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The Lund Monte Carlo for Hadronic Processes - PYTHIA version 4.8

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Abstract:

PYTHIA is a Monte Carlo program intended for the study of high-p_T physics in hadronic interactions, but covers also the domain of low-p_T interactions as an integral part of the total cross-section. In its present form, version 4.8, it includes matrix elements for the basic $2 \to 1$ and $2 \to 2$ standard model (strong and electroweak) subprocesses (as well as some non-standard model subprocesses), elastic and diffractive scattering, multiple interactions, structure functions and initial and final state parton showers. In this paper, the physics assumptions are summarized, and a detailed manual on how to use the program is given.

1. Introduction

The study of high energy hadron-hadron collisions has attracted considerable attention in recent years. In particular, the successes of the CERN $S\bar{p}pS$ program has made attractive the possibility of building hadron colliders with considerably higher energies – the LHC in Europe (pp, $E_{CM} \approx 15$ TeV) and the SSC in the US (pp, $E_{CM} \approx 40$ TeV). While those projects belong to the nineties, first physics runs have started with the 2 TeV $\bar{p}p$ Tevatron I project at FNAL and upgrade work is under way with the new antiproton accumulator ACOL at CERN. Add fixed target runs – particularly at FNAL – and the field promises to be an active one for some time to come.

Mixed with the successes of the $W^{\pm}$ and Z^0 discoveries, the problems encountered in the searches for the top quark and for supersymmetry have brought home the extreme complexity of the field. Signals of a few nb, in the future even pb, have to be found against the background of 70 mb standard QCD processes, which by themselves show a tremendous amount of variability. Furthermore, the fact that a process is 'standard QCD' does not guarantee that it is understood: so far nobody can offer the hope of calculating (starting from the QCD Lagrangian) even gross properties such as the charged multiplicity distribution of minimum bias events, let alone provide a more detailed picture.

Perhaps the most promising way to tackle these problems has been the construction of computer Monte Carlo programs, in which complete events are generated (and then maybe tracked through a detector, present or planned) for direct comparison with, or prediction of, experimental data. Then the work can be based on the time-honoured principle of 'divide and conquer,' i.e., the generation of a complete event can be subdivided into a number of more manageable tasks. These include the generation of a hard interaction by a convolution of (i) hard scattering matrix elements and (ii) structure functions; the addition of (iii) initial state and (iv) final state radiation; the inclusion of (v) beam jets; and, finally, (vi) the fragmentation of partons into hadrons and the subsequent decay of some hadrons. Of these components, (i) and (ii) are based on work in the literature; (iv) and (vi) come from work done by us in other connections (e^+e^- physics); and (iii), (v) and the colour flow issues in connection with (i) are development work done

expressly for PYTHIA.

Put together, the resulting program, PYTHIA version 4.8 (with tasks (iv) and (vi) performed by JETSET version 6.3 [1]), is of considerable complexity, and is able to give a good description of a number of phenomena. This should not allow one to lose sight of the fact that we here present a largely heuristic model, not a theory. As further experimental evidence warrants it, there will no doubt be room for further improvements. Conversely, PYTHIA 4.8 has had its predecessors, which should now be considered obsolete. Two earlier manuals have been published [2,3], containing some important information – particularly about string drawing in hard interactions – not repeated here.

Among other Monte Carlo programs, only ISAJET by Paige and Protopopescu [4] is of comparable scope and complexity. The two programs have most of the hard processes that can be generated in common; however, PYTHIA is presently the only to include Higgs production – both H^0 and $H^{\pm}$ –, a horizontal gauge boson R, and an additional extended electroweak gauge boson Z'^0, while ISAJET is the only to allow the generation of a large number of supersymmetric processes. ISAJET includes a very sophisticated machinery for setting the kinematics of a hard scattering within given boundaries, and for selecting specific decay chains, where the abilities of PYTHIA are somewhat more limited. On the other hand, PYTHIA has a wider selection of physics options, so that the uncertainties arising from our incomplete understanding of QCD etc. can be more properly assessed. The programs of Odorico [5] cover the domain of QCD processes and single Z^0 and $W^{\pm}$ production. The program of Field et al. [6] only covers hard QCD processes. More importantly, it is significantly slower than any of the other programs and is not publicly available. Finally, EUROJET of van Eijk et al. [7] is based on a slightly different philosophy, including hard $2 \to 3$ processes using explicit matrix elements rather than obtaining them as part of initial and final state showering corrections to the basic $2 \to 2$ processes. This is an approach that makes perfect sense at $S\bar{p}pS$ energies, but would fall short of describing more complicated jet topologies at higher energies.

Considering the complexity of hadron physics, and the ever haunting spectre of unknown program bugs, it is comforting to have two programs like PYTHIA and ISAJET that can be cross-checked against each other – extensive work of this kind has actually been taking place under the aegis of SSC studies [8]. Furthermore, there are many instances where the physics outlook differ. In particular, while PYTHIA can be run with any fragmentation scheme, the strong

ties to JETSET make string fragmentation the obvious choice. All the other programs listed above use independent fragmentation which, apart from breaking Lorentz covariance and abandoning explicit conservation of energy, momentum and flavour, has been shown to disagree with e^+e^- annihilation data [9]. Direct evidence is more difficult to come by in hadron physics; suggestions have been presented for the study of prompt photon events [10] and charm events [11].

This paper is organized as follows. Sections 2-5 give an overview of the physics assumptions made in PYTHIA, with hard interactions covered in 2, initial and final state radiation in 3, beam jets in 4 and fragmentation in 5. Further details are here contained in the references given. Section 6 is the main one of this paper, giving a self-contained and detailed description of all subroutines and common block variables that can be accessed by the PYTHIA user. Since most of the variables are provided with sensible default values, a user need not learn every detail here. In section 7 some examples and further information are given, while section 8 contains a summary and outlook.

2. Basic Hard Scattering

At the core of all present Monte Carlo programs devoted to high-p_T physics lie the matrix elements of the simple $2 \to 2$ subprocesses. (It is true that exact cross-sections for the $2 \to 3$ QCD subprocesses and the associated virtual corrections to the $2 \to 2$ subprocesses have now been calculated [12], but a Monte Carlo implementation of these, if combined with shower algorithms for multi-jets, runs into problems of double counting.) The cross-sections $\hat{\sigma}(\hat{s},\hat{t},\hat{u})$ for the $2 \to 2$ hard scatterings are convoluted with structure functions incorporating leading-log scaling violations to form a total cross-section σ for the subprocess, i.e.

$$\sigma = \sum_{i,j,k} \iiint \frac{d\tau\, dx_F}{(x_F^2 + 4\tau)^{1/2}}\, d\hat{t}\, \hat{\sigma}^k_{ij}(\hat{s},\hat{t},\hat{u})\, f^1_i(x_1,Q^2)\, f^2_j(x_2,Q^2), \qquad (1)$$

where i and j give the partons from particles 1 and 2, respectively, k specifies the final state (when a given initial state can lead e.g. to different final state colour configurations; see below), and we have used the standard definitions

$$\tau = x_1 x_2$$
$$x_F = x_1 - x_2. \qquad (2)$$

2.1. Matrix Elements

The following list of hard scattering subprocesses has been implemented in PYTHIA 4.8:

$q_i(\bar{q}_i)+q_j(\bar{q}_j) \to q_i(\bar{q}_i)+q_j(\bar{q}_j)$	$q_i+\bar{q}_i \to \gamma+Z^0$
$q_i+\bar{q}_i \to q_k+\bar{q}_k$	$q_i+\bar{q}_j \to \gamma+W^\pm$
$q_i+\bar{q}_i \to g+g$	$q_i+\bar{q}_i \to Z^0+Z^0$
$q_i(\bar{q}_i)+g \to q_i(\bar{q}_i)+g$	$q_i+\bar{q}_j \to Z^0+W^\pm$
$g+g \to q_k+\bar{q}_k$	$q_i+\bar{q}_i \to W^+ + W^-$
$g+g \to g+g$	$q_i+\bar{q}_i \to H^0$
$q_i+\bar{q}_i \to Z^0/\gamma^*$	$g+g \to H^0$
$q_i+\bar{q}_j \to W^\pm$	$Z^0+Z^0 \to H^0$
$g+q_i(\bar{q}_i) \to \gamma+q_i(\bar{q}_i)$	$W^+ + W^- \to H^0$
$g+q_i(\bar{q}_i) \to Z^0+q_i(\bar{q}_i)$	$q_i+\bar{q}_i \to H^0+Z^0$
$g+q_i(\bar{q}_i) \to W^\pm+q_j(\bar{q}_j)$	$q_i+\bar{q}_j \to H^0+W^\pm$
$q_i+\bar{q}_i \to g+\gamma$	$q_i+\bar{q}_j \to R$
$q_i+\bar{q}_i \to g+Z^0$	$q_i+\bar{q}_j \to H^\pm$
$q_i+\bar{q}_j \to g+W^\pm$	$q_i+\bar{q}_i \to Z'^0/Z^0/\gamma^*$
$q_i+\bar{q}_i \to \gamma+\gamma$.	

This includes practically all $2 \to 2$ and $2 \to 1$ subprocesses possible in the standard model, i.e. quark and gluon scattering, resonance production of Z^0/γ^*, $W^\pm$ and H^0 (the latter from WW and ZZ fusion, as well as from the more conventional gg and $q\bar{q}$ reactions), pair production of gauge bosons, and production of one gauge boson plus a quark or a gluon jet. These cross-sections are given e.g. in [13]; note comments in subsection 2.2, however.

A major task of PYTHIA is to generate unbiased events in accordance with the cross-section of eq. (1), for any single subprocess or combination of subprocesses above. This is achieved using a fairly sophisticated weighting

technique, where the most populated regions of phase space are sampled most frequently. The different kinds of subprocesses have different kinematical behaviours and are handled with varying methods, see comments inline in program code.

In the cross-sections, the first order expression for α_S is used:

$$\alpha_S(Q^2) = \frac{12\pi}{(33 - 2n_f)\ \ln(Q^2/\Lambda^2)}, \tag{3}$$

where the Λ scale is usually chosen in accordance with the structure function set used. The number of active flavours, n_f, is given by the number of quarks with $Q^2 > 4m_q^2$, but is always taken to be at least 3. Electroweak couplings are consistently expressed in terms of $\alpha_{em} \approx 1/137$, m_Z, m_W and $\sin^2\theta_W \approx 0.229$ [14] (i.e. the Fermi constant G_F has been eliminated).

Quarks are generally treated as massless in the matrix elements; an obvious exception is e.g. the reaction $q + \bar{q} \to H^0$, where the coupling is proportional to $(m_q/m_H)^2$ and a neglect of the quark masses would have rather disconcerting results. All possible standard model decays of the resonances are implemented, and specific decay product flavours can be chosen for each resonance separately. Furthermore, the allowed recoiling quark flavours q' (q'', q''') in the reactions $g + q \to q' + W^\pm$ ([$q + q' \to q'' + q'''$ +] $W^+ + W^- \to H^0$ [+ q'' + q''']) can also be chosen separately, as can the initial flavours entering the hard scattering for any subprocess.

In the production of a single resonance, the mass is chosen according to the proper cross-section, i.e. the basic Breit-Wigner shape folded with the structure functions. Since the latter are falling with x, the high-mass tail of the resonance is in general suppressed, whereas the low-mass tail is significantly enhanced. Indeed, a secondary peak in the cross-section may appear for $m \to 0$. The minimum mass can be selected by the user to avoid the generation of undesirable events. Decays are into the channels allowed by the user, according to conventional mass dependent branching ratios, and with the correct angular distribution [15]; for the Z^0/γ^* and $Z^{0\prime}/Z^0/\gamma^*$ this means the implementation of the full interference structure and forward-backward correlations.

Resonances produced in $2 \to 2$ processes are assumed to be on mass-shell; optionally a symmetric Breit-Wigner shape may be obtained. Further, the full Z^0/γ^* coupling is not here implemented in the production of a Z^0. In the decay

of resonances, the angular distribution is chosen according to the correct matrix elements [15]. These matrix elements are of the $2 \to 4$ type for the production of a pair of resonances and of the $2 \to 3$ type for a single resonance recoiling against a q, a g, or a γ. Correct angular distributions are also included for the decay chain $H^0 \to Z^0Z^0$, $W^+W^- \to 4$ fermions. It should be emphasized that for a heavy H^0, it is no longer a good approximation to consider (Z^0Z^0, $W^+W^- \to$) $H^0 \to Z^0Z^0$, W^+W^- separate from other W and Z scattering subprocesses with the same final state. A correct treatment of the complete structure of the theory then becomes very complex [16], and has not so far been included.

It will be noted that some non-standard processes have been included in the list above, namely the production of a heavy flavour-changing neutral boson, R, as proposed by Hou and Soni [17]; the production of a charged Higgs, $H^\pm$, as suggested in minimal extensions of the standard model [18]; and the production of a new electroweak gauge boson Z'^0, as implied by superstring theories [19]. This latter subprocess has been implemented with the full $Z'^0/Z^0/\gamma^*$ interference structure included. Since many different symmetry breaking and Z^0-Z'^0 mixing scenarios are possible, the couplings of the Z'^0 to quarks and leptons are not uniquely known. The couplings are therefore assumed to be the same as those to the Z^0, but this can easily be changed. A further non-standard model possibility incorporated into PYTHIA 4.8 is the decay channel $Z^0/\gamma^* \to H^+ + H^-$. Apart from being interesting reactions in their own rights, these subprocesses also serve as examples of how other non-standard processes can be implemented into the program by the enterprising user.

2.2. String Drawing

The cross-sections for all the above subprocesses are readily available in the literature [13,17,18]. However, since PYTHIA is designed to set up a partonic system that can eventually be hadronized by string fragmentation, some care must be exercised. As will be explained below, the string representing a colour flux tube is spanned according to the ordering in colour space of the coloured partons, quarks and gluons. A simple partonic system consisting e.g. of two colour triplets (quarks, say) and two colour antitriplets (antiquarks, say) already admits of two entirely different string configurations when colour singlet systems are to be formed (see Fig. 1). If hadrons are produced by subsequent breakups along the strings, these different colour field topologies translate into different final state hadron distributions, which

(at least in principle) should be experimentally distinguishable. This will be true not only of string fragmentation, but of any essentially longitudinal fragmentation model that respects fundamental colour ordering, such as cluster fragmentation. The situation becomes even more complicated with the introduction into the partonic system of one or more colour octets (gluons): a given subprocess can now give rise to several different colour field topologies with very different properties as to the final state hadron distributions. As an example, the reaction $q + g \to q + g$ which has contributions from the three Feynman diagrams in Fig. 2 contains two different colour flows (Fig. 3): either from 1 to 2 to 3 to 4 (a) or from 1 to 3 to 2 to 4 (b). These colour flows translate into the colour field configurations of Fig. 4. (For this reaction the experimental consequences of the two different colour field topologies have recently been studied, and an observable capable of distinguishing between them been constructed [20].)

What is needed then is the cross-section for a specific colour configuration rather than for a specific subprocess. In many cases these two amount to the same thing; processes like $q + \bar{q}' \to W^{\pm}$, e.g., where the final state is a colour singlet, admit of only one colour topology (a string spanned between the remnants of the two hadrons from which the quark and the antiquark have scattered), and the cross-section for the colour configuration is thus identical to the cross-section for the subprocess as a whole. As gleaned from the above, however, this is in general not true for the pure QCD processes, and a recipe is needed for calculating the cross-sections of the different colour topologies. It has been shown [21] that QCD processes can be formulated in a gauge-invariant way in terms of colour flows, for which a set of 'Feynman rules' can be given. Using these rules, the amplitude for any colour flow can be written down and contact be made with the normal Feynman diagrams by inspection of the colour content of their corresponding amplitudes. In this fashion the desired cross-sections can be calculated; when summed over different colour flows, the standard cross-sections for the QCD subprocesses are regained (except for possible interference terms). These calculations were carried out already for the earliest version of PYTHIA and can be found in [2], together with the set of rules necessary for the mathematical interpretation of colour flow diagrams. The results are fully implemented in PYTHIA 4.8.

It should perhaps be noted that although a straightforward treatment would seem to preclude the existence of interference terms between different colour flows belonging to the same subprocess – and consequently in some instances

lead to a different cross-section from the one obtained by standard QCD calculations –, PYTHIA contains options for running both with and without the inclusion of these interference terms in the matrix elements. Also, in conjunction with independent fragmentation which does not respect colour flows, the division of the cross-section of a subprocess on different colour topologies of course has no meaning.

