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THE LUND MONTE CARLO FOR JET FRAGMENTATION

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PROGRAM SUMMARY

Title of program: JETSET 4.3 G

Catalogue number: AAVJ

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Computer for which the program is designed and others on which it is operable: ND, Univac, CDC and others with a FORTRAN 77 compiler

Computer: ND-50; *Installation*: University of Lund, Lund, Sweden

Operating system: SINTRAN III/VS

Programming language used: FORTRAN 77

High speed storage required: 28 Kwords

No. of bits in word: 32

Overlay structure: none

Peripherals used: terminal or card reader for input, terminal or line printer for output

No. of cards in combined program and test deck: 1987

Card image code: ASCII

Keywords: jet fragmentation, hadronization, quark jet, gluon jet, multiparticle production, Monte Carlo simulation

Nature of physical problem
In high energy collisions normally most of the particles in the final state appear within a few rather narrow cones. Each of these collections of particles, called jets, are assumed to be coming from the hadronization of an outgoing quark or gluon. QCD, the candidate theory of strong interactions, can be used perturbatively to describe the scattering or creation of these partons at small distance scales (high Q^2), and there are reasons to believe that the large distance behaviour of QCD makes quarks and gluons confined inside hadrons. Exactly how the confinement forces transform e.g. a quark into a jet of particles is, however, not known at present.

Method of solution
The Lund model provides a phenomenological description of hadronization. Colour charges are assumed to be connected by colour flux tubes, kinematically described by the massless relativistic string with no transverse excitations. A quark then corresponds to an endpoint on a string and a gluon to a kink on it. The breakup of these strings is described in an essentially iterative fashion, string → hadron + remainder-string, for fast particles corresponding to an iteration jet → hadron + remainder-jet, but at the same time providing a natural joining of the jets in the central region.

Restrictions on the complexity of the problem
Each string piece must have a certain minimum energy so as to be able to fragment into at least two particles. This corresponds to a minimum invariant mass between each two partons connected by a colour flux tube. Also, in the present implementation a jet system may contain at most ten connected partons and a total of at most 250 particles produced (including unstable particles which subsequently decay), but this is easily changed.

Typical running time
An event with a CM energy of 40 GeV and an average of 30 particles (of which 14 are charged) in the final state takes approximately 0.2 s. Generation time is roughly proportional to the multiplicity.

Unusual features of the program
A random number generator is required. Energy, momentum and flavour are conserved step by step in the fragmentation process.

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LONG WRITE-UP

We present a Monte Carlo program based on the Lund model for jet fragmentation. Quark, gluon, diquark and hadron jets are considered. Special emphasis is put on the fragmentation of colour singlet jet systems, for which energy, momentum and flavour are conserved explicitly. The model for decays of unstable particles, in particular the weak decay of heavy hadrons, is described. The central part of the paper is a detailed description on how to use the FORTRAN 77 program.

1. Introduction

The concept of jets is by now well established in the high energy physics folklore, both experimentally and theoretically. Jets inevitably seem to be present in the final state of processes involving large momentum transfers to partons, in processes as disparate as e^+e^- annihilation, leptoproduction and high-p_t hadron collisions. Also a large part of the low-p_t physics can be understood in terms of jets. The jets are often associated with "struck" partons, i.e. quarks or gluons interacting with a high energy probe, but a basic observation is that "spectator" jets seem to have a very similar structure.

General features of the events in the processes above are in agreement with what is expected from QCD, the candidate theory of strong interactions. What has been extensively explored is the perturbative expansion of QCD at high Q^2, where the running coupling constant is small and where, with different degrees of confidence for different processes, the expansion could be expected to converge reasonably fast. But whereas QCD in this way provides a description of coloured quark and gluon interactions at high energies, the observable final states basically consist of colourless hadrons (with some photons and leptons from decays). The intervening process of hadronization, which is very closely connected to the mechanism of confinement, can at present not be given an exact description within the QCD framework.

Looking closer, a typical event can phenomenologically be separated into three phases. The first phase contains the hard primary interaction and e.g. hard gluon bremsstrahlung in immediate connection herewith. This part is characterized by high Q^2 and small distances; confinement effects are negligible and a process-dependent description can be given in terms of perturbative QCD. In the second phase the partons are receding from each other. Gluons emitted at this stage are soft or collinear and know little of the primary vertex. Confinement forces begin to dominate and eventually lead to a breakup of the system into a number of primary hadrons. The third phase consists of the decay of unstable hadrons into the observable particles. The transition between the first and second phase should of course be continuous, yet it is for practical purposes convenient to draw a line somewhere and consider the subsequent jet fragmentation and particle decays as independent of the primary interaction.

In the study of QCD there are then two reasons to introduce phenomenological models of jet fragmentation. One is that a detailed comparison between experiments and the results obtained in perturbative QCD is almost impossible if not the fragmentation and decay effects are properly taken into account. The other is that the behaviour of the confinement mechanism, which we would like to understand better, is obscured by the large multiplicities encountered in most jets, so that an extraction of the interesting features becomes highly nontrivial.

One model of jet fragmentation is the one developed by the Lund group [1–9], which has been applied to a number of different processes with good results. The hard reactions, the soft fragmentation and the decays of unstable particles are stochastic processes in our model; it is therefore natural to give a description in terms of a Monte Carlo program simulating the complete event chain. This allows comparisons with and predictions for any experimentally observable quantity to be made in a straightforward fashion.

In this paper we present a Monte Carlo program for the soft fragmentation of jets and decays of unstable particles based on the Lund model, i.e. containing all the ingredients assumed to be independent of the primary reaction. In companion papers we present Monte Carlo programs for the hard, reaction-dependent, pieces of different processes: e^+e^- annihilation [10], leptoproduction [11] and lepton pair (Drell–Yan) and high-p_t events [12]. These are directly utilizing the program presented here for the subsequent event chain, but they by no means exhaust the possible applications of this program.

The program presented here is a natural outgrowth from previous versions [13], however with many new features included. The default parameter values correspond to a "standard" Lund model, from which deviations, warranted by physics or otherwise, can be described in a well-defined way. For comparison purposes we include some options not properly part of the Lund framework, e.g. Field–Feynman type jets [14].

The plan of the paper is as follows. The next section contains a brief introduction to the Lund model. In section 3 the scheme for the fragmentation of a single jet is presented, with main emphasis on the flavour generation scheme. The fragmentation of jet systems is considered in section 4, here in particular reviewing the kinematics. A survey of particle (and parton) names, masses and decay modes is next presented. Section 6 contains the "raison d'être" of this paper, a detailed description of the program elements: subprograms and common blocks, arguments and parameters. Finally, some simple examples are presented in section 7.

2. The Lund model

Before describing the practical details of jet fragmentation and particle decay in the program, we would like to give a short summary of the Lund model for soft hadronization, which provides the conceptual framework for the program. A more detailed description and comparisons with experiments are beyond the scope of the present paper.

2.1. Longitudinal fragmentation scheme

Consider the process $e^+e^- \to q\bar{q}$. The picture then is of a quark q and an antiquark $\bar{q}$ going out in opposite directions. Between them a colour flux tube, an elongated colour bag, is stretched. From charmonium spectroscopy, bag model calculations or Regge phenomenology it is motivated to assume that the potential is basically linearly rising with the distance between the q and the $\bar{q}$. To denote the constant energy stored per unit length of the colour flux tube we introduce κ, where phenomenologically $\kappa \approx 1$ GeV/fm $\simeq 0.2$ GeV^2. A causal and relativistically invariant description of the kinematics can then be given in terms of the massless relativistic string with no transverse excitations [15], where the momentum-carrying endpoints correspond to the q and $\bar{q}$ and the string in between to the flux tube [2].

To simulate the dynamics of jet fragmentation, a probability is introduced for the string to break up into two pieces, corresponding to the production of a $q'\bar{q}'$ pair in the field. Due to the polarity of the colour field the q' is pulled towards the $\bar{q}$ end of the string and the $\bar{q}'$ to the q end. Several breakups may take place in this way, and the q_1 from one such $q_1\bar{q}_1$ pair may then combine with the $\bar{q}_2$ from the adjacent $q_2\bar{q}_2$ pair to form a $q_1\bar{q}_2$ colour singlet meson. On the average these $q'\bar{q}'$ creation vertices will appear along a hyperbola of constant proper time, however with rather large fluctuations. The distribution of vertices can be interpreted as a stochastic process, both in energy–momentum and in space–time. Further, while the mesons thus formed are strictly ordered with respect to flavour (cf. the concept of rank) this ordering only in the mean corresponds to the ordering in rapidity.

In any given Lorentz frame, the breakups that produce the slowest hadrons (in that frame) are also those that will take place first. Hence formally we have an "inside out" cascade. It is, however, always possible to go to a frame in which one of the endpoint quarks q is slow. In that frame the meson closest to this quark ($q\bar{q}_1$, the fist rank meson) will be produced first, then the next closest ($q_1\bar{q}_2$, the second rank meson), etc. This suggests the use of an iterative structure to describe the breakup [16,1,14].

With the q going out along the $+z$ axis (and the $\bar{q}$ along the $-z$ one) light-cone variables $W_+ = E + p_z$ and $W_- = E - p_z$ are introduced to describe the longitudinal fragmentation. A use for W_+ rather than e.g. E and p_z will ensure that the fragmentation scheme becomes Lorentz invariant under boosts along the z axis. For the q jet, each meson will take a random fraction z_+ of the W_+ remaining from previous steps, where z_+ is distributed according to

$$f(z_+)\,\mathrm{d}z_+ = 1\,\mathrm{d}z_+ . \qquad (1)$$

This choice is motivated by the assumptions that the density of states as a function of the mass squared M^2 of a highly excited q$\bar{\text{q}}$ system is $\mathrm{d}n/\mathrm{d}M^2 =$ constant, and that all kinematically allowed states are equally populated in the decay of a q$\bar{\text{q}}$ system into a meson and a remainder-system. An iteration of this formula leads to a Poissonian distribution of the number of particles per unit in rapidity, with a mean of 1. This is in agreement with what is obtained in the Schwinger-model for 1 + 1-dimensional QED [17,18].

2.2. The tunneling phenomenon

A q$'\bar{\text{q}}'$ pair where the quarks have no mass and no tranverse momentum can classically be created in one point and then be pulled apart by the field. However, if the quarks have mass and/or transverse momentum they must classically be produced at a certain distance so that the field energy between them can be transformed into the transverse mass m_t. This can be treated as a tunneling phenomenon and the production probability will be proportional to [17,19]

$$\exp\left(-\frac{\pi}{\kappa}m_t^2\right) = \exp\left(-\frac{\pi}{\kappa}m^2\right)\exp\left(-\frac{\pi}{\kappa}p_t^2\right). \qquad (2)$$

The factorization of the transverse momentum and the mass terms leads to a flavour-independent Gaussian spectrum for the transverse momentum of q$'\bar{\text{q}}'$ pairs. Since the string is assumed to have no transverse excitations, this p_t is locally compensated between the quark and the antiquark of the pair.

The formula also implies a suppression of heavy quark production $\text{u}:\text{d}:\text{s}:\text{c} \approx 1:1:0.3:10^{-11}$. Charm and heavier quarks are hence not expected to be produced in the soft fragmentation.

One possibility to understand baryon production in e.g. e^+e^- annihilation is if, in addition to quark–antiquark pairs, also antidiquark–diquark (colour triplet–antitriplet) pairs occasionally are produced in the field [7]. Such an assumption does not imply that a diquark should be considered as a single excitation of an elementary field, only that the soft chromoelectric field effectively acts on a diquark as were it a unit. For simplicity, the notation q$'\bar{\text{q}}'$ for a colour triplet–antitriplet pair created in the field will henceforth be used with the understanding that q$'$ either may represent a quark or an antidiquark.

Due to the large uncertainty in the definition of diquark masses, the tunneling formula (eq. (2)) can not be used directly to predict the expected rate of diquark production. From low energy SPEAR Mark II data the relative probability of diquark to quark production is determined to $\text{qq}:\text{q} = 0.065:1$ (with errors of $\pm 25\%$ mainly due to systematic experimental uncertainties), corresponding to a typical nonstrange diquark mass around 450 MeV. Using this in combination with expected mass differences between different diquarks, the relative probability for the production of the various diquarks is determined by the tunneling formula and the number of spin states available.

A very important constraint is the fact that a baryon is a symmetric system of three quarks (neglecting the colour degree of freedom). When a diquark joins a quark to form a baryon, we therefore weight the different flavour and spin states by the probability that they form a symmetric three-quark system. This means that, were it not for the tunneling suppression factors, all states in the SU(6) 56-multiplet would become equally probable. Of course also heavier baryons may come from the fragmentation of e.g. c quark jets, but although the particle classification scheme used in the program is SU(16), i.e. with eight flavours, all possible quark–diquark combinations can be related to SU(6) by symmetry arguments.

In our survey of the tunneling phenomenon so far, longitudinal fragmentation properties have not entered the picture. However, in order to produce a q$'\bar{\text{q}}'$ pair with nonzero m_t the field must be sufficiently long, i.e. we have to wait until the original q$\bar{\text{q}}$ pair has come sufficiently far apart. On the other hand, in order to produce a very energetic hadron in the jet the field must break very early. A simple quantum mechanical treatment [4] suggests that this can be described by the introduction of a vertex weighting factor $|g(\kappa\tau/m_t)|^2$ where τ is the proper time for the vertex (of the asymptotes to the outgoing q′ and $\bar{q}'$). Although the precise shape of g is model-dependent, it turns out that different, reasonable parametrizations of g give very similar results. Hence we will here use

$$|g|^2 = (\kappa\tau)^2\left[(\kappa\tau)^2 + m_t^2\right]^{-1}. \quad (3)$$

Among other things, this will lead to a softer particle spectrum than the one implied by eq. (1).

2.3. Gluons

In the massless relativistic string formalism it is possible to have a pointlike part of the string carry a finite amount of energy and momentum. Such a "kink" mode is acted upon by the string by twice the force acting upon an endpoint quark. This gives features very similar to those of a gluon in QCD, where the corresponding force ratio is expected to be $2/(1-1/N_C^2)$ with N_C the number of colours. Our picture of e.g. a $q\bar{q}g$ event is thus that a string is stretched from the q via the g to the $\bar{q}$ [3].

Again here the string pieces between the q and g and between the g and $\bar{q}$ may break up by the creation of new quark–antiquark pairs. The gluon itself can, however, not break up into a $q'\bar{q}'$ pair until after it has lost its energy and momentum. For a hard and acollinear gluon, the string piece on either side of the gluon will break before this time and give a "first rank" hadron at the gluon "corner" of the string. The two remaining string pieces will then fragment like ordinary quark–antiquark jet systems (if the hadron at the gluon corner is $q_1\bar{q}_2$ then the remainder-systems are $q\bar{q}_1$ and $q_2\bar{q}$).

Since the energy of a gluon jet is shared between two string pieces, a gluon jet will in general be softer than a quark one. At presently accessible energies the difference in multiplicity will, however, be much smaller than the factor 2 one could expect. The particles produced in the qg and $g\bar{q}$ string pieces will in mometum space appear along two hyperbolae, typically with a distance from the hyperbolae to the origin of around 300 MeV/c for primary hadrons, i.e. comparable to typical p_t within a jet. Hence we expect to see more particles in the qg and $g\bar{q}$ angular ranges than in the $q\bar{q}$ one [5]. An asymmetry of this kind is actually observed by the JADE group at PETRA [20].

In our model, with a string stretched from the q via the g to the $\bar{q}$, there is a natural transition to the simple two-jet $q\bar{q}$ event for the cases of a soft or collinear gluon. A soft gluon will lose its energy and disappear before the string breaks the first time, so that the fragmentation will proceed as in an ordinary $q\bar{q}$ event, with some extra p_t imparted to the hadrons within approximately one unit of rapidity around the gluon (pseudo-)rapidity and a corresponding recoil taken up by the endpoint q and $\bar{q}$ [9]. For a collinear gluon, the energy in the qg (or $\bar{q}g$) leg is so small that this cannot break and produce a hadron at the gluon corner. The first break is instead on the other side of the gluon and the first rank hadron will contain the whole qg piece.

The singularities encountered in the gluon emission probability are thus in a natural way regularized by the soft fragmentation process. This manifestation of infrared stability is in fact necessary in order that a description of the strong interaction in terms of quarks and gluons should be meaningful.

For a given process, the three kinds of gluons are then taken care of in different ways. Perturbative QCD gives the probability for the emission of a hard, acollinear gluon in the process and such a gluon is explicitly described as a kink on a string that fragments. Soft central gluons do not significantly alter longitudinal fragmentation properties but give particles extra p_t as discussed above. We will in section 4.1 mention a scheme to simulate the p_t coming from such soft gluons, a simpler but often reasonable approximation is to maintain the Gaussian distribution of eq. (2) but increase the width. Collinear gluons, finally, give a negligible contribution to transverse momentum properties, but give a softening of the longitudinal fragmentation spectrum. This is because they delay the breaking of the colour field, and to produce a fast particle the field has to break early. Although the physical interpretation differs, the numerical results obtained here is similar to the one obtained e.g. in jet calculus [21].

2.4. Hadron and diquark fragmentation

In a low-p_t nondiffractive hadronic interaction, we picture the incoming hadrons as colour bags containing two or three (for mesons and baryons, respectively) colour "blobs", corresponding to the smeared-out valence quark wavefunctions [6]. We then expect that, with a certain probability, there will be a connection between two blobs from the two incoming hadrons, so that the two bags do not separate again after the collision. Instead a string is stretched in the central region just like between a $q\bar{q}$ pair in e^+e^- annihilation. The energy for this string is taken from the valence quarks, which hence are retarded. Depending on the original hadron wavefunction the quarks will initially have different amounts of energy, and thus lose their energy differently fast. After one quark has lost its energy it will stop, but the remaining quark(s) may continue until the string has been stretched to a full length determined only by the initial hadron energy. The quark at the end of the string, which was the last to stop, we will refer to as the L-quark (L for leading), the quark closest to the central region will be called I-quark (I for interacting) and the middle quark in a baryon jet J-quark (J for junction). The positions along the string at which the J- and I-quarks stop are called x_J and x_I, respectively, with $x_L = 1$ by definition.

Quark–antiquark (antidiquark–diquark) pairs can as usual be produced in the field stretched between the endpoint L-quarks via the J- and I-quarks. Since the absolute positions of the J- and I-quarks are determined by the wavefunction, the iterative structure of section 2.1 will be somewhat broken. We note that for a baryon jet the field changes direction at the J-quark, so that a produced quark is always pulled towards the J-quark. Hence the string piece that contains the J-quark always becomes a baryon. Also the L- or I-quark or both of them may be included in the baryon if no breaks occur in the corresponding string pieces. The L- and J-quarks, if included in the same baryon, are assumed to retain a memory of their total spin and in this case act just like a LJ diquark. The I-quark, which takes part in the primary interaction and also is the first to stop, is, however, always assumed to lose all spin correlations with the rest of the system. As previously, SU(6) factors are included for the production of a baryon.

The precise physical structure of the colour field in the central region, i.e. between the two I-quarks, is still not well explored. We will assume that this central region is spanned by an ordinary string with a random "endpoint" quark (antidiquark) in direct association with one I-quark and its antiquark with the other I-quark. One could, however, imagine a more complicated structure, e.g. with gluons at the endpoints rather than quarks.

In e.g. leptoproduction, when one quark is kicked out by the virtual probe, the fragmentation of the target remnant will be very similar to that of a baryon jet as described above [8]. The difference is that the I-quark (which is kicked out) will give rise to a jet of its own in the current fragmentation region. We will then use the same idea of a stepwise stretching of the string for the LJ diquark fragmentation as we did for baryon fragmentation. Even the distribution of x_J will be assumed the same, although this is not strictly necessary.

It might seem that this diquark picture is in disagreement with the one presented in section 2.2. This need not be so. In that case the important point was the probability to create a diquark–antidiquark pair which then is accelerated by the field. How the two quarks of the diquark share the energy gain is, however, of no interest, since they anyhow will enter the same hadron. In the present case a diquark exists in the initial state and is retarded by the field. Depending on the initial baryon wavefunction and on how the field breaks, the L- and J-quarks may but need not end up in the same hadron. In the case that they do (i.e. actually more than 50% of the time) there will be no difference compared to a diquark in the sense of section 2.2.

3. Single jets

A jet is created by an outgoing coloured parton (quark, diquark, gluon) and can hence never appear alone. Sometimes it is however useful to study the fragmentation of a single jet as a first approximation, without the added complication of joining the jets in the centre etc. In this chapter we will then consider such "infinite energy" jets of different kinds.

3.1. Quark jets

Assume a primary quark q ($q = u, d, s, c, b, \ldots$) going out along the $+z$ axis. In the colour field behind q a $q_1\bar{q}_1$ pair is created and pulled apart. A meson $q\bar{q}_1$ is formed leaving a remainder-jet q_1 which then will serve as starting point for further breaks in an iterative fashion. Hence primary mesons $q\bar{q}_1$, $q_1\bar{q}_2$, $q_2\bar{q}_3$, etc., are formed.

The production of different quarks in the field is in principle determined by the tunneling formula (eq. (2)), which e.g. tells us that c quark production in the field can be completely neglected. Quark masses are, however, uncertain enough that we choose to introduce as free parameter the suppression of s-quark production compared to u- or d-quark one. Experimentally this seems to be a number in the range $s/u = 0.30–0.35$, in agreement with theoretical prejudices.

The quark and the antiquark may combine either to produce a pseudoscalar or a vector meson (higher resonances are neglected). From SU(6) spin counting one would expect this to take place in the proportions 1:3, whereas the experimental figures seems to be closer to 1:1. This could be related to the difference between pseudoscalar and vector meson masses, but we have no theory for this and hence accept it as a free parameter. The diagonal flavour combinations $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ are mixed to produce the pseudoscalars π^0, η and η' and the vectors ρ^0, ω and ϕ. Basically this flavour mixing is known, although with some uncertainties for η and η'.

Occasionally an antidiquark–diquark pair may be created in the field rather than a quark–antiquark one, with the constraint that two adjacent breaks may not both be of this type, since we disregard the possibility of bound diquark–antidiquark states. In addition to the s-quark suppression, three further parameters are introduced to describe the production probabilities in this case. The first is the suppression of diquark pair production compared to quark pair production. From SPEAR data we determined it to be $qq/q = 0.065$ [7,22], while recent PETRA and PEP data [23] would suggest a higher value, perhaps 0.08. Within the errors there need be no contradiction between these two figures; as a compromise we choose 0.075. The second parameter is the suppression of spin 1 diquarks compared to spin 0 ones, excluding the naive enhancement of spin 1 diquarks by a factor of 3 due to spin counting. This can be related to the $ud_1 - ud_0$ mass difference and from there to the $\Sigma^0 - \Lambda$ ditto, however with rather large uncertainties. The value used in the program is $(1/3)ud_1/ud_0 = 0.05$, but very little will depend critically on this choice. The final parameter is the extra suppression of strange diquarks in addition to what is implied by the strange quark suppression. This comes about since the tunneling probability is an exponential in m^2 and not in m, so that the diquark and strange quark suppressions do not factorize. In the program we use $(us/ud)/(s/d) = 0.2$, but again this is not critical.

A given quark–diquark pair may combine either to produce a spin 1/2 ("octet" if only u, d and s quarks are considered) or a spin 3/2 ("decuplet") baryon (again neglecting higher resonances). Special case is here necessary since, in distinction to the meson care, different flavour combination have different number of states available (for uuu only Δ^{++} is available, while uds may either become Λ, Σ^0 or Σ^{*0}). In SU(6) this may be expressed by giving each quark–diquark combination a weight, i.e. probability to be accepted so that, were it not for the tunneling suppression factors above, the different baryons would be produced in proportion to their number of spin states, i.e. 2 for spin 1/2 and 4 for spin 3/2 baryons. As in the case for mesons, one could imagine a suppression of the heavier spin 3/2 baryons, parametrized by reducing the weight for the spin 3/2 states by a given factor. Due to lack of data it is not known if such a reduction is necessary, and we will hence neglect it for the moment.

If a given quark–diquark combination is not accepted above, properly both the quark and diquark flavours should be chosen anew. This would become a tedious process since then the hadron produced in the step before has to be thrown away as well. In practice only the last produced pair, be that the quark or diquark one, is thrown away. The error introduced by this is small.

Every quark or diquark is also supposed to have a transverse momentum $\bar{p}_t$ randomly distributed according to

$$f_q(\bar{p}_t)\,d^2p_t = \frac{1}{\pi\sigma^2}\exp\left(-\frac{p_t^2}{\sigma^2}\right)d^2p_t \qquad (4)$$

with the constraint that the total $\bar{p}_t$ of each pair created in the field be zero. The transverse momenta of the quarks are then added vectorially to give the $\bar{p}_t$ of the mesons formed from them. In principle σ is given by $\sigma^2 = \kappa/\pi$ from eq. (2), but then soft gluon effects, etc., come in addition, so that we leave σ as a free parameter. Experimentally $\sigma = 0.40$–0.45 GeV/c.

Since we by definition have chosen the primary quark q to go out along the z axis, it would in principle have no transverse momentum. However, the recoil effect from soft gluon emission can often be approximated by giving q a $\bar{p}_t$ just like for the pairs created in the field with this momentum assumed to be balanced elsewhere in the event. Hence such an option is available.

The primary quark q, going out along the $+z$ axis, initially carries the quantity $W_{+0} = E_0 + p_{z0}$. From W_{+0} the fist rank hadron $q\bar{q}_1$ takes the $E + p_z$ fraction $z_{+1} = (E + p_z)_{q\bar{q}1}/W_{+0}$ leaving $W_{+1} = (1 - z_{+1})W_{+0}$ to the remaining q_1 jet, from which the second rank hadron $q_1\bar{q}_2$ takes a fraction z_{+2}, etc. Basically we expect to have a flat distribution in z_+ (eq. (1)), however with corrections from collinear gluons and finite field sizes.

Collinear gluons modify eq. (1) to an effective distribution

$$f(z_+)\,dz_+ = (1 + c)(1 - z_+)^c\,dz_+\,, \qquad (5)$$

where c in first order QCD is given by

$$c = \frac{4}{3}\,\frac{12}{33 - 2n_f}\left(\ln\ln\frac{M^2_{\text{upper}}}{\Lambda^2} - \ln\ln\frac{M^2_{\text{lower}}}{\Lambda^2}\right). \qquad (6)$$

Here M^2_{upper} corresponds to the limit above which a gluon is explicitly taken into account (see section 4.3) while M^2_{lower} corresponds to a cutoff at typical hadron masses. Λ is the usual QCD scale parameter. Again the theoretical uncertainty is large enough that it is feasible e.g. to choose the c value for u and d quarks as free parameter and only use eq. (6) to relate this to what is implied for the fragmentation of a heavier quark (where M^2_{upper} and M^2_{lower} are different). Experimentally then $c \approx 0.5$ for u and d quarks, which implies $c \approx 0.35$ for s, ≈ 0.15 for c and ≈ 0.05 for b quarks. The formula is derived explicitly for the case of a first rank hadron, but we will assume that the effect in further steps will be of the same type, where the flavour of the remnant-jet specifies the c value to be used.

The effects of finite field lengths will be taken into account by the introduction of a weighting factor at each pair production vertex

$$|g|^2 = \frac{(\kappa\tau)^2}{(\kappa\tau)^2 + m^2_{tq}} = \frac{\Gamma}{\Gamma + m^2_{tq}}, \qquad (7)$$

where m_{tq} is the transverse mass of the quark (or diquark) pair created at the vertex. The factor Γ_i may be calculated recursively

$$\Gamma_0 = 0, \qquad (8)$$

$$\Gamma_i = (1 - z_{+i})\left(\Gamma_{i-1} + \frac{m^2_{ti}}{z_{+i}}\right), \qquad (9)$$

with m_{ti} the transverse mass of the hadron $q_{i-1}\bar{q}_i$. If this "Γ-weighting" fails, the latest choice of flavour, transverse momