it is natural to attempt to move also event generators in that direction. User-friendly interfaces will have to hide the considerable underlying complexity from the non-expert. The Pythia 7 project got going three years ago, and is an effort to reformulate the event generation process in object oriented language. A strategy document [11] was followed by a first 'proof of concept version' in June 2000 [12], containing the generic event generation machinery, some processes, and the string fragmentation routines. In the next few years, the hope is to produce useful versions, even if still limited in scope. Due to the considerable complexity of the undertaking, it will still be several years before the C++ version of PYTHIA will contain more and better physics than the FORTRAN one. A corresponding project exists for a HERWIG++, with two postdocs dedicated to the task, and some code sharing with that project is likely.

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