One might worry that the colour flow derived from the lowest order matrix elements would be completely messed up by higher order QCD corrections. This probably does not happen, due to the 'colour coherence' [22] property: additional partons (mainly gluons) are emitted in an ordered fashion, such that the overall colour flow is minimally disturbed. An appealing picture of this phenomenon is the colour antennae of the Leningrad group [23] – a perturbative counterpoint to the Lund string. While most studies on this subject have been for the simpler case of e^+e^- annihilation, a recent paper by Ellis, Marchesini and Webber [24] shows that the same basic behaviour is implicit in the 2→3 matrix elements in hadron physics.

2.3. Structure Functions

The structure functions $f_i^a(x,Q^2)$ give the probability for finding a parton i with a fraction x of the total energy-momentum of hadron a when this hadron is probed at a scale Q^2. So far, theory can not be used to predict the absolute form of structure functions, but the leading log formalism (see also subsection 3.2) does give the Q^2 evolution. Leptoproduction data have given good quark structure function determinations for $Q^2 \approx 10 - 100$ GeV^2. This leaves undetermined the gluon structure function and the Λ parameter of the strong coupling constant $\alpha_s(Q^2)$. Broadly speaking, the observed (anti)quark structure function scaling violations can be reproduced over some range of Λ values, provided that a hard (soft) gluon structure function is assumed for a small (large) Λ. This uncertainty should be added to the statistical and systematic experimental errors (both bin-by-bin and in overall normalization) and to the leeway given in the exact application of the leading log formalism. Therefore several slightly different parametrizations have been presented; some of the most recent are included here. For the proton structure functions this includes the two sets by Eichten, Hinchliffe, Lane and Quigg (EHLQ) [13] with Λ = 0.2 and 0.29 GeV, respectively; the two by Duke and Owens [25] with Λ = 0.2 and 0.4 GeV, respectively; and the one by Glück, Hoffman and Reya [26] with Λ = 0.4 GeV. The neutron is obtained by isospin conjugation.

For the charged pions the two sets by Owens [27] are available. Since these pion structure functions were determined assuming that protons are described by the Duke-Owens structure functions, consistency would best be served if all simulations of πp- and πn-interactions were made with this matched set.

For applications at high energies, only the EHLQ sets can be recommended: these parametrizations cover the range $5\ \mathrm{GeV}^2 \leq Q^2 \leq 10^8\ \mathrm{GeV}^2$. This goes much further than any of the other parametrizations, and some of these may give nonsensical answers if applied at LHC/SSC energies. The EHLQ parametrizations also provide the largest range in x: down to $x = 10^{-4}$, values which are frequently probed by hard processes at higher energies. Here it has been shown that, if the Q^2 scale is large enough, the structure function is fairly well determined in this region by evolution down from larger x values, so that uncertainties in the original ansatz do not matter that much [13]. This argument does not remove the uncertainty in the ansatz when both x and Q^2 are small [28], and here arguments have been raised why the naïve x^{-1} behaviour should be replaced by something more like $x^{-1.3}$ [29]. The region of small x and Q^2 may be particularly relevant for the understanding of beam jet structure (see section 4); at the LHC/SSC even the region $x < 10^{-4}$ has to be taken into account, which is here done by extending the EHLQ value at $x = 10^{-4}$ downwards assuming an x^{-1} behaviour.

A complete program for fast and efficient structure function evolution has been developed by Tung [30]. The structure functions at low Q^2 and the Λ scale have to be provided as input. PYTHIA has been equipped with an interface to this package, so that the user who so wishes can access this rather than the standard parametrizations. Since the renormalization scheme used to handle heavy flavour threshold effects [31] is somewhat different from what is used by EHLQ, the heavy flavour content will differ even when the same initial conditions are assumed.

2.4. Elastic and Diffractive Events

Apart from the hard scattering subprocesses, PYTHIA 4.8 can also generate 'genuine' low-p_T events (see section 4), and events with elastic as well as single and double diffractive scattering. These latter processes have the same general structure: t, the momentum transfer between the incoming hadron and the outgoing system (a hadron or an excited state), is given by a distribution

$$\exp(Bt + Ct^2)\ dt \tag{4}$$

where B is the nuclear slope parameter and C the curvature parameter. (For diffractive scattering, the distribution in t is the square-root of the distribution for elastic events, i.e. B and C are rescaled by a factor 1/2.) For each diffractive system an additional factor dM^2/M^2 is multiplied on to give the mass M of the excited state. The diffractive system is subsequently treated as a string with the quantum numbers of the original hadron. Since the exact nature of the 'pomeron' exchanged between the hadrons is unknown, two alternatives are included. In the first, the pomeron is assumed to couple to (valence) quarks, so that the string is stretched directly between the struck quark and the remnant diquark (antiquark) of the diffractive state. In the second, the interaction is rather with a gluon, giving rise to a 'hairpin' configuration in which the string is stretched from a quark to a gluon and then back to a diquark (antiquark). The total hadronic cross-section and the elastic cross-section, as well as the nuclear slope parameter B, are calculated using the parametrizations of Block and Cahn [32]; for the diffractive cross-sections the ansatz of Goulianos [33] is used. The curvature parameter C is found from a simple parabola fit to the values at different energies calculated by Block and Cahn in the Chou-Yang model [34], incorporating also the value of $C \approx 5\ \mathrm{GeV}^{-4}$ measured at the ISR.

3. Initial and Final State Radiation

The previous section dealt with hard $2 \to 2$ (or $2 \to 1$) processes. The cross-sections for these processes are obtained by applying lowest order perturbation theory; thus higher order corrections are, at this point, unaccounted for. In principle perturbations should be calculated both with respect to QCD and QFD (SU(2)×U(1)) corrections. As an example, if the lowest order process is $q + g \to q + g$, then processes in the next order include $q + g \to q + g + g$, $q + g \to q + q' + \bar{q}'$, $q + g \to q + g + \gamma$, $q + g \to q + g + Z^0$ and $q + g \to q' + g + W^{\pm}$. In the same order, there will also be loop corrections to the $q + g \to q + g$ matrix element; these corrections are needed in order to cancel soft and collinear divergences in the $2 \to 3$ processes.

In practice, one can often neglect the QFD corrections, but never the QCD ones. There are two reasons for the latter point: firstly, the strong coupling constant α_S is large, and secondly, by virtue of having incoming hadrons, all hard processes must involve coloured partons. By contrast, α_{em} is much

smaller, and a graph like $g + g \to g + g$ does not contain any charged particles at all. The interest in QFD corrections is therefore more process-specific: contributions from $q + g \to q' + g + W^{\pm}$ are negligible when seen as just another source of high-p_T jets, but not necessarily so when studying the probability of finding a W in conjunction with extra high-p_T jets. As of yet, no QFD corrections have been included in PYTHIA, except for the well-known shift of W and Z masses. The following will therefore deal exclusively with QCD corrections.

By now, all QCD graphs of order α_S^3 have been calculated, i.e. all $2 \to 3$ processes including virtual corrections to $2 \to 2$ ones [12]. Additionally, many $2 \to 4$ results are available [35], but here without any study of virtual corrections to the same order. Already at present energies, events with four or more well separated high-p_T jets are legio, and most of these jets actually have (we believe) a subjet structure that is not experimentally resolvable but does affect properties like charged multiplicities and transverse momenta. At higher energies, like the SSC, this will be even more true. It was therefore decided to forego a matrix element approach in favour of a parton cascade picture, where the emission of an arbitrary number of partons is automatically included. The price to be paid is a less accurate representation of the cross-section for well separated jets, where the result from showers could easily deviate from the 'true' matrix element answer by factors of two or more. It may be possible to find schemes for trying to correct this discrepancy [36], but this has so far not been carried out.

In the parton shower approach, one distinguishes between initial state radiation and final state radiation. In general, such a separation is not possible, because of the presence of interference terms. However, bremsstrahlung close to the directions of the two incoming partons (in the basic $2 \to 2$ process) is obviously dominated by the collinear divergences from initial state radiation graphs, and correspondingly final state radiation dominates close to the directions of the two outgoing partons. The neglect of interference terms should therefore not be crucial in the important regions.

Initial and final state radiation are in the following considered separately: although they share a common structure, the details are actually quite different.

3.1. Final State Radiation

Final state parton showers are timelike: all partons have $m^2 \geq 0$. The evolution is based on an iterative use of the branchings $q \to qg$, $g \to gg$ and $g \to q\bar{q}$, as given by the Altarelli-Parisi evolution equations [37]:

$$\frac{dP_{a\to bc}}{dt} = \int dz \, \frac{\alpha_S(Q^2)}{2\pi} \, P_{a\to bc}(z). \tag{5}$$

Here z gives the sharing of energy (or some combination of energy and momentum) between the daughters b and c, and t is the evolution parameter: usually $t = \ln(m_a^2/\Lambda^2)$. The Altarelli-Parisi splitting kernels $P_{a\to bc}(z)$ are

$$\begin{aligned} P_{q\to qg}(z) &= \frac{4}{3}\,\frac{1+z^2}{1-z} \\ P_{g\to gg}(z) &= 6\,\frac{(1-z(1-z))^2}{z(1-z)} \\ P_{g\to q\bar{q}}(z) &= \frac{1}{2}\,(z^2 + (1-z)^2), \end{aligned} \tag{6}$$

(where an additional factor 1/2 for identical particles should be included when integrating $P_{g\to gg}(z)$).

Starting at the maximum allowed mass for parton a, t may be successively degraded until a branching occurs. The products b and c may be allowed to branch in their turn, and so on. The parton branching is stopped when a parton mass is evolved below some minimum value, i.e. $t < t_{min} = \ln(m_{min}^2/\Lambda^2)$. Obviously, this cutoff will have to depend on the quark masses involved, in particular for heavy flavours. The probability that a parton does not branch between some initial maximum t and t_{min} is given by the Sudakov form factor

$$S_a(t) = \exp\{-\sum_b \int_{t_{min}}^{t} dt' \int dz \, \frac{\alpha_S(Q'^2)}{2\pi} \, P_{a\to bc}(z)\}. \tag{7}$$

The probability distribution $P_a(t_{max},t)$ that a parton a with maximum allowed virtuality t_{max} will actually obtain the virtuality t is then

$$P_a(t_{max},t)\, dt = S_a(t_{max}) \, \frac{d}{dt}\{\frac{1}{S_a(t)}\}. \tag{8}$$

A wide selection of algorithms have been developed, see e.g. [38,39], which differ mainly in the interpretation of the variables t, Q^2 and z. Many of the variations are formally of a subleading character, and are therefore not constrained by theoretical leading log analyses. The coherence phenomenon [22]

is an exception: it has been shown that destructive interference plays an important rôle in reducing the amount of parton branchings. This was first correctly included in the Marchesini-Webber program [39].

In the algorithm in [40], which is used in JETSET 6.3, coherence effects are also included by default, but can be switched off for comparison. The evolution parameter t is chosen as $t = \ln(m_a^2/\Lambda^2)$ and four different z choices are available. All of them correspond to a sharing of energy, and are obtained by combining a 'local' or a 'global' z definition with a 'constrained' or an 'unconstrained' maximum daughter virtuality. In the local case, z is interpreted as the energy fraction in the rest frame of the grandmother, i.e. for the branching $1 \to 3 + 4$ in Fig. 5 in the rest frame of 0; for $3 \to 5 + 6$ in the rest frame of 1, etc. In the global case, z is always defined in the rest frame of the showering system, i.e. parton 0 in Fig. 5. For a given mother mass and z value, the kinematics of a z definition allows only a restricted (coupled) range of daughter masses, which is strictly observed in the constrained evolution. In the unconstrained alternative, these limitations are relaxed, by allowing the actual sharing of energy also to depend somewhat on the daughter masses involved. The default option is the global unconstrained one; it is indeed for this option that parameters have been tuned in e^+e^- annihilation. Further details are found in [40,1].

The evolution equations contain $\alpha_S(Q^2)$, and thus depend on the choice of Q^2 scale for each branching $a \to bc$. Studies of coherence effects [41] suggest that the p_T^2 of the daughters b and c should be more relevant than the more obvious choice m_a^2. As default option we therefore have $Q^2 = z(1 - z)m_a^2 \approx p_T^2$, but leave $Q^2 = m_a^2/4$ as another choice.

Some details specific to applications of final state radiation in hadron physics also warrant mentioning. The two outgoing partons are always boosted to their CM frame and evolved there, and in this frame the total energy is also preserved during the shower evolution. Thus, in a process like $q + g \to q + \gamma$, if the final q acquires a mass, the p_T (and p) of the γ is reduced accordingly. The maximum virtuality Q^2_{max} is by default chosen to be $4p_T^2$, with p_T the scale of the hard $2 \to 2$ interaction. Thus, for a 90° scattering, $Q^2_{max} = \hat{s}$, which is the same value as allowed e.g. in final state evolution in W and Z decays. On the other hand, $Q^2_{max} \to 0$ for scatterings with $p_T \to 0$, even if the $\hat{s}$ of the scatterings remains finite. The Λ value may be chosen separately, but it is by default taken to be the same as the one given by the choice of structure functions.

3.2. Initial State Radiation

A fast hadron may be viewed as a cloud of quasireal partons. At each instant, an individual parton can initiate a cascade, branching into a number of partons [42]. These partons do not have enough energy to be on mass-shell, and thus only live for a finite time before reassembling. In a hard interaction between two incoming hadrons, when two partons scatter to high p_T, the other partons in the two related cascades are also provided with the necessary energy to live indefinitely. For Monte Carlo applications, it is convenient to imagine that the full spacelike virtuality, $m^2 < 0$, $Q^2 \approx -m^2 > 0$, is carried by the two interacting partons. Then the momentum transfer given by the central $2 \to 2$ hard scattering subprocess is enough to ensure that all partons of the two related cascades may end up on mass shell.

In principle, the evolution of a cascade could be carried out from the cascade intiating parton at a low Q^2 scale to the incoming parton at the hard interaction, i.e. forward in time [5,6]. There are a number of problems associated with this approach, which have to do with the fact that the flavour, x and Q^2 values at the hard interaction are then not known until the very end of the evolution [5]. Instead, a 'backwards evolution' algorithm [43] has been developed, in which an already chosen hard scattering forms the starting point. The evolution is then reconstructed step by step in falling Q^2 sequence back towards the shower initiators. An analogue to the Sudakov form factor, eq. (7), may be constructed as follows.

The Q^2 evolution of partons inside a cascade is again given by the Altarelli-Parisi equations; if written for the structure functions they take the form

$$\frac{df_b(x,t)}{dt} = \frac{\alpha_S(Q^2)}{2\pi} \sum_a \int \frac{dx'}{x'} f_a(x',t)\, P_{a\to bc}\left(\frac{x}{x'}\right). \tag{9}$$

Here, $f_i(x,t)$ is the structure function for flavour i, x is the momentum fraction carried by a parton, and $P_{a\to bc}(z)$ are the splitting functions of eq. (6) (here without any symmetrization factor 1/2 for the $g \to gg$ integral). The Altarelli-Parisi equations express the fact that during a small increase dt there is a probability for a parton a with the momentum fraction x' to become resolved into a parton b at $x = zx'$ and a parton c at $x' - x = (1 - z)x'$. Correspondingly, during a decrease dt a parton b may be 'unresolved' into a parton a. The probability dP_b for this to happen is given by df_b/f_b which,

using eq. (9), becomes

$$dP_b = \frac{df_b(x,t)}{f_b(x,t)} = |dt| \frac{\alpha_S(Q^2)}{2\pi} \sum_a \int \frac{dx'}{x'} \frac{f_a(x',t)}{f_b(x,t)} P_{a\to bc}(\frac{x}{x'}). \qquad (10)$$

Summing up the cumulative effect of many small changes dt, the probability for no radiation exponentiates. Therefore one may define a form factor (with z = x/x')

$$S_b(x,t_{max},t) = \exp\{-\int_t^{t_{max}} dt' \frac{\alpha_S(Q'^2)}{2\pi} \sum_a \int dz \frac{x'f_a(x',t')}{xf_b(x,t')} P_{a\to bc}(z)\}, \qquad (11)$$

giving the probability that a parton b remains at x from t_{max} to $t < t_{max}$. Implicit in S_b is also information on flavour, t and x values for the branchings that do occur (see [43] for details).

The reconstruction of the kinematics of the branchings is nontrivial. It depends, e.g., on the choice of interpretation of the z = x/x' splitting variable. In this work, z is defined as the ratio of $\hat{s}$ values before and after a branching. Further, the parton c in the branching a → bc may be timelike, just like the two hard scattered partons, and give rise to a final state shower of its own, to be treated in the spirit of the previous subsection. Finally, the interpretation of t and Q^2 is ambiguous. The standard choice is $t = \ln(Q^2/\Lambda^2)$ with $Q^2 = -m^2/4$, but a wide selection of alternative definitions is available. For the phenomenology at present energies, uncertainties in these details do not seem to be particularly crucial for the outcome [43]. Like the evolution itself, the branchings are reconstructed with start at the hard 2 → 2 interaction, and with incoming partons along the ± z axis. As each branching a → bc is considered, the event is rotated and boosted so that a rather than b becomes the parton coming in along +z or -z.

4. Beam Jets and Multiple Interactions

The differential cross-section for a parton-parton interaction is singular for the momentum transfer $\hat{t} \to 0$ (or $\hat{u} \to 0$), as expressed e.g. in the well-known rule of thumb that the p_T-spectrum for a parton from hard interactions should behave roughly like dp_T^2/p_T^4. The integrated cross-section of all interactions with $p_T > p_{Tmin}$, $\sigma_{hard}(p_{Tmin})$, is therefore divergent for $p_{Tmin} \to 0$. At present collider energies, $\sigma_{hard}(p_{Tmin})$ becomes comparable to the total cross-section for $p_{Tmin} \approx 1.5 - 2.0$ GeV/c. This need not lead to contradictions: $\sigma_{hard}(p_{Tmin})$ does not give the hadron-hadron cross-section but the parton-

parton one. Each of the two incoming hadrons may be viewed as a beam of partons, with the possibility of several parton-parton interactions when the hadrons pass through each other, so that $\sigma_{hard} > \sigma_{tot}$ is perfectly allowed.

In [44] it is argued that collider data indicate a significant probability for multiple interactions at 540 GeV. This conclusion is based on the complete simulation of hadronic events with PYTHIA. Specifically, if at most one hard interaction per event is allowed, the predicted multiplicity distribution is much narrower than the experimental one, and forward-backward correlations are almost absent. First direct experimental evidence for multiple parton-parton interactions has also recently been reported by the AFS Collaboration [45] in a study of four-jet events.

If different parton interactions above p_{Tmin} are assumed to take place (essentially) independently of each other, one obtains a Poissonian multiplicity distribution in the number of interactions, with mean given by $\sigma_{hard}(p_{Tmin})/\sigma_{tot}$, where σ_{tot} is the total inelastic, nondiffractive cross-section. With a varying number of interactions, the multiplicity fluctuations are increased, and strong forward-backward multiplicity correlations are introduced. Results are sensitive to the choice of p_{Tmin} value, with a reasonable description obtained for $p_{Tmin} \approx 1.6$ GeV/c. Forward-backward multiplicity correlations, the rate of hot spots and other phenomena are also well described with this choice.

The value of the p_{Tmin} scale is not given by any external arguments, but is the main free parameter of the model. The cutoff should be essentially energy-independent, but some slight increase with energy can not be excluded. One of the specific aspects of hadron physics is the 'dense packing' problem [42]: at very high energies and small x values, the effective number of partons inside the colliding hadrons becomes larger than what can 'fit in' the hadron, and recombination effects (when two partons combine to one, opposite to the ordinary Altarelli-Parisi evolution) become important. Fortunately, it has been shown [46] that this problem is negligible all the way up to SSC energies for parton-parton interactions at a p_T of 2 GeV or above.

A number of details remains to be discussed. If no interaction occurs above p_{Tmin}, it is assumed that a very soft gg → gg interaction still takes place, so that the colour flow is redirected. A 'low-p_T' event then consists of two strings, in pp collisions stretched between a diquark from one p and a quark from the other; in $\bar{p}p$ collisions one between diquark and antidiquark, and one

between quark and antiquark. This provides a natural continuation to events above p_{Tmin}, where the dominant one-gluon exchange processes $qq' \to qq'$, $qg \to qg$ and $gg \to gg$ (with q valence quarks or antiquarks) have the same overall string drawing – in the last two processes with one or two extra intermediate gluons.

If two strings are stretched to a baryon remnant, it remains to be specified how the diquark and the quark share the remaining energy and momentum. With χ representing the $E + p_L$ ($p_L = \pm p_z$ longitudinal momentum) fraction taken by the quark, a form

$$P(\chi)\, d\chi = \frac{(1-\chi)^3}{(\chi^2 + c^2)^{1/2}}\, d\chi \qquad (12)$$

is used. Here, $c = 2m_q/s^{1/2} = 0.6\ \mathrm{GeV}/s^{1/2}$ gives a cut-off of the singularity at $\chi = 0$. The shape has been chosen in rough agreement with the valence quark distribution, and seems to give sensible results, but it is by no means obvious.

Similar energy sharing distributions are needed when a sea quark is kicked out of the incoming hadron, producing a qqqq or $qqq\bar{q}$ colour triplet remnant. In these cases the remnant is split into a hadron plus a remainder-jet: either a baryon plus a quark jet, or a meson plus a diquark jet. Flavours are paired taking into account that a sea $q\bar{q}$ pair comes from the splitting of a colour octet gluon so that, if one of them is kicked out, the other should end up in the hadron split off. Simple counting rules are used, based on the number of valence quarks in an object. Thus the χ fraction of the quark jet or meson in the first or second case above, respectively, is given by

$$P(\chi)\, d\chi = 2(1-\chi)\, d\chi. \qquad (13)$$

For the generation of multiple interactions, the natural course is to start with the hardest interaction, i.e. the one with the highest p_T, and sequentially generate further interactions in falling p_T order, until p_{Tmin} is reached [44]. In such a scheme, it is straightforward to have the hard interaction be any of the processes described above, with kinematics constrained as required by the user. Alternatively, the hard interaction can be just a normal QCD $2 \to 2$ process with the proper distribution for minimum bias events, including a fraction of events with no interactions at all above p_{Tmin}. Further, by having the interactions ordered, it is possible to take into account the energy carried away by preceding interactions, by letting the x obtained from structure functions always refer to remaining energy. This may

be considered as the simplest possible approach to the complicated issue of defining simultaneous parton distribution functions.

So far, it has been assumed that the initial state of all hadron collisions is the same, whereas in fact each collision is also characterized by a varying impact parameter b. A small b value corresponds to a large overlap between the two colliding hadrons, and hence an enhanced probability for multiple interactions. A large b, on the other hand, corresponds to a grazing collision, with a large probability that no parton interactions at all take place. This element of variability tends to broaden the multiplicity distribution, particularly at higher energies. At present energies, it helps give an explanation of the 'pedestal effect': events that contain a hard interaction are biased towards small impact parameters, and hence have a larger than average multiple interaction probability.

A realistic model for multiple interactions with a varying impact parameter is developed in [47], as follows. First, the abrupt cutoff at p_{Tmin} is replaced by a more continuous cutoff at an effective scale p_{T0}. This is achieved by multiplying the ordinary matrix elements, which diverge roughly like dp_T^2/p_T^4, by a factor $p_T^4/(p_{T0}^2+p_T^2)^2$. Further, α_S is evaluated at a scale $p_{T0}^2+p_T^2$. Interactions can then be generated with $p_T \to 0$. This modification of the cross-section can be motivated by the fact that an incoming hadron consists of a collection of partons with net colour charge zero. As smaller and smaller transverse momenta are considered, the wavelength of the exchanged gluon becomes larger and larger, the individual colour charges are no longer resolved, and the cross-section therefore does not increase as fast as naïvely expected.

Assuming some (spherically symmetric) matter distribution inside the colliding hadrons, one may calculate the total overlap $\tilde{O}(b)$ of the two hadrons during the course of an encounter with impact parameter b. The average number of interactions is assumed proportional to this overlap

$$\langle n_{int}(b)\rangle = k\tilde{O}(b), \qquad (14)$$

where the constant of proportionality k is related to the integrated parton-parton cross-section, and hence increases with the CM energy. For a given impact parameter, the number of interactions is assumed to be distributed according to a Poissonian. If the matter distribution has a tail to infinity, events may be obtained with arbitrarily large b values. In order to obtain finite cross-sections, one has to assume that each event contains at least one semihard interaction (this in contrast to the simpler model with fixed p_{Tmin}

cutoff). The probability that two hadrons, passing by each other with an impact parameter b, will actually interact is then given by

$$P_{int}(b) = 1 - \exp(-k\tilde{O}(b)). \qquad (15)$$

For a given p_{T0} scale, the ratio of the (regularized) integrated parton-parton cross-section and the total (inelastic, nondiffractive) cross-section can be used to determine k.

Using the equations above, the probability distribution in b of events may be obtained, and for each b the average number of interactions to be expected. This method, of first selecting the impact parameter once and for all and only afterwards generating the interactions, does not work e.g. when only hard scatterings are to be generated and the b distribution is consequently biased. Instead the program is based on an algorithm, in which the b value and the hardest p_T are chosen simultaneously (according to well-defined distributions), and this setup is then to be retained with the probability that no interactions should have taken place at a larger p_T value (a probability that is decreased for small p_T values or large overlaps). Once the hardest interaction has been fixed, the probability for further interactions is known, and these may again be generated in falling p_T sequence.

Phenomenologically, this approach seems to work well, but a few comments should be given. In order fully to understand the size of the experimental pedestal effect [48] a Gaussian matter distribution does not seem to be enough. A double Gaussian with half the hadronic matter concentrated in a central core 1/5 of the full radius works, however. Further, the experimental minijet rate is not quite reproduced (at least not with EHLQ set 1 structure functions and Λ = 0.2 GeV). This can be corrected by introducing the approximate K factor found in [12], i.e. by evaluating α_S at the hard interaction at the reduced scale $\alpha_S(0.075\cdot(p_{T0}^2+p_T^2))$, using the second order expression for α_S. The typical p_{T0} scale needed is then $p_{T0} \approx 2.1$ GeV, i.e. somewhat larger than before.

In the variable impact parameter approach outlined above, each event contains at least one hard or semihard interaction, and there are thus no 'true' low-p_T events that have to be treated specially (e.g. by assuming an infinitely soft gg-interaction). This does not reduce the problem of how to share the energy in a hadron remnant that consists e.g. of a quark and a diquark. It is likely that the position of the single quark is related to the scattered gluon it is (usually) connected to; a simple way of obtaining this is to assume that, as $p_T \to 0$, the scattered partons can effectively be taken to correspond to

valence quarks (suppressing the ordinary flavour assignment by a factor $p_T^4/(p_{T0}^2+p_T^2)^2$).

The question of string drawing, nontrivial already when an event contains only one hard scattering, becomes even more ambiguous when several interactions are allowed. A few possibilities have been tried, with rather similar results in most respects. The scheme actually used in PYTHIA consists of an even mixture of three of these recipes, and as such gives a reasonable compromise. Thus one third of secondary interactions (i.e. excluding the hardest one, which is treated as described in subsection 2.2) is assumed to consist of gluon-gluon scatterings with the gluons in a colour singlet, one third of quark-antiquark scatterings with the $q\bar{q}$ in a colour singlet, and one third of gluon-gluon scatterings where the scattered gluons are connected onto the already existing string regions that are 'closest'.

In summary, although quite some work has gone into the study of beam jet structure, there is no doubt that this is the least well understood aspect of the program. Further studies are therefore certainly warranted. From a phenomenological point of view, however, the multiple interaction picture with varying impact parameters seems to be not too bad an approach.

5. Fragmentation

The task of PYTHIA is to describe the partonic processes taking place in hadronic collisions. How these partons are transformed into the experimentally measurable particles, i.e. the process of fragmentation, is beyond its scope, at least in principle. With the information provided, PYTHIA could be combined with any well-defined fragmentation scheme. Of course, the most natural choice is to use the Lund Monte Carlo for jet fragmentation, JETSET version 6.3 [1], for which all the necessary interfaces are incorporated into PYTHIA.

Although independent fragmentation is included as an option, the standard fragmentation scheme of JETSET is the Lund string model [49]. This model takes as its starting point the belief that QCD is linearly confining at large distances. The simplest Lorentz covariant and causal implementation of a linear potential is provided by the massless relativistic string. The mathematical string has no transverse extent, but the physical interpretation should rather be that the string coordinates parametrize the position of the axis of a cylindrically symmetric colour flux tube. The true nature of this

tube need not be specified, but order-of-magnitude estimates give a flux tube radius of typical hadronic dimensions.

The endpoints of the string are associated with quarks and antiquarks, diquarks and antidiquarks. As a q (or $\bar{q}\bar{q}$) and a $\bar{q}$ (or qq) move apart, the potential energy stored in the intermediate string increases. The string may then break by the production of a new $q'\bar{q}'$ pair, so that the system splits into two colour singlet subsystems $q\bar{q}'$ and $q'\bar{q}$. If the invariant mass in either of these systems is large enough, further breaks may occur, and so on until only ordinary hadrons remain. Each of these hadrons is formed by the quark from one break and the antiquark from an adjacent break. Included is the production of pseudoscalar and vector mesons, and spin 1/2 and spin 3/2 baryons, most of which are unstable and decay further. The string breaking mechanism is understood as a tunnelling phenomenon, automatically providing a suppression of heavy flavour production and a Gaussian transverse momentum spectrum for primary hadrons.

The various $q'\bar{q}'$ breaks have a spacelike separation, i.e. they are causally disconnected. This spacelike separation implies that the time ordering of the breakup vertices is Lorentz frame dependent and hence irrelevant. It is therefore convenient to introduce an iterative procedure, in which the production closest to the ends is considered first, then the next closest ones, etc. The fraction z of remaining $E + p_L$ taken by a hadron is given by the symmetric Lund fragmentation function

$$f(z) = \frac{1}{z}(1-z)^a \exp\{-\frac{b\, m_T^2}{z}\}, \tag{16}$$

where m_T is the transverse mass of the hadron and a and b are two parameters. In particular, this form implies that the heavier a hadron is, the larger an $E + p_L$ fraction will it take.

In the string model, gluons correspond to energy and momentum carrying kinks on the string spanned between a q and a $\bar{q}$ end. For a $q\bar{q}g$ system, e.g., the string is stretched from the quark via the gluon to the antiquark. Whereas a quark or antiquark thus has one string piece attached to it, a gluon has two, corresponding to the double colour charge of a gluon. In e^+e^- annihilation, the string and the independent fragmentation pictures predict rather different event structures, in particular for low-momentum particles. Evidence supporting the string picture was first observed by JADE, and has since been confirmed by several other groups [9]. Similar differences are predicted for

hadron physics, but are much more difficult to study experimentally, and no conclusive evidence exists. When a string system contains many gluons, the resulting string motion may become rather complicated. This entails special problems, that are discussed and solved in [50].

It should be noted that the free parameters of the fragmentation model have been determined entirely from e^+e^- data. Comparisons with hadron physics will therefore offer immediate tests of jet universality. In the string approach, this not only applies to high-p_T jets but also to beam jets. The structure of beam jets can therefore be adjusted only by modifying the non-fragmentation components, like the details of multiple interactions.

6. The Program Components

It is useful to distinguish three phases in a normal run with PYTHIA. In the first phase, the initialization, the general character of the run is determined. At a minimum, this requires a specification of the incoming hadrons and the energies involved. At the discretion of the user, it is also possible to select specific final states, and to make a number of decisions about details in the subsequent generation. This step is finished by a PYINIT call, at which time several variables are initialized in accordance with the values set. The second phase consists of the main loop over the number of events, with each new event being generated by a PYTHIA call. This event may then be analyzed using information stored in some common blocks, and the statistics accumulated. In the final phase, results are to be presented. This may often be done without the invocation of any PYTHIA routines. From PYSTAT, however, it is possible to obtain a useful list of cross-sections for the different subprocesses.

In the presentation in this section, the ordering above is not strictly adhered to. Rather, the material is grouped roughly in falling sequence of how essential information is for an efficient use of PYTHIA. In subsection 6.1 the subroutines to be called by the user are introduced, particularly PYINIT, PYTHIA and PYSTAT. The information available on each new event is covered in 6.2 and 6.3, in the former the general type of process (introducing the important ISUB code) and some kinematical variables, in the latter the detailed list of all particles generated. The following two subsections, 6.4 and 6.5, deal with variables that can be set in the initialization phase (before the PYINIT call), if the default values should not be desirable. In

6.4 is collected the switches for the type of process to generate. Subsection 6.5 is a long one, covering all the switches and parameters which regulate the details of the generation, such as choice of structure functions and Q^2 scale, on/off switches for parton showers and fragmentation, etc. Contained here are also some futher variables with information about the events generated. In subsection 6.6 the further subroutines, functions and common blocks in PYTHIA 4.8 are listed, with brief information about their purpose. The fragmentation routines of JETSET 6.3 are amply described elsewhere [1], but in subsection 6.7 a brief reminder is given, with special emphasis on aspects of relevance when running PYTHIA. Finally, subsection 6.8 contains a note on how cross-section calculations are handled by the program and should be interpreted by the user.

6.1. The Main Subroutines

There are two routines that users must know: PYINIT for initialization and PYTHIA for the subsequent generation of each new event. In addition, the cross-section information available with PYSTAT is frequently useful. The two other routines described here, PYFRAM and PYKCUT, are of more specialized interest.

SUBROUTINE PYINIT(FRAME,BEAM,TARGET,WIN,QTMIN)

Purpose: to initialize the generation procedure.

Note: capital letters are used for the character arguments below; this may make a difference on some machines.

FRAME : a character variable used to specify the frame of the experiment.

= 'FIXT' : fixed target experiment, with beam particle momentum pointing in +z direction.

= 'CMS' : colliding beam experiment in CM frame, with beam momentum in +z direction and target momentum in -z direction.

= 'USER' : full freedom to specify frame by giving beam momentum in P(1,1), P(1,2) and P(1,3) and target momentum in P(2,1), P(2,2) and P(2,3) in common block LUJETS.

BEAM, TARGET : character variables to specify beam and target particles.

= 'P' : proton.

= 'PBAR' : antiproton.

= 'N' : neutron.

= 'NBAR' : antineutron.

= 'PI+' : positive pion.

= 'PI-' : negative pion.

WIN : related to energy of system, exact meaning depends on FRAME.

FRAME='FIXT' : momentum of beam particle (in GeV/c).

FRAME='CMS' : total energy of system (in GeV).

FRAME='USER' : dummy.

QTMIN : minimum transverse momentum of the central hard parton-parton scattering. Because of initial and final state radiation and mass effects, the actual q_T-distribution of jets will not cut off sharply at QTMIN. With the default value ISELEC=1, QCD 2 → 2 processes are included; if QTMIN is below PYPAR(32) (≈1.6 GeV/c) additionally low-p_T events are generated to fill out the inelastic, nondiffractive cross-section. For ISELEC=2, QTMIN is a dummy argument.

SUBROUTINE PYTHIA

Purpose: to generate one event of the type specified by the PYINIT call. (This is the main routine, which calls a number of other routines for specific tasks.)

SUBROUTINE PYSTAT(ISTAT)

Purpose: to print out statistics on cross-sections, decay widths, branching ratios, status codes and parameter values. PYSTAT may be called at any time, e.g. at the end of the run, or not at all.

ISTAT : specification of statistics desired.

= 0 : prints a table of how many events of the different kinds that have been generated and the corresponding cross-sections. All numbers already include the effects of cuts required by the user in PYKCUT.

= 1 : prints a table of the decay channels for the resonances with partial decay widths, branching ratios and effective branching ratios (in the event some channels have been excluded by the user) for each.

= 2 : prints a table with all the values of the status codes IPY(..) and the parameters PYPAR(..) used in the current run.

SUBROUTINE PYFRAM(IFRAME)

Purpose: to transform event between different frames, if so desired.

IFRAME : specification of frame the event is to be boosted to.

= 1 : frame specified by user in the PYINIT call.

= 2 : CM frame of incoming particles.

SUBROUTINE PYKCUT(X1,X2,SH,TH,QT,Q2,ICUT)

Purpose: to enable a user to reject a given set of kinematic variables at an

early stage of the generation procedure, so as not to spend unnecessary time on the generation of events that are not wanted. This routine is called (indirectly) from PYTHIA, once for each new kinematical configuration generated. The routine will not be called if low-p_T events are to be generated as well. A dummy routine PYKCUT is included in the program file. When several copies of the same routine are linked, on most machines it is the first that is actually used, so remember to link the user-written PYKCUT before the PYTHIA file.

X1,X2 : x-values for the two incoming partons at the hard scattering.

SH : invariant mass-square $\hat{s}$ of incoming partons.

TH : momentum transfer $\hat{t}$ of hard scattering.

QT : transverse momentum q_T of the two outgoing partons in frame where incoming partons are back-to-back.

Q2 : Q^2 scale of hard interaction, as used e.g. for α_S.

ICUT : flag set by user to signal effect of user-defined cuts.

= 0 : event is to be retained and generated in full.

= 1 : event is to be rejected and a new one generated.

6.2. General Event Information

The common block PYPROC contains some overall information about the event that was generated in the latest PYTHIA call, and additionally some cross-section information. Of particular interest is the ISUB code, where each type of subprocess has been assigned an integer between 1 and 40. The ISUB variable itself is used to specify which subprocess took place in the latest event, but the same code is used in a host of other connections: for the subprocess cross-sections in XSEC, for the on/off switches for different subprocesses in ISUBPR (see subsection 6.4), etc.

COMMON/PYPROC/ISUB,KFL(3,2),X(2),SH,TH,UH,Q2,XSEC(0:40)

Purpose: to provide user with event information on parton level.

ISUB : specifies the general type of subprocess that has occured, with notation as follows (with the symbol Z^0/γ^* it is understood that interference terms between Z^0 and the virtual photon are also properly included; the corresponding is true for the symbol $Z'^0/Z^0/\gamma^*$):

= 1 : $q + q' \to q + q'$.

= 2 : $q + \bar{q} \to q' + \bar{q}'$.

= 3 : $q + \bar{q} \to g + g$.

= 4 : $q + g \to q + g$.

= 5 : $g + g \to q + \bar{q}$.

= 6 : $g + g \to g + g$.

= 7 : low-p_T scattering.

= 8 : double diffractive scattering.

= 9 : single diffractive scattering.

= 10 : elastic scattering.

= 11 : $q + \bar{q} \to Z^0/\gamma^*$ ($\to q + \bar{q}$, $l^- + l^+$, $\nu + \bar{\nu}$, $H^+ + H^-$).

= 12 : $q + qb' \to W^\pm$ ($\to q + \bar{q}'$, $l^\pm + \nu$).

= 13 : $g + q \to \gamma + q$.

= 14 : $g + q \to Z^0 + q$.

= 15 : $g + q \to W^\pm + q'$.

= 16 : $q + \bar{q} \to g + \gamma$.

= 17 : $q + \bar{q} \to g + Z^0$.

= 18 : $q + \bar{q}' \to g + W^\pm$.

= 19 : $q + \bar{q} \to \gamma + \gamma$.

= 20 : $q + \bar{q} \to \gamma + Z^0$.

= 21 : $q + \bar{q}' \to \gamma + W^\pm$.

= 22 : $q + \bar{q} \to Z^0 + Z^0$.

= 23 : $q + \bar{q}' \to Z^0 + W^\pm$.

= 24 : $q + \bar{q} \to W^+ + W^-$.

= 25 : $q + \bar{q} \to H^0$ ($\to q + \bar{q}$, $l^- + l^+$, $W^+ + W^-$, $Z^0 + Z^0$).

= 26 : $g + g \to H^0$.

= 27 : $[q + q' \to q + q' +]$ $Z^0 + Z^0 \to [q + q' +]$ H^0.

= 28 : $[q + q' \to q'' + q''' +]$ $W^+ + W^- \to [q'' + q''' +]$ H^0.

= 29 : $q + \bar{q} \to H^0 + Z^0$.

= 30 : $q + \bar{q}' \to H^0 + W^\pm$.

= 31 : $q + \bar{q}' \to R$ ($\to q + \bar{q}'$, $l^- + l'^+$).

= 32 : $q + \bar{q}' \to H^\pm$ ($\to q + \bar{q}'$, $l^\pm + \nu$).

= 33 : $q + \bar{q} \to Z'^0/Z^0/\gamma^*$ ($\to q + \bar{q}$, $l^- + l^+$, $\nu + \bar{\nu}$).

= 34 - 40 : not used.

KFL: gives flavour of partons/leptons/gauge bosons participating in event using the KF flavour codes (see subsection 6.3).

KFL(1,j) : original partons before initial state parton shower; j=1 for beam side, j=2 for target side.

KFL(2,j) : incoming partons to hard scattering; j=1 for beam side, j=2 for target side.

KFL(3,j) : outgoing partons/leptons/gauge bosons from hard scattering; j=1, j=2 arbitrary.

X : gives the momentum fractions taken by the partons at the hard scattering, as used e.g. in structure functions, with X(1) for beam side parton and

X(2) for target side parton.

SH : $\hat{s}$, invariant mass-square of reacting subsystem at hard scattering.

TH : $\hat{t}$, momentum transfer of hard scattering.

UH : $\hat{u}$, remaining Mandelstam variable, related to $\hat{s}$ and $\hat{t}$ via the equality $\hat{s} + \hat{t} + \hat{u} = \Sigma\, m^2$.

Q2 : the Q^2-scale used for the hard scattering, cf. IPY(4).

XSEC : calculated cross-sections within given cuts in mb, based on all events up till the last generated one.

XSEC(0) : estimate for total cross-section.

XSEC(1) - XSEC(40) : estimate for the various subprocesses (ordering as for ISUB above).

6.3. The Event Record

When an event is generated by a PYTHIA call, it is stored in the common block LUJETS. Here each parton and particle is represented by one line of information, giving a history pointer, parton/particle code, momentum, energy and mass. The LUJETS common block is used extensively both by the PYTHIA and the JETSET routines; indeed it provides the bridge that allows the general utility routines in JETSET to be used also for PYTHIA events. A detailed description of LUJETS is found in [1]. The PYTHIA event listing begins (optionally) with a few lines of event summary, specific to the hard process simulated and therefore not described in [1]. Further, some extensions to the particle code have been introduced. Therefore we here give a brief summary on the general structure of the LUJETS common block, followed by details specific to PYTHIA.

COMMON/LUJETS/N,K(2000,2),P(2000,5)

N : number of lines used in the K and P matrices for the current event.

K(I,1) : contains status and history information about the entry in the I:th line, in the form K(I,1) = 10000·KS + KH.

KH = MOD(K(I,1),10000): gives the line number for the 'parent' in fragmentation and decay chains (note that this is not always well defined, in particular not for string fragmentation).

KS = K(I,1)/10000 = 0, 1 : an entry that has not decayed or fragmented.

KS = 2, 3 : an entry that has decayed or fragmented.

KS = 4 : an event summary line in beginning of event listing.

KS ⩾ 5 : line with extra information, e.g. on colour flow.

K(I,2) : KF flavour code for partons and particles. Complete list contains

hundreds of codes, some of the most frequently used ones are

1	γ	17	π^+	37	K^0_S	500	g
2	Z^0	18	K^+	38	K^0_L	501	u
3	W^+	19	K^0			502	d
4	H^0	20	D^0	41	p	503	s
5	Z^0/γ^*	21	D^+	42	n	504	c
		23	π^0	57	Λ	505	b
7	e^-	24	η			506	t
8	ν_e	25	η'	91	R	507	l
9	μ^-	27	ρ^+	92	H^+	508	h
10	ν_μ	28	K^{*+}	93	Z'^0		
11	τ^-	29	K^{*0}			511	uu_1
12	ν_τ	33	ρ^0			512	ud_0
13	χ^-	34	ω			521	ud_1
14	ν_χ	35	ϕ			522	dd_1

A negative KF code, where existing, always corresponds to the antiparticle of the one listed above. Codes 13, 14, 507 and 508 give the leptons and quarks of a possible fourth generation, and 4 denotes a neutral Higgs H^0. Codes 91, 92 and 93 are used for an assumed horizontal gauge boson R, the charged Higgs $H^\pm$, and the new electroweak gauge boson Z'^0 predicted e.g. in superstring theories. Codes 39 and 40 are defined by PYTHIA at initialization to signify excited (diffractive) states of the beam and target particles. In an event listing, these states will be denoted PI*, P* or N*.

The IFL code, which is sometimes used in other connections, is a related code that only covers gluons, quarks and diquarks. It can be obtained by a subtraction of 500 from the KF codes above (-500 for negative KF values), so that 0 = g, 1 = u, -1 = $\bar{u}$, etc.

P(I,1) : p_x, momentum in the x direction (in GeV/c).

P(I,2) : p_y, momentum in the y direction (in GeV/c).

P(I,3) : p_z, momentum in the z direction (in GeV/c).

P(I,4) : E, energy (in GeV).

P(I,5) : m, mass (in GeV/c^2).

In most instances, only the actual partons and particles produced are of interest. For IPY(34)=0, the event record starts off with the parton configuration existing after hard interaction, initial and final state radiation, multiple interactions and beam remnants have been considered. The partons are arranged in colour singlet clusters, ordered as required for string fragmentation. Also photons and leptons produced as part of the hard interaction (e.g. from $q + \bar{q} \to g + \gamma$ or $u + \bar{u} \to Z^0 \to e^+ + e^-$) appear in this part of the event record. These original entries appear with history pointer KH = 0, whereas the products of the subsequent fragmentation and decay have KH numbers pointing back to the line of the parent (however, note warning in K(I,1) description).

The standard documentation, obtained with IPY(34)=1, includes a few lines in the beginning of the event record, which contain a brief summary of the process that has taken place. The number of lines used depends on the nature of the hard process, and is stored in IPY(40) for the current event. These lines all have $40000 \leq K(I,1) < 50000$. For all processes, lines 1 and 2 give the two incoming hadrons. For diffractive and elastic events, the two outgoing states in lines 3 and 4 completes the list. Otherwise, lines 3 and 4 contain the two partons that initiate the two initial state parton showers, and 5 and 6 the endproducts of these showers, i.e. the partons that enter the hard interaction. With initial state radiation switched off, lines 3 and 5 and lines 4 and 6 coincide. For a simple $2 \to 2$ hard scattering, lines 7 and 8 give the two outgoing partons/particles from the hard interaction, before any final state radiation. For $2 \to 2$ processes proceeding via an intermediate resonance such as Z^0/γ^*, $W^\pm$, H^0 or R, the resonance is found in 7 and the two outgoing partons/particles in 8 and 9. In some cases one or both of these may be a resonance in its own right, so that further pairs of lines are added for subsequent decays. If the decay of a given resonance has been switched off, then no decay products are listed either in this initial summary or in the subsequent ordinary listing. Whenever partons are listed, they are assumed on mass shell for simplicity. The fact that effective masses may be generated by initial and final state radiation is taken into account in the actual parton configuration that is allowed to fragment, however. A special case is provided by W^+W^- or Z^0Z^0 fusion to a H^0. Then the virtual W:s or Z:s are shown in lines 7 and 8, the H^0 in line 9 and the two recoiling quarks (that emitted the bosons) in 10 and 11, followed by the Higgs decay products. Since the W:s and Z:s are spacelike, what is actually listed as the mass for them is $-(-m^2)^{1/2}$.

A few examples may help clarify the picture. For a single diffractive event $p + \bar{p} \to p^* + \bar{p}$, the event record will start with

I	K(I,1)	K(I,2)	comment
1	40000	41	incoming p
2	40000	-41	incoming $\bar{p}$
3	40001	39	outgoing p^*
4	40002	-41	outgoing $\bar{p}$

The typical QCD $2 \to 2$ process would be

I	K(I,1)	K(I,2)	comment
1	40000	41	incoming p
2	40000	-41	incoming $\bar{p}$
3	40001	501	u picked from incoming p
4	40002	-502	$\bar{d}$ picked from incoming $\bar{p}$
5	40003	500	u evolved to g at hard scattering
6	40004	-502	still $\bar{d}$ at hard scattering
7	40000	500	outgoing g from hard scattering
8	40000	-502	outgoing $\bar{d}$ from hard scattering

Note that, where well defined, the KH code does contain information on which side the different partons come from, e.g. above the gluon in line 5 points back to the u in line 3, which points back to the proton in line 1. In the example above it would have been possible to associate the scattered g in line 7 with the incoming one in line 5, but this is not possible in the general case, consider e.g. $g + g \to g + g$. As a final example, WW fusion to a H^0 might look like

I	K(I,1)	K(I,2)	comment
1	40000	41	first incoming p
2	40000	41	second incoming p
3	40001	501	u picked from first p
4	40002	500	g picked from second p
5	40003	501	still u after initial state radiation
6	40004	-504	g evolved to $\bar{c}$
7	40005	3	spacelike W^+ emitted by u quark
8	40006	-3	spacelike W^- emitted by $\bar{c}$ quark
9	40000	4	Higgs produced by W^+W^- fusion
10	40005	502	u turned into d by emission of W^+
11	40006	-503	$\bar{c}$ turned into $\bar{s}$ by emission of W^-
12	40009	2	first Z^0 coming from decay of H^0
13	40009	2	second Z^0 coming from decay of H^0
14	40012	8	ν_e from first Z^0 decay

15	40012	-8	$\bar{\nu}_e$ from first Z^0 decay
16	40013	505	b quark from second Z^0 decay
17	40013	-505	$\bar{b}$ quark from second Z^0 decay

After these lines with initial information, the event record looks the same as for IPY(34)=0, i.e. first comes the parton configuration that is to be fragmented and afterwards the products of subsequent fragmentation and decay chains. The history pointers for the partons, as well as leptons and photons produced in the hard interaction, are now pointing towards the documentation lines above, however. In particular, beam remnants have KH equal to 1 or 2, depending on which side they belong to, and partons emitted in the initial state parton showers point to 3 or 4. In the second example above, the partons produced by final state radiation will be pointing back to 7 and 8; as usual, it should be remembered that a specific assignment to 7 or 8 need not be unique. For the third example, final state radiation partons will come both from partons 10 and 11 and from partons 16 and 17, and additionally there will be a neutrino-antineutrino pair pointing to 14 and 15. The extra pairs of partons that are generated by multiple interactions do not point back to anything, i.e. they have KH = 0.

There exists a third documentation option, IPY(34)=2. Here the complete history of initial and final state parton branchings may be traced, including all details on colour flow. This information has not been optimized for user-friendliness, and can not be recommended for general usage. With this option, the initial documentation lines are the same. They are followed by blank lines, K(I,1) = 80000, up to line 20. From 21 and onwards each parton is associated with two lines, the first giving flavour and momentum as usual, the second (with 70000 ≤ K(I,1) < 80000) giving colour flow information. Thus for the parton in line I, P(I+1,1) and P(I+1,2) point to the partons from which the colour and anticolour come, and P(I+1,3) and P(I+1,4) to where the colour and anticolour go. For an ordinary 2 → 2 scattering, the two incoming partons at the hard scattering are stored in 21 and 23, and the two outgoing in 25 and 27. The colour flow between these partons have to be chosen according to the proper relative probabilities in cases when many alternatives are possible, see [2]. If there is initial state radiation, the two partons in line 21 and 23 are copied down to line 29 and 31, from which the initial state showers are reconstructed backwards step by step. The branching history may be read by noting that, for a branching a → b + c, the KH codes of b and c point towards the line number of a. Since the showers are reconstructed backwards, this actually means that parton b would appear in the listing before parton a and

c, and hence have a pointer to a position below itself in the list. Associated timelike partons c may initiate timelike showers, as may the partons of the hard scattering. Again a showering parton or pair of partons will be copied down towards the end of the list and allowed to undergo successive branchings c → d + e, with d and e pointing towards c. The mass of timelike partons is properly stored in P(I,5), for spacelike partons instead $-(-m^2)^{1/2}$ is stored. After this section containing all the branchings comes the final parton configuration, followed by all subsequent fragmentation and decay products, as usual.

6.4. Switches for Event Type Selection

By default, only QCD processes are generated by PYTHIA. For large QTMIN values in PYINIT this means hard 2 → 2 partonic processes; for small QTMIN this is mixed with low-p_T events to give the QCD 'minimum bias' event sample. With the help of the common block PYSUBS, it is possible to select for the generation of another process, or a combination of processes. It is also possible to restrict the generation to specific incoming partons or produced particles in the hard interaction.

COMMON/PYSUBS/ISELEC,ISUBPR(40),IREAC(2,-6:6),IPROD(0:10,30)

Purpose: to allow the user to run the program with any desired subset of processes. If the default values, below denoted by (D=...), are not satisfactory, they must be changed before the PYINIT call.

ISELEC : (D=1) a switch to select between full user control and some preprogrammed alternatives.

- = 0 : desired subprocesses have to be switched on in ISUBPR.
- = 1 : QCD high-p_T processes (ISUB = 1-6) switched on; additionally low-p_T if QTMIN of PYINIT call is below PYPAR(32).
- = 2 : all QCD processes, including low-p_T, single and double diffractive and elastic scattering, are included (ISUB = 1-10).
- = 3 : prompt photons (ISUB = 13,16,19).
- = 4 : Z^0/γ^* production (ISUB = 11).
- = 5 : $W^\pm$ production (ISUB = 12).
- = 6 : Z^0 + jet production (ISUB = 14,17).
- = 7 : $W^\pm$ + jet production (ISUB = 15,18).
- = 8 : pair production of different combinations of γ, Z^0 and $W^\pm$ (except $\gamma + \gamma$; see ISELEC = 3) (ISUB = 20-24).

= 9 : H^0 production (ISUB = 25-28).
= 10 : $H^0 + Z^0$ or $W^\pm$ (ISUB = 29-30).

ISUBPR : (D=40*0) array to be set when ISELEC=0 (for ISELEC≥1 relevant entries are set in PYINIT) to choose which subset of subprocesses to include in the generation. The ordering follows the ISUB code in subsection 6.2, with ISUBPR(ISUB) = 0 corresponding to the subprocess being excluded, and = 1 to it being included.

Note 1: The subprocess 7, low-p_T events, is somewhat unique, in that no meaningful physical borderline to high-p_T events can be defined. Even if subprocesses 1-6 are formally switched off, some of the events generated will be classified as belonging to this group, with a p_T spectrum of interactions to match the "minimum bias" event sample. Only with the option IPY(12)=-1 will subprocess 7 yield strictly low-p_T events, events which will then probably not be compatible with any experimental event sample.

Note 2: The subprocesses 14, 15, 17 and 18, with a $Z^0/W^\pm$ recoiling against a q/g jet, are also effectively generated by initial state radiation corrections to the subprocesses 11 and 12, which cover the production of a single $\gamma^*/Z^0/W^\pm$. In order to avoid double-counting, these processes should therefore not be switched on at the same time. The basic rule is to use 11 and 12 for the inclusive generation of $Z^0/W^\pm$, and 14, 15, 17 and 18 for the study of the $Z^0/W^\pm$ subsample with high transverse momentum.

Note 3: The introduction of the Z'^0 with full interference structure has caused some redundancy, in the sense that e.g. the process $q + \bar{q} \to Z^0/\gamma^*$ can be run either as subprocess 11 with full interference (IPY(11)=3) or as subprocess 33 including only the Z^0/γ^* part of the matrix element (IPY(39)=4). The only difference between the two options is that when run through subprocess 11, Z^0 can be set to decay also to the charged Higgs, $H^\pm$.

IREAC : (D=26*1) provides an option selectively to switch on and off contributions to the cross-sections from the different flavours in the beam and target particles. First index is 1 for beam and 2 for target; second index enumerates the flavour content, with 0 = g, 1 = u, -1 = $\bar{u}$, etc., according to standard IFL code (subsection 6.3). A value = 1 means that the corresponding flavour is allowed, whereas a value = 0 means that it is forbidden.

Note: As with ISUBPR above, special conceptual problems are encountered with subprocess 7 if the incoming flavours are unduly restricted. This

freedom should therefore never be used when low-p_T events are to be generated.

IPROD : array that can be set to regulate the production of new quark, lepton and gauge boson flavours in annihilation graphs. The first index corresponds to the annihilation process, the second to the flavour produced. The exception is IPROD(0,J), which is used to regulate the recoil quark flavours q' allowed in the reaction $q + g \to q' + W^\pm$ and the recoil quark flavours q'', q''' allowed in the reaction $[q + q' \to q'' + q''' +]\ W^+ + W^- \to [q'' + q''' +]\ H^0$. If IPROD(I,J) = 1 production of the corresponding flavour is allowed, if IPROD(I,J) = 0 it is forbidden. A value IPROD(I,J) = -1 means that the corresponding channel does not exist (these flavours can never be accessed by the user, since the program automatically sets the corresponding IPROD values to -1 at initialization). The default values are chosen such that all existing channels are allowed, with the exception of $Z^0 \to H^+ + H^-$ (since the charged Higgs is a non-standard model particle). At initialization, the program also automatically switches off flavours incompatible with maximum number of generations (see IPY(9)). The code is as follows:

I = 0 : REC (recoiling quark in the reactions $q + g \to q' + W^\pm$ and $[q + q' \to q'' + q''' +]\ W^+ + W^- \to [q'' + q''' +]\ H^0$).
I = 1 : QCD ($q + \bar{q} \to q' + \bar{q}'$; $g + g \to q + \bar{q}$).
I = 2 : Z^0/γ^* ($Z^0/\gamma^* \to q + \bar{q}$, $l^- + l^+$, $\nu + \bar{\nu}$, $H^+ + H^-$).
I = 3 : $W^\pm$ ($W^\pm \to q + \bar{q}'$, $l^\pm + \nu$).
I = 4 : H^0 ($H^0 \to q + \bar{q}$, $l^- + l^+$, $W^+ + W^-$, $Z^0 + Z^0$).
I = 5 : R (R → q + $\bar{q}'$, $l^- + l'^+$).
I = 6 : $H^\pm$ ($H^\pm \to q + \bar{q}'$, $l^\pm + \nu$).
I = 7 : $Z'^0/Z^0/\gamma^*$ ($Z'^0/Z^0/\gamma^* \to q + \bar{q}$, $l^- + l^+$, $\nu + \bar{\nu}$).
I = 8-10 : not used (but reserved for other non-standard resonances ut supra).
J = 1 : u.
J = 2 : d.
J = 3 : s.
J = 4 : c.
J = 5 : b.
J = 6 : t.
J = 7 : l (4th generation d-quark).
J = 8 : h (4th generation u-quark).
J = 9-10 : not used.
J = 11 : e^-.

J = 12 : ν_e.
J = 13 : μ^-.
J = 14 : ν_μ.
J = 15 : τ^-.
J = 16 : ν_τ.
J = 17 : χ^- (4th generation charged lepton).
J = 18 : ν_χ (4th generation neutrino).
J = 19-20 : not used.
J = 21 : Z^0.
J = 22 : $W^\pm$.
J = 23 : $H^\pm$.
J = 24-30 : not used.

6.5. The General Switches and Parameters

The commonblock PYPARA contains the status codes and parameters which regulate the performance of the program. All of them are provided with sensible default values, so that a novice user can neglect them, and only gradually explore the full range of possibilities. Some further event specific information is also stored here.

COMMON/PYPARA/IPY(80),PYPAR(80),PYVAR(80)

Purpose: to give access to status codes and parameters which regulate the performance of the program. If the default values, below denoted by (D=...), are not satisfactory, they must in general be changed before the PYINIT call. Exceptions, i.e. variables which can be changed for each new event, are denoted by (C). While PYPAR contains input variables to the program and PYVAR variables calculated in the course of program execution, IPY contains a mixture of the two; the input variables are the ones for which default values are quoted below.

IPY(1) : (D=0) calculation of differential cross-section maxima for subprocesses included (by user or default).
= 0 : not known, to be calculated at initialization.
= 1 : known, stored by user in XMAX-array in common block PYCROS before initialization.

IPY(2) : (D=0) switch to generate events with weights; used to increase the number of events with a high q_T (defined for the hard scattering) at the expense of giving the events smaller weights at higher q_T. This switch can

only be used for QCD high-p_T processes, and is automatically set to 0 if any other subprocess is included.
= 0 : all events have weight 1, i.e. the user need not bother about weights.
= 1 : events have an associated weight $(q_{Tmin}/q_T)^2$, stored in PYVAR(21), meaning that the relative probability to have an event at q_T has been increased by a factor q_T^2.
= 2 : events have an associated weight $(q_{Tmin}/q_T)^4$, stored in PYVAR(21), meaning that the relative probability to have an event at q_T has been increased by a factor q_T^4.
= 3 : events have an associated weight $(q_{Tmin}/q_T)^6$, stored in PYVAR(21), meaning that the relative probability to have an event at q_T has been increased by a factor q_T^6.

IPY(3) : (D=2) calculation of α_S.
= 0 : fixed α_S given by PYPAR(3). Values for initial (see PYPAR(21)) and final state radiation (see PARE(21) in common block LUDATE in JETSET) are chosen separately.
= 1 : first order running α_S for hard scattering, with Λ given by PYPAR(4). Initial and final state radiation as for IPY(3) = 0.
= 2 : Λ value is chosen according to the structure function parametrizations, i.e. Λ = 0.2 GeV for EHLQ set 1 (IPY(7) = 1, 11 or -11), Λ = 0.29 GeV for EHLQ set 2 (IPY(7) = 2, 12 or -12), Λ = 0.2 GeV for Duke-Owens set 1 (IPY(7) = 3, 13 or -13), Λ = 0.4 GeV for Duke-Owens set 2 (IPY(7) = 4, 14 or -14), Λ = 0.4 GeV for Glück-Hoffman-Reya (IPY(7) = 5), and Λ = PYPAR(4) for user-defined structure functions (IPY(7) = 10 or -10), respectively. This Λ value is used both for the hard scattering and the initial and final state radiation. The ambiguity in the choice of Q^2 argument still remains (see IPY(4), PYPAR(27), and MSTE(14) in common block LUDATE in JETSET). For IPY(7) = 0, an artificial value Λ = PYPAR(4) is used; actually, the sensible choice for the scaling structure functions would be to use IPY(3) = 0 and have no initial or final state radiation.
= 11 : like =1, but at the hard interaction a second order α_S is evaluated at the scale PYPAR(9)$\cdot Q^2$ rather than Q^2, in order to simulate an effective K-factor.
= 12 : like =2, but at the hard interaction a second order α_S is evaluated at the scale PYPAR(9)$\cdot Q^2$ rather than Q^2, in order to simulate an effective K-factor.

IPY(4) : (D=2) Q^2-definition in hard scattering for 2 $\rightarrow$ 2 processes; for

resonance production Q^2 is always chosen to be m_{res}^2, where m_{res} is the mass of the resonance.

= 1 : $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2+\hat{t}^2+\hat{u}^2)$.

= 2 : $Q^2 = 0.5\cdot(m_{T1}^2+m_{T2}^2)$.

= 3 : $Q^2 = \min(-\hat{t},-\hat{u})$.

IPY(5) : (D=min(6,2·IPY(9))) maximum number of active flavours in α_S of hard scattering.

IPY(6) : (D=1) parametrization of total and elastic cross-sections, and nuclear slope parameter B [32].

= 1 : Block-Cahn fit 1 for cross-section, fit 1 for slope parameter.

= 2 : Block-Cahn fit 2 for cross-section, fit 1 for slope parameter.

= 3 : Block-Cahn fit 3 for cross-section, fit 1 for slope parameter.

= 4 : Block-Cahn fit 6 for cross-section, fit 2 for slope parameter.

= 5 : Block-Cahn fit 8 for cross-section, fit 2 for slope parameter.

Note: sets 1-3 for cross-section and set 1 for slope parameter are fits excluding recent measurements from $S\bar{p}pS$, whereas sets 4-5 for cross-section and set 2 for slope parameter are fits including the $S\bar{p}pS$ measurements.

IPY(7) : (D=1) choice of structure functions.

= 0 : simple scaling functions.

= 1 : EHLQ set 1 (1986 updated version) for p, Owens set 1 for π.

= 2 : EHLQ set 2 (1986 updated version) for p, Owens set 2 for π.

= 3 : Duke-Owens set 1 for p, Owens set 1 for π.

= 4 : Duke-Owens set 2 for p, Owens set 2 for π.

= 5 : Glück-Hoffman-Reya for p, Owens set 2 for π.

Note: PYTHIA 4.8 also allows the use of proton structure functions from Tung [30]. The initial parton distributions at Q_0 = PYPAR(41) to be used in the evolution calculation are then regulated by IPY(7) ut infra. See also IPY(54), PYPAR(41) - PYPAR(43), COMMON/PYFILE/ and comments in section 7.

$\geq$ 10 : evolution calculation performed, result of calculation written to file FLNM (see common block PYFILE) when IPY(54) = 1.

= 10 : initial parton distribution supplied by user as FINI(IFL,X), where IFL is the normal Lund parton flavour code. Concerning Λ, see IPY(3).

= 11 : EHLQ set 1 used as initial parton distribution.

= 12 : EHLQ set 2 used as initial parton distribution.

= 13 : Duke-Owens set 1 used as initial parton distribution.

= 14 : Duke-Owens set 2 used as initial parton distribution.

$\leq$ -10 : evolution calculation not performed, result assumed to exist on file FLNM (see common block PYFILE).

= -10 : initial parton distribution supplied by user as FINI(IFL,X), where IFL is the normal Lund parton flavour code.

= -11 : EHLQ set 1 used as initial parton distribution.

= -12 : EHLQ set 2 used as initial parton distribution.

= -13 : Duke-Owens set 1 used as initial parton distribution.

= -14 : Duke-Owens set 2 used as initial parton distribution.

IPY(8) : (D=min(6,2·IPY(9))) maximum number of quark flavours in structure functions, and thus also for initial state spacelike showers.

IPY(9) : (D=3) maximum number of generations. Automatically set $\leq$ 4.

IPY(10) : (D=1) use of interference term in matrix elements for QCD processes.

= 1 : excluded (i.e. string-inspired matrix elements).

= 2 : included (i.e. conventional QCD matrix elements).

IPY(11) : (D=3) treatment of Z^0/γ^* interference in matrix elements.

= 1 : only γ^* included.

= 2 : only Z^0 included.

= 3 : complete Z^0/γ^* structure (with interference) included.

IPY(12) : (D=1) structure of multiple interactions.

= 0 : only one interaction per event.

= 1 : multiple interactions assuming the same probability in all events, with an abrupt p_{Tmin} cutoff at PYPAR(32).

= 2 : multiple interactions assuming the same probability in all events, with a continuous turnoff of the cross-section at p_{T0} = PYPAR(32).

= 3 : multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a Gaussian matter distribution, with a continuous turnoff of the cross-section at p_{T0} = PYPAR(32).

= 4 : multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution given by PYPAR(33) and PYPAR(34), with a continuous turnoff of the cross-section at p_{T0} = PYPAR(32).

= -1 : simple two-string model without any hard interactions.

Note: For IPY(12) $\geq$ 2 and QTMIN (in PYINIT) > PYPAR(32), cross-sections given with PYSTAT(0) (i.e. XSEC in common block PYPROC) may be somewhat too large, since (for reasons of efficiency) the probability factor that the hard interaction is indeed the hardest in the event is not included in the cross-sections. It is included in the event selection, however. For QTMIN a couple of times larger than PYPAR(32) this ceases to be a problem.

IPY(13) : (D=1) (C) final state timelike parton showers.

= 0 : not included.

= 1 : included.

Note: additional switches (e.g. for conventional/coherent showers) are available in common block LUDATE.

IPY(14) : (D=2) (C) details of initial state spacelike parton showers.

= 0 : not included.

= 1 : included with evolution performed in Q^2, i.e. the spacelike parton virtuality is used as argument in evolution parameter t, in α_S and in structure functions (optionally modified by a constant factor, see PYPAR(27)); associated timelike partons put on mass shell.

= 2 : as 1, but associated timelike partons may shower.

= 3 : included with evolution performed in $k_T^2 = (1-z)Q^2$, i.e. k_T^2 is used as argument in t, in α_S and in structure functions (PYPAR(27) may still be used to introduce an extra factor, but normally one would wish to put PYPAR(27)=1. here); the backwards evolution is started from k_{Tmax}^2 = PYPAR(26)$\cdot Q_{hard}^2$, with only kinematical restrictions on allowed $Q^2 = k_T^2/(1-z)$ values; associated timelike partons put on mass shell.

= 4 : as 3, but associated timelike partons may shower.

= 5 : essentially as 3, but for the two "hardest" branchings (the one on each side closest to the hard interaction) it is additionally required that $Q^2 = k_T^2/(1-z) <$ PYPAR(26)$\cdot Q_{hard}^2$; associated timelike partons put on mass shell.

= 6 : as 5, but associated timelike partons may shower.

= 7 : included with hybrid alternative, in which evolution is performed in Q^2, which is used as argument in t and structure functions, whereas α_S is evaluated for $k_T^2 = (1-z)Q^2$ and parton shower cutoff is defined in terms of k_T^2 (PYPAR(27) may still be used to introduce an extra factor, but normally one would wish to put PYPAR(27)=1 here); associated timelike partons put on mass shell.

= 8 : as 7, but associated timelike partons may shower.

= 9 : included with evolution in Q^2 (as in 1) but without allowance for coherence effects, i.e. Q^2 values need not be ordered; associated timelike partons put on mass shell.

= 10 : as 9, but associated timelike partons may shower.

IPY(15) : (D=1) (C) treatment of soft gluon emission in spacelike parton shower evolution.

= 0 : soft gluons are entirely neglected.

= 1 : soft gluon emission is resummed and included together with the hard radiation as an effective z shift.

IPY(16) : (D=1) (C) primordial k_T distribution.

= 0 : no primordial k_T.

= 1 : Gaussian, width given in PYPAR(7).

= 2 : exponential, width given in PYPAR(8).

IPY(17) : (D=4) (C) energy partitioning in hadron remnant. The energy fraction χ taken by one of the two objects, with conventions as described for PYPAR(13) - PYPAR(16), is chosen according to the different distributions below.

= 1 : 1 for meson, $2\cdot(1-\chi)$ for baryon, i.e. simple counting rules.

= 2 : $(k+1)\cdot(1-\chi)^k$, with k as given in PYPAR(13) - PYPAR(16).

= 3 : as 2 for remnant splitting into hadron plus jet, but proportional to $(1-\chi)^k/(\chi^2+c^2)^{1/4}$ for remnant splitting into two jets, with k given by PYPAR(13) or PYPAR(15) and $c = 2\cdot m_q/s^{1/2} = 0.6$ GeV/$s^{1/2}$.

= 4 : as 2 for remnant splitting into hadron plus jet, but proportional to $(1-\chi)^k/(\chi^2+c^2)^{1/2}$ for remnant splitting into two jets, with k given by PYPAR(13) or PYPAR(15) and $c = 2\cdot m_q/s^{1/2} = 0.6$ GeV/$s^{1/2}$.

IPY(18) : (D=1) (C) structure of diffractive system.

= 1 : forward moving diquark + interacting quark.

= 2 : forward moving diquark + quark joined via interacting gluon ('hairpin' configuration).

IPY(19) : (D=1) cuts on partonic events.

= 0 : no cuts (can be used only with independent fragmentation).

= 1 : string cuts (as normally required for fragmentation); in practice this option nowadays affects only an exceedingly tiny fraction of events, at least so long as MST(12)=1.

IPY(20) : (D=1) (C) switch for fragmentation.

= 0 : fragmentation not performed.

= 1 : fragmentation performed.

= -1 : only choose kinematical variables for hard scattering (KFL(2,1), KFL(2,2), X(1), X(2), SH, TH, UH and Q2 in common block PYPROC), i.e. no jets are defined. This is useful e.g. to calculate cross-sections (by Monte Carlo integration) without wanting to simulate events; information in XSEC as printed by PYSTAT will be correct.

IPY(21) : (D=0) (C) mass treatment of final state particles with finite width.

= 0 : particles put on mass-shell.

= 1 : mass generated according to Breit-Wigner.

IPY(22) : (D=1) (C) treatment of Z^0 decay.

= 0 : Z^0 considered stable.

= 1 : Z^0 allowed to decay.

Note: in both the above cases, the cross-section is calculated using the decay channels set in IPROD(2,...).

IPY(23) : (D=1) (C) treatment of $W^\pm$ decay.

= 0 : $W^{\pm}$ considered stable.

= 1 : $W^{\pm}$ allowed to decay.

Note: in both the above cases, the cross-section is calculated using the decay channels set in IPROD(3,...).

IPY(24) : (D=1) (C) treatment of H^0 decay.

= 0 : H^0 considered stable.

= 1 : H^0 allowed to decay.

Note: in both the above cases, the cross-section is calculated using the decay channels set in IPROD(4,...).

IPY(25) : (D=1) (C) treatment of R decay.

= 0 : R considered stable.

= 1 : R allowed to decay.

Note: in both the above cases, the cross-section is calculated using the decay channels set in IPROD(5,...).

IPY(26) : (D=1) (C) treatment of $H^{\pm}$ decay.

= 0 : $H^{\pm}$ considered stable.

= 1 : $H^{\pm}$ allowed to decay.

Note: in both the above cases, the cross-section is calculated using the decay channels set in IPROD(6,...).

IPY(27) : (D=1) (C) treatment of Z'^0 decay.

= 0 : Z'^0 considered stable.

= 1 : Z'^0 allowed to decay.

Note: in both the above cases, the cross-section is calculated using the decay channels set in IPROD(7,...).

IPY(28) - IPY(30) : not used (but reserved for treatment of decays of other non-standard resonances ut supra).

IPY(31) : (D=1) initialization and differential cross-section maximization printout.

= 0 : none.

= 1 : short message.

= 2 : detailed message, including full maximization.

IPY(32) : (D=2) reaction to violation of maximum differential cross-section.

= 0 : stop generation, print message.

= 1 : continue generation, print message for each subsequently larger violation.

= 2 : as 1, but also increase value of maximum.

IPY(33) : (D=1) (C) frame for presentation of event.

= 1 : as specified in PYINIT.

= 2 : CM frame of incoming particles.

IPY(34) : (D=1) (C) documentation of partonic process, see subsection 6.3 for

details.

= 0 : only list ultimate string/particle configuration.

= 1 : additionally list short summary of the hard process.

= 2 : list complete documentation of intermediate steps of parton shower evolution.

IPY(35) : (D=30) ISUB-number for highest standard model subprocess included.

IPY(36) : (D=33) ISUB-number for highest non-standard subprocess included.

IPY(37) : (D=1) (C) recalculation of energies of partons from their momenta and masses, to be done immediately before fragmentation, to compensate in parts for some numerical problems appearing at high energies.

= 0 : not performed.

= 1 : performed.

IPY(38) : (D=1) (C) angular orientation of W and Z decay products for WW, ZZ, WZ, Wγ and Zγ pair processes, including pairs from H^0 decays.

= 0 : independent decay of two resonances, isotropic in CM frame of each resonance.

= 1 : correlated decay angular distributions according to proper matrix elements.

IPY(39) : (D=7) treatment of $Z'^0/Z^0/\gamma^*$ interference in matrix elements.

= 1 : only γ^* included.

= 2 : only Z^0 included.

= 3 : only Z'^0 included.

= 4 : only Z^0/γ^* (with interference) included.

= 5 : only Z'^0/γ^* (with interference) included.

= 6 : only Z'^0/Z^0 (with interference) included.

= 7 : complete $Z'^0/Z^0/\gamma^*$ structure (with interference) included.

IPY(40) : number of documentation lines in beginning of common block LUJETS that are given with K(I,1)=40000; 0 for IPY(34)=0.

IPY(41) : KF flavour code for beam particle.

IPY(42) : KF flavour code for target particle.

IPY(43) : whenever ISUB, KFL(2,1) and KFL(2,2) are not enough to specify the type of process uniquely (as e.g. for QCD processes) IPY(43) provides an ordering of the different possibilities. With I=KFL(2,1), J=KFL(2,2) and K=IPY(43), the possibilities for the QCD case are as follows (for details on colour configurations, see [2]):

I•J > 0, I and J not equal : non-identical quarks and antiquarks.

K = 1 : q(I)q(J).

I•J > 0, I = J : identical quarks or antiquarks.

K = 1 : q(I)q(I) (colour configuration A).

K = 2 : q(I)q(I) (colour configuration B).

I·J < 0, I and -J not equal: non-identical quark-antiquark pair.

K = 1 : q(I)q(J).

I·J < 0, I = -J : identical quark-antiquark pair.

K = 1 : q(I)q(J) (i.e. old flavour retained).

K = 2 : q(L)q(-L) (i.e. annihilation to new flavour, which of course *can* be equal to old flavour).

K = 3 : gg (colour configuration A).

K = 4 : gg (colour configuration B).

I·J = 0, I and J not equal : quark or antiquark plus gluon.

K = 1 : qg (colour configuration A).

K = 2 : qg (colour configuration B).

I = J = 0 : gluon-gluon.

K = 1 : q(L)q(-L) (colour configuration A).

K = 2 : q(L)q(-L) (colour configuration B).

K = 3 : gg (colour configuration A).

K = 4 : gg (colour configuration B).

K = 5 : gg (colour configuration C).

IPY(44) : group of subprocesses (IGRP), coincides with ISUB for numbers 7 and above, but gives the IPY(50) value for QCD processes.

IPY(45) : number of hard or semihard interactions that occured in current event; is =0 for a low-p_T event.

IPY(46) : current frame of event, cf. IPY(33).

IPY(47) : internal counter for number of primary documentation lines.

IPY(48) : internal flag that event failed cuts.

IPY(49) : number of subprocesses that are switched on, apart from elastic and single and double diffractive.

IPY(50) : internal flag for method to generate QCD high-p_T events, normally IPY(2)+1, but 0 if no QCD processes are included and 5 if low-p_T events are allowed.

IPY(51) - IPY(52) : internal flags to signal if particle 1 (2) is scattered diffractively.

IPY(53) : not used.

IPY(54) : (D=1) switch to regulate whether the result of the evolution calculation in the program of Tung [30] is written to file or not.

= 0 : result not written to file.

= 1 : result written to file FLNM (see common block PYFILE).

IPY(55) : (D=100) number of Monte Carlo generated phase space points per bin (whereof there are 20) in the initialization (in PYINMU) of multiple interactions for IPY(12)≥2.

IPY(56) - IPY(80) : not used.

PYPAR(1) : (D=0.007299) α_{em}, the electromagnetic coupling constant.

PYPAR(2) : (D=0.229) $\sin^2\theta_W$, weak mixing angle in QFD.

PYPAR(3) : (D=0.2) constant α_S value used for IPY(3)=0.

PYPAR(4) : (D=0.25 GeV) Λ_{QCD} used in running α_S for hard scattering (see also IPY(3) and IPY(7)).

PYPAR(5) : (D=4. GeV^2) mimimum Q^2 value in α_S for hard scattering, below which α_S is frozen (does not apply for the $\alpha_S(p_{T0}^2+p_T^2)$ used for multiple interactions with variable impact parameter).

PYPAR(6) : (D=1.) K-factor for cross section for flavour annihilation graphs, including resonance production. Actually, the K-factor refers rather to graphs in which colour is annihilated; this (when K is different from 1.) has some consequences for the relative size of the cross-sections for identical processes with different colour flows (e.g. g + g → g + g).

PYPAR(7) : (D=0.44 GeV/c) (C) width of Gaussian primordial k_T distribution for IPY(16)=1.

PYPAR(8) : (D=0.44 GeV/c) (C) width of exponential primordial k_T distribution for IPY(16)=2.

PYPAR(9) : (D=0.075) is used for IPY(3)= 11 or 12 to multiply the Q^2 scale in the effective argument used in α_S at the hard interaction, as a simple way of including an effective K-factor in the cross-section, with default in accordance with the results in [12].

PYPAR(10) : not used.

PYPAR(11) : (D=2. GeV/c) (C) upper cutoff for primordial k_T distribution.

PYPAR(12) : (D=2. GeV/c^2) (C) used to define the minimum invariant mass of the remnant hadronic system (i.e. when interacting partons have been taken away), together with original hadron masses and extra parton masses.

PYPAR(13) : (D=1.) (C) for IPY(17)≥2 this gives the value of the parameter k for the case when a pion remnant is split into two fragments (which is which is chosen at random).

PYPAR(14) : (D=0.) (C) for IPY(17)≥2 this gives the value of the parameter k for the case when a pion remnant is split into a meson and a spectator fragment jet, with χ giving the energy fraction taken by the meson.

PYPAR(15) : (D=3.) (C) for IPY(17)≥2 this gives the value of the parameter k for the case when a nucleon remnant is split into a diquark and a quark fragment, with χ giving the energy fraction taken by the quark jet.

PYPAR(16) : (D=1.) (C) for IPY(17)≥2 this gives the value of the parameter k for the case when a nucleon remnant is split into a baryon and a quark jet or a meson and a diquark jet, with χ giving the energy fraction taken by the quark jet or meson, respectively.

PYPAR(17) : not used.

PYPAR(18) : (D=0.) minimum value of q_T allowed at initialization of multiple interactions.

PYPAR(19) : (D=0.) probability for exchange of 'off-white' gluons in qq-scattering.

PYPAR(20) : (D=1. GeV/c^2) minimum invariant mass of hard scattering subsystem.

PYPAR(21) : (D=0.25 GeV) Λ_{QCD} value used in spacelike parton shower (see also IPY(3)).

PYPAR(22) : (D=1. GeV^2) (C) effective cutoff Q^2 value, below which spacelike parton showers are not evolved.

PYPAR(23) : (D=2. GeV) (C) effective minimum energy (in CM frame) of timelike or on-shell parton emitted in spacelike shower, see also PYPAR(24).

PYPAR(24) : (D=0.001) (C) effective lower cutoff on 1-z in spacelike showers, in addition to the cut implied by PYPAR(23).

PYPAR(25) : (D=4.) (C) the Q^2 scale of the hard scattering (see IPY(4)) is multiplied by PYPAR(25) to define the maximum parton virtuality allowed in timelike showers.

PYPAR(26) : (D=4.) (C) as PYPAR(25), but for the spacelike showers rather than the timelike ones.

PYPAR(27) : (D=0.25) (C) in spacelike shower evolution the virtuality Q^2 of a parton is multiplied by PYPAR(27) for use as a scale in α_S and structure functions (note that PYPAR(26)·PYPAR(27) = 1 corresponds to a smooth joining of Q^2 scales in α_S and structure function usage between the hard scattering and the spacelike parton shower).

PYPAR(28) : (D=-0.02 GeV^2) minimum value of $\hat{t}$ in (diffractive and) elastic scattering.

PYPAR(29) : (D=-0.01 GeV^2) $\hat{t}$ value used in calculation of effective slope parameter in $\hat{t}$ distribution for (diffractive and) elastic scattering.

PYPAR(30) - PYPAR(31) : not used.

PYPAR(32) : (D=1.6 GeV/c) effective minimum transverse momentum for multiple interactions, the abrupt cutoff p_{Tmin} for IPY(12)=1, the continuous turnoff p_{T0} for IPY(12)≥2. This parameter should be retuned if options are changed that affect average multiplicity in events, see discussion in section 7.

PYPAR(33) - PYPAR(34) : (D=0.5, 0.2) parameters of an assumed double Gaussian matter distribution inside the colliding hadrons for IPY(12)=4, of the form (1-PYPAR(33))·exp($-r^2$) + PYPAR(33)·PYPAR(34)$^{-3}$·exp($-r^2$/PYPAR(34)^2), i.e. with a core of radius PYPAR(34) of the main radius and containing a fraction PYPAR(33) of the total hadronic matter.

PYPAR(35) : (D=0.3894) conversion factor GeV^{-2} → mb.

PYPAR(36) : (D=1.) $\tan^2\beta$, mixing angle in $H^\pm$ interactions.

PYPAR(37) : (D=0.33) probability that an additional interaction in the multiple interaction formalism gives two gluons, with colour connections to 'nearest neighbours' in momentum space.

PYPAR(38) : (D=0.66) probability that an additional interaction in the multiple interaction formalism gives two gluons, either as described in PYPAR(37) or as a closed gluon loop. Remaining fraction is supposed to consist of quark-antiquark pairs. One must have PYPAR(38) ≥ PYPAR(37); to ensure this the program actually uses max(PYPAR(37),PYPAR(38)) rather than PYPAR(38).

PYPAR(39) : not used.

PYPAR(40) : (D=1.) if the EHLQ (set 1 or set 2) structure functions for light flavours have to be used for $x < 10^{-4}$, the structure function value at $x = 10^{-4}$ is extrapolated assuming an $x^{-PYPAR(40)}$ behaviour.

PYPAR(41) : (D=2.26 GeV) initial Q-value used in Tung's evolution of structure functions.

PYPAR(42) : (D=10^4 GeV) maximum Q-value used in Tung's evolution of structure functions.

PYPAR(43) : (D=10^{-4}) minimum x-value used in Tung's evolution of structure functions.

PYPAR(44) - PYPAR(80) : not used.

PYVAR(1) : E_{CM}, CM energy.

PYVAR(2) : s (=E_{CM}^2) mass-square of complete system.

PYVAR(3) : mass of beam particle.

PYVAR(4) : mass of target particle.

PYVAR(5) : momentum of beam (and target) particle in CM frame.

PYVAR(6) - PYVAR(10) : θ, ϕ and $\bar{\beta}$ for rotation and boost between user-specified frame and CM frame.

PYVAR(11) : q_{Tmin} as given in PYINIT.

PYVAR(12) : q_{Tmin}^2 from above.

PYVAR(13) : x_{Tmin} for multiple interactions/low-p_T.

PYVAR(14) : m^2 of particle 1 in final state.

PYVAR(15) : m^2 of particle 2 in final state.

PYVAR(16) : τ_{min} for colliding partons.

PYVAR(17) : lower limit of $\hat{t}$ range (THL) in PYTHAT.

PYVAR(18) : upper limit of $\hat{t}$ range (THU) in PYTHAT.

PYVAR(19) : q_T^2 of hard scattering in CM frame of hard scattering.

PYVAR(20) : $\cos\theta$ for hard scattering angle in CM frame of hard scattering.

PYVAR(21) : weight associated with event for IPY(2)≥1 (1 for IPY(2)=0).

PYVAR(22) : sum of PYVAR(21) weights for the events generated (i.e. the number of events for IPY(2)=0). At the end of a run, the conversion from events with relative weights PYVAR(21) to absolute cross sections (in mb) is obtained by multiplying by a factor XSEC(0)/PYVAR(22).

PYVAR(23) : latest value of α_S used for hard scattering.

PYVAR(24) : latest value of Λ_{QCD} used in structure function call.

PYVAR(25) : $h = m_H^2/s$ for Higgs production via intermediate vector boson fusion.

PYVAR(26) : minimum value of h (see PYVAR(25)).

PYVAR(27) : estimate of total parton-parton cross-section for multiple interactions, used for IPY(12)≥2.

PYVAR(28) : common correction factor f_c in the multiple interaction probability, used for IPY(12)≥2.

PYVAR(29) : average hadronic matter overlap, used for IPY(12)≥2.

PYVAR(30) : enhancement factor for current event in multiple interaction probability, defined as the actual overlap $\tilde{O}(b)$ divided by the average overlap $\langle\tilde{O}\rangle$, used for IPY(12)≥2.

PYVAR(31), PYVAR(32) : x-values for partons before initial state radiation.

PYVAR(33), PYVAR(34) : sum of x-values for multiple interaction partons, i.e. excluding partons of the hard scattering.

PYVAR(35), PYVAR(36) : 1 - (sum of x-values for all interactions), used for rescaling each new x-value in the multiple interaction structure function evaluation.

PYVAR(37) : nuclear slope parameter B in $\hat{t}$ distribution for (diffractive and) elastic scattering.

PYVAR(38) : curvature parameter C in $\hat{t}$ distribution for (diffractive and) elastic scattering.

PYVAR(39) - PYVAR(40) : not used.

PYVAR(41) : maximum differential cross-section for QCD high-p_T processes.

PYVAR(42) : PYVAR(41) plus single and double diffractive and elastic cross-sections.

PYVAR(43) : PYVAR(42) plus maximum differential cross-section for other standard model high-p_T processes (ISUB=11-30).

PYVAR(44) : not used.

PYVAR(45) : sum of weights for final state configurations (FSIGS).

PYVAR(46) - PYVAR(49) : not used.

PYVAR(50) : total cross-section.

PYVAR(51) : double diffractive cross-section.

PYVAR(52) : single diffractive cross-section.

PYVAR(53) : elastic cross-section.

PYVAR(54) : total nondiffractive, inelastic cross-section.

PYVAR(55) - PYVAR(61) : not used.

PYVAR(62) : effective Z^0 width (including channels set by IPROD(2,...) only, and taking into account also the effective width of $H^\pm$ when this is among the Z^0 decay products) divided by full Z^0 width; used in cross-section calculations.

PYVAR(63) : effective $W^\pm$ width (including channels set by IPROD(3,...) only) divided by full $W^\pm$ width; used in cross-section calculations.

PYVAR(64) : effective H^0 width (including channels set by IPROD(4,...) only, and taking into account also the effective widths of Z^0 and $W^\pm$ when these are among the Higgs decay products) divided by full H^0 width; used in cross-section calculations.

PYVAR(65) : effective R width (including channels set by IPROD(5,...) only) divided by full R width; used in cross-section calculations.

PYVAR(66) : effective $H^\pm$ width (including channels set by IPROD(6,...) only) divided by full $H^\pm$ width; used in cross-section calculations.

PYVAR(66) : effective Z'^0 width (including channels set by IPROD(7,...) only) divided by full Z'^0 width; used in cross-section calculations.

PYVAR(68) - PYVAR(70) : not used (but reserved for effective width divided by full width for other non-standard resonances ut supra).

PYVAR(71) - PYVAR(80) : not used.

6.6. Other Routines and Common Blocks

The subroutines and common blocks that a user will come in direct contact with have already been described. A number of other routines and common blocks exist, and are here briefly listed for the sake of completeness.

SUBROUTINE PYXTOT

Purpose: to give parametrized total, double diffractive, single diffractive and elastic cross-sections for different energies and colliding particles.

SUBROUTINE PYMAXI

Purpose: to find a maximum for the differential cross-section of each of the subprocesses included.

SUBROUTINE PYINMU

Purpose: to initialize the generation of multiple interactions by the calculation of some necessary integrated cross-sections.

SUBROUTINE PYRAND

Purpose: to generate the quantities characterizing a hard scattering on the parton level, according to the relevant matrix elements.

SUBROUTINE PYSCAT

Purpose: to find outgoing flavours and event type and to set up the kinematics and colour flow of the hard scattering.

SUBROUTINE PYSSPA(IP1,IP2)

Purpose: to generate the spacelike showers of the initial state radiation.

SUBROUTINE PYMULT

Purpose: to generate additional semihard interactions according to the multiple interaction formalism.

SUBROUTINE PYREMN(IPU1,IPU2)

Purpose: to add on target remnants and include primordial k_T.

SUBROUTINE PYRESD

Purpose: to allow Z^0, $W^\pm$, H^0, $H^\pm$ and Z'^0 resonances to decay, including chains of successive decays and parton showers.

SUBROUTINE PYDIFF

Purpose: to handle diffractive and elastic scattering events.

SUBROUTINE PYDSIG(TAU,XF,XT2,DSIGS)

Purpose: to give the differential cross-section (multiplied by the relevant Jacobians) for a given subprocess and kinematical setup.

SUBROUTINE PYSTFU(KF,X,Q2,XPQ)

Purpose: to give gluon, quark and antiquark structure functions for given x and Q^2 values for p, $\bar{p}$, n, $\bar{n}$ or $\pi^\pm$.

SUBROUTINE PYTHAT(THL,THU)

Purpose: to give the allowed range for the $\hat{t}$ variable.

SUBROUTINE PYPRKT(PTX,PTY)

Purpose: to give primordial k_T to the reacting partons.

SUBROUTINE PYSPLI(KPART,KFLIN,KFLCH,KFLSP)

Purpose: to give hadron remnant or remnants left when the reacting parton is kicked out.

SUBROUTINE PYCHID(KPART,KFL,CHI)

Purpose: to give the relative sharing of energy between hadron remnants.

FUNCTION PYALPH(Q2)

Purpose: to give the value of the strong coupling constant $\alpha_S(Q^2)$.

FUNCTION PYGAMM(X)

Purpose: to give the value of the ordinary gamma function $\Gamma(x)$ (used in some structure function parametrizations).

BLOCK DATA PYDATA

Purpose: to give sensible default values to all status codes and parameters.

SUBROUTINE PSETUP(I1,IHDRN,ALAM,TPMS,QINI,QMAX,XMIN,FLNM,I2,I3,IRET,IRR)

Purpose: dummy subroutine to be replaced by Tung structure function evolution package.

FUNCTION PDF(ISET,IHDRN,IPRTN,X,Q,IR)

Purpose: dummy subroutine to be replaced by Tung structure function evolution package.

COMMON/PYCROS/XMAX(0:40),NGEN(0:40,3),XPRI(0:40),VMAX

Purpose: to store information necessary for cross-section calculation and differential cross-section maximum violation. Should not be touched by any user.

COMMON/PYINT1/XQ(2,-6:6),DSIG(-6:6,-6:6,5),FSIG(10,10,3)

Purpose: to store information on structure functions, subprocess cross-sections and different final state relative weights. Should not be touched by any user.

COMMON/PYINT2/KPR(-6:6,-6:6),NMX(6),ICOL(40,4,2),ICH(30),VKM2(4,4)

Purpose: to store information on mapping of parton-parton pairs into different classes, number of QCD processes, colour flow information, quark/lepton charges and the Kobayashi-Maskawa flavour mixing matrix.

COMMON/PYINT3/ISET(40),COEF(40,8),WM(40,4),NMUL(20),SIGMUL(20)

Purpose: to store information necessary for efficient generation of the different subprocesses, specifically type of generation scheme, coefficients of the Jacobian, and masses and widths of final state particles, and also to store cumulative cross-sections needed for the generation of multiple interactions for IPY(12)>2.

COMMON/PYINT4/PWTOT(10),PW(10,10,10,3),EWTOT(10),EW(10,10,10,3)

Purpose: to store partial and effective decay widths for the different resonances. Should not be touched by any user.

COMMON/PYCHAR/PROC(-5:40)

CHARACTER PROC*26

Purpose: to store character strings for the different possible subprocesses; used when printing tables.

COMMON/PYFILE/FLNM

CHARACTER FLNM*40

Purpose: to store the name of the file to (from) which data is to be written (read) when using the structure function evolution program of Tung [30].

FLNM: a character variable giving the name of the file.

6.7. The JETSET Routines

Since the fragmentation and decay of an original parton configuration is handled by the JETSET routines, using the LUJETS common block described above, all of the non-e^+e^- routines and parameters in JETSET are at the disposal of the PYTHIA user. This section is intended as a brief reminder of some of the most useful ones, in particular for hadron physics applications.

The subroutine LULIST can be used to list an event; for output that fits onto a normal terminal screen CALL LULIST(1) is recommended, whereas CALL LULIST(11) gives a slightly more comprehensive listing. The event record nominally contains not only the stable final particles, but also the original partons and intermediate resonances (see subsection 6.3). With CALL LUEDIT(1) all partons/particles that have fragmented/decayed are removed from the event record, and N is updated accordingly. A CALL LUEDIT(2) will remove neutrinos as well, and CALL LUEDIT(3) will leave only charged, stable particles. Some of the information indirectly stored in LUJETS can be accessed more easily by

using the PLU and KLU functions, thus e.g. Y = PLU(I,17) gives the true rapidity and ETA = PLU(I,19) the pseudorapidity of particle I.

With IPY(20)=0, fragmentation and decays are switched off in the PYTHIA call. If one desires to fragment the event at some later opportunity, this can be achieved by a CALL LUEXEC. The action of the program during this call (which is done automatically from PYTHIA for IPY(20)=1) can be controlled by the switches and parameters in the LUDAT1 common block. Thus MST(7)=0 will switch off particle decays but keep jet fragmentation on, MST(5) can be set to give independent fragmentation rather than the standard string fragmentation, etc. Contrary to most PYTHIA variables, the user can freely change the values during the course of the run.

The common block LUDAT2 contains several pieces of information, in particular particle masses. Since these masses are directly taken over by the PYTHIA routines, any changes to these should be made before the PYINIT call. Of particular interest are the following:

PMAS(2) : (D=94. GeV/c^2) Z^0 nominal mass.

PMAS(3) : (D=83. GeV/c^2) $W^\pm$ nominal mass.

PMAS(4) : (D=15. GeV/c^2) H^0 nominal mass.

PMAS(13) : (D=60. GeV/c^2) mass of χ, potential fourth generation lepton.

PMAS(91) : (D=5000. GeV/c^2) R nominal mass.

PMAS(92) : (D=300. GeV/c^2) $H^\pm$ nominal mass.

PMAS(93) : (D=900. GeV/c^2) Z'^0 nominal mass.

PMAS(106) : (D=40. GeV/c^2) mass of top quark.

PMAS(107) : (D=60. GeV/c^2) mass of l, potential fourth generation down quark.

PMAS(108) : (D=200. GeV/c^2) mass of h, potential fourth generation up quark.

For Z^0, $W^\pm$, H^0, R, $H^\pm$, and Z'^0 s-channel production, the resonance width is calculated at PYINIT initialization, taking into account the channels assumed possible for resonance decays (for H^0 this will depend very much on the mass assumed), so the nominal widths stored in LUDAT1 are actually not used for this purpose.

The common block LUDAT3 contains all particle decay data, and can in particular be used to switch off the decay of some particles selectively. In order to keep the event record from becoming uncomfortably large, switching off π^0 decays by putting IDB(23)=0 is probably the single most effective action. Since the decays of Z^0, $W^\pm$, H^0, R, $H^\pm$ and Z'^0 are handled from PYTHIA rather than JETSET, corresponding switches for these resonances are found in IPY(22) - IPY(27). If one wants to change the top quark or fourth generation

masses, it may become necessary to change the decay modes stored in LUDAT3 for these particles; use CALL LULIST(3) to obtain a listing of current decay data. For major changes in particle properties, it may pay off to learn how to use LUUPDA.

The event analysis routines can be called on to evaluate the event stored in the LUJETS common block. Particularly useful is the cluster finding routine LUCELL, which assumes a (modifiable) grid of cells in pseudorapidity and azimuthal angle and carries out a cluster finding algorithm à la the UA1 one. With a CALL LUCELL(NJET) the number of jets found is given by NJET and the position and E_T of those jets are stored after the event proper, in lines N+1 through N+NJET.

6.8. On Cross-Sections

As already mentioned, the routine PYSTAT can be used to print out a table of cross-sections in the current run. A few comments about these cross-sections may be in order. We will first consider high-p_T event generation only, and later cover low-p_T physics.

At initialization, maxima for the various differential cross-sections are searched for. For efficiency reasons, the set of independent kinematical variables is not τ, x_F and $\hat{t}$, but rather a suitably transformed set of these, for which the differential cross-section is less rapidly varying. In case several different high-p_T processes are allowed, these maxima are used to find the initial relative probability for each process. In order to generate an event, a process is first chosen, and thereafter a set of kinematical variables for this process is selected. The probability for accepting this set is given by the differential cross-section in this point divided by the maximum found earlier. In case of rejection, both process and kinematical variables are to be chosen anew.

For each individual subprocess, there are counters giving the number of points tried and the sum of the differential cross-section in these points, multiplied by the integral of the allowed phase space (which is just a simple multiplicative factor). At the end of each PYTHIA call, the ratio of these two numbers is calculated, providing a Monte Carlo estimate of the actual cross-section for each process. If only very few events have been generated, the statistical fluctuations are large. Therefore it is recommended to call

PYSTAT(0) only after all events have been generated, although a call could in principle be made at any time. In PYSTAT the cross-sections will be listed together with the number of phase space points tried and the number of events actually generated. The QCD $2 \to 2$ parton-parton scatterings are, for historical reasons, treated slightly differently: all the relevant $2 \to 2$ cross-sections are evaluated before a choice is made on which subprocess to generate. Therefore the number of phase space points tried is common for subprocesses 1-6, and the cross-sections also of the more rare subprocesses are obtained with fair accuracy.

The cross-sections for each subprocess are calculated taking into account which initial and final states are allowed by the IREAC and IPROD arrays in the common block PYSUBS. The allowed initial state flavours (in this particular connection the gluon is also considered a separate flavour), as given by IREAC, are by default everything up to and including top. If some initial states are switched off, the cross-sections will be reduced accordingly. For several processes, like $q + g \to q + g$, the flavours in the final state are the ones of the initial state, and for these IPROD has no effect. In processes like $g + g \to q + \bar{q}$ or $q + \bar{q} \to Z^0/\gamma^* \to \mu^+ + \mu^-$, on the other hand, the quark and lepton flavours allowed in the final state can be selected using IPROD, and cross-sections are based only on those channels that are actually allowed. We emphasize that, for resonances like Z^0 or $W^\pm$, the total widths are assumed given as the sum over three (or, optionally, four) full generations of quarks and leptons. By only allowing a few channels, we do thus in no way alter the basic properties of the resonances, such as their full widths, but only restrict the generation of events to those particular channels we happen to be interested in, with the cross-sections reduced accordingly. The IPROD array actually must be set separately for QCD processes ($q + \bar{q} \to q' + \bar{q}'$ and $g + g \to q' + \bar{q}'$), Z^0/γ^*, $W^\pm$, H^0, R, $H^\pm$ and $Z'^0/Z^0/\gamma^*$; furthermore, the final state flavours q' in reactions like $g + q \to W^\pm + q'$ can also be set from IPROD. The H^0 is a special case; it can either decay directly into a quark-antiquark or lepton-antilepton pair, or into a Z^0Z^0 or W^+W^- pair, which then can decay further. Therefore the cross-section for Higgs production given by the program is reduced, not only by switching off some decay channels of the H^0 itself, but also by switching off subsequent Z or W decay modes (and the branching ratios for H^0 decays into Z^0Z^0 or W^+W^- are reduced accordingly). This is also true for Z^0 when allowed to decay into a H^+H^- pair. The switches IPY(22)-IPY(27) can be set to turn off the decays of Z^0, $W^\pm$, H^0, R, $H^\pm$, and Z'^0, respectively, but even if the decays are not actually performed by the program, cross-sections are still based on the decay

channels allowed by the IPROD values.

The cross-section values printed by PYSTAT(0) are stored in XSEC(0:40) in common block PYPROC. In particular, XSEC(0) gives the total cross-section for all subprocesses studied in current run. Normally, events are generated with unit weight. At the end of a run, histogram contents etc. can be converted from number of events to differential cross-sections by multiplying by XSEC(0) and dividing by the total number of events, the latter stored in PYVAR(22). (For histograms one should also divide by the bin width.) For QCD processes only, it is possible to bias the event selection towards events with large q_T values, q_T being the transverse momentum generated in the hard interaction. Each event then comes with a weight stored in PYVAR(21), that must be used e.g. when filling histograms. Total cross-sections given by PYSTAT are still correct, and conversion to absolute cross-sections can still be obtained at the end of the run by multiplying by XSEC(0)/PYVAR(22) (and dividing by bin width), but PYVAR(22) no longer is the number of events generated.

What has been said so far applies when only hard interactions are studied. The total hadronic cross-section, as well as the elastic, single diffractive and double diffractive cross-sections are taken from parametrizations available in the literature. For the total and elastic cross-sections this means the fits of Block-Cahn [32] (see IPY(6)), for diffractive events the ansatz of Goulianos [33] is used. The cross-section for nondiffractive low-p_T events is then obtained by subtraction. When the multiple interaction formalism is used to generate these latter events, some of them will actually contain a semihard interaction, and be listed in PYSTAT as such ($1 \leq$ ISUB ≤ 6), with only the events without any semihard interactions being classified as low-p_T (ISUB=7). This matter of classification does not remove the constraint that the total cross-section is fixed, however. Neither can the IREAC switches be set to suppress some of the flavours of the initial hadrons (the inclusion of heavy flavours or not can still be set using IPY(8), however).

7. Comments and Examples on How to Use the Program

The program is built as a slave system, i.e. the user supplies the main program, which calls on the PYTHIA and JETSET routines to perform specific tasks and then resumes control. The program is written entirely in standard Fortran 77, and should run on any machine with such a compiler. The one nonstandard feature is the need for a random number generator returning

numbers uniformly distributed between 0 and 1. In JETSET is included a function RLU with this purpose, which can be interfaced to existing routines.

Note that the BLOCK DATA subprograms have to be linked before execution (PYDATA in PYTHIA and LUDATA and LUEDAT in JETSET); this does not occur automatically with all loaders (in particular not if treating the files as libraries). All output from PYTHIA and JETSET is directed to unit MST(20) (in common block LUDAT1 in JETSET). By default this is taken to be unit 6, and it is up to the user to see to it that this unit is open for write.

A typical program for analysis of collider events at 540 GeV CM energy with a minimum p_T of 10 GeV/c at the hard scattering (because of initial state radiation, fragmentation effects, etc., the actual p_T-cutoff will be smeared around this value) might look like

```
      COMMON/LUJETS/N,K(2000,2),P(2000,5)
      COMMON/PYPARA/IPY(80),PYPAR(80),PYVAR(80)
      COMMON/PYPROC/ISUB,KFL(3,2),X(2),SH,TH,UH,Q2,XSEC(0:40)
      COMMON/PYSUBS/ISELEC,ISUBPR(40),IREAC(2,-6:6),IPROD(0:10,30)
      ...                    ! set all common block variables that
      ...                    ! did not have desired default values
      CALL PYINIT('CMS','P','PBAR',540.,10.)         ! initialize
      ...                    ! initialize analysis statistics
      DO 100 IEVENT=1,1000                  ! loop over events
      CALL PYTHIA                           ! generate event
      IF(IEVENT.EQ.1) CALL LULIST(11)       ! list first event
      ...                    ! insert desired analysis chain for
      ...                    ! each event
  100 CONTINUE
      CALL PYSTAT(0)         ! print cross-sections
      ...                    ! user output
      END
```

As an example of default values that could be changed before PYINIT, consider the simulation of $u\bar{u} \to W^+W^- \to e^+\nu_e e^-\bar{\nu}_e$ with EHLQ set 2 structure functions, but without initial or final state radiation (the latter absent anyhow for this particular process) or multiple interactions:

```
      ISELEC=0               ! allow free choice of subprocesses
      ISUBPR(24)=1           ! switch on process q+q̄→ W+ +W-
      DO 110 J=-6,6
```

```
      IREAC(1,J)=0          ! switch off all flavours in hadron 1
  110 IREAC(2,J)=0          ! switch off all flavours in hadron 2
      IREAC(1,1)=1          ! switch on u flavour in hadron 1
      IREAC(2,-1)=1         ! switch on ū flavour in hadron 2
      DO 120 J=1,30
  120 IPROD(3,J)=0          ! switch off all W decay products
      IPROD(3,11)=1         ! switch on e± as W decay product
      IPROD(3,12)=1         ! switch on νe, ν̄e as W decay product
      IPY(7)=2              ! EHLQ set 2 structure functions
      IPY(12)=0             ! no multiple interactions
      IPY(13)=0             ! no final state radiation
      IPY(14)=0             ! no initial state radiation
```

Apart from the interface with JETSET, only one other program has been directly interfaced with PYTHIA, namely the structure function evolution program of Tung [30]. Since many users may not have it at hand, or wish to use it anyhow, dummy routines PSETUP and PDF are provided at the end of PYTHIA, to avoid problems with unsatisfied external references when linking the program. On most computers, these dummy routines will do no harm if the correct Tung routines are linked before PYTHIA. Also note that if a separate file (with name to be given in COMMON/PYFILE/FLNM) is used to store or read results, this file must be properly opened by the user. Although fast, the structure function evolution may take several minutes, and it therefore makes sense to have results stored on a file if they are to be reused. The options available are found in IPY(7).

The study of beam jets is fairly complicated, and is still ongoing. If the beam jet structure is of no interest in a run, switching off multiple interactions (IPY(12)=0) will save a lot of time in program execution. What is obtained by default (IPY(12)=1) is the simpler approach, where all events are assumed equivalent (i.e. have the same impact parameter) and multiple interactions are generated above some p_{Tmin} = PYPAR(32) ≈ 1.6 GeV. This is not because we believe this to be the most realistic picture, but because it is minimal. Of the alternatives available, we feel the 'best' one is (IPY(12)=4) with a variable impact parameter based on a double Gaussian matter distribution (see PYPAR(33), PYPAR(34)), with an effective K-factor included via the α_S (IPY(3)=12) and a continuous cross-section turnoff at a scale p_{T0} = PYPAR(32) ≈ 2.1 GeV. This is also the most time-consuming alternative, however. For detailed studies, where low-p_T particles are of interest, we recommend its use. One should note that the value to use for the PYPAR(32)

parameter depends very much on the exact choice of structure functions, Q^2 scale, Λ value, etc.; if the program is to be run with some nonstandard combination of these, PYPAR(32) has to be retuned so that the program gives the correct mean charged multiplicity. Once this retuning is done, however, the difference between the different choices largely vanish. In that sense, a lot of uncertainty is pushed into that one single parameter, p_{Tmin} or p_{T0}.

8. Summary and Future Plans

PYTHIA version 4.8 is a program with roughly 6800 lines of code. The present paper does not discuss every detail of what is going on within these lines; that would have required far more space. Rather, the physics discussion is included to give the flavour of what is going on, without becoming too technical. People who really want to know how this program works are therefore referred to the further references given in the text and to the inline comments in the program. On the other hand, it is entirely possible to make efficient use of PYTHIA without this specialized knowledge.

Requests for the program, as well as questions and comments, can be sent to DECNET address UCLA::GOLLUM (H.-U. B.; only valid within the USA), BITNET address V3343@FNAL (H.-U. B.) or EARN/BITNET address THEP@SELDC51 (T. S.).

There are two major revisions planned for the next version of PYTHIA (5.1). The first is the inclusion of massive matrix elements for the 2 → 2 hard subprocesses. This will remove the need for a lower cut-off in p_T of the hard scattering and allow the user to study phenomena like charm production at SPS energies or bottom production at $S\bar{p}pS$ energies with more confidence as to the lower end of the p_T-spectrum. (At present, a preliminary version with massive matrix elements tailored for SPS energies exists as CHARIS and is being used by the LEBC-EHS Collaboration for comparisons with data [51].) The second is the expansion of the program to allow also e^+e^- and ep in the initial configuration, which means that PYTHIA will mature into a multi-purpose program capable of handling questions in all major branches of high-energy physics, as behooves a true oracle.

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Figure Captions

Fig. 1. A partonic system of two colour triplets and two colour antitriplets and the corresponding two possible colour field topologies.

Fig. 2. The three Feynman diagrams contributing to the process q + g → q + g.

Fig. 3. The two possible colour flows of the process q + g → q + g.

Fig. 4. The two string configurations corresponding to the two colour flows in Fig. 3. $\bar{1}$ and $\bar{2}$ denote the remnants in colour space of hadrons 1 and 2, respectively, after partons 1 and 2 have scattered.

Fig. 5. Schematic diagram of timelike parton shower evolution. The numbering of the first branches is shown, where parton 0 corresponds to the total energy-momentum of the showering system. Sometimes this may correspond to a real s-channel particle, say a Z^0, sometimes not.

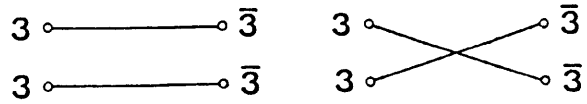

Fig. 1

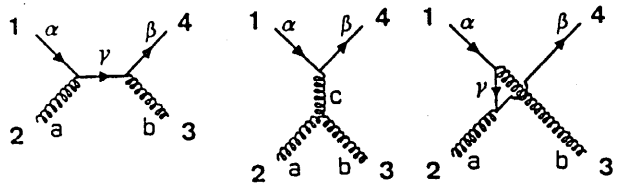

Fig. 2

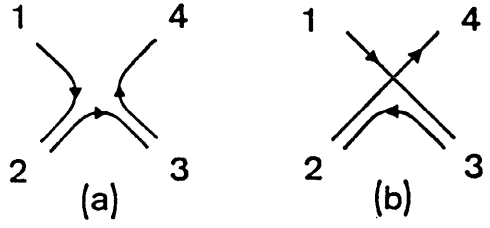

Fig. 3

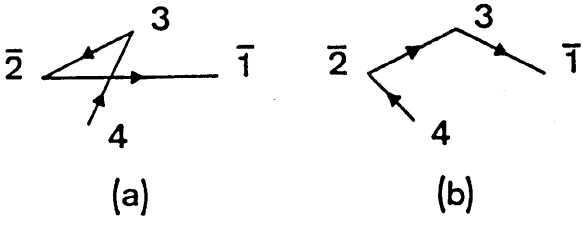

Fig. 4

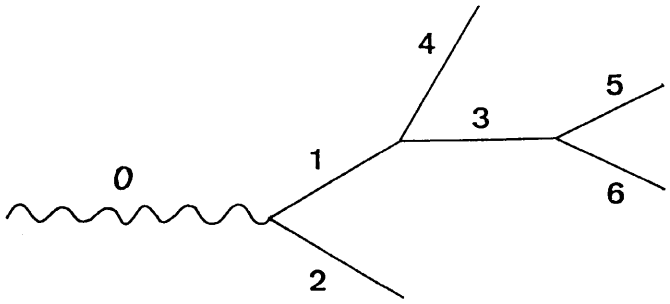

Fig. 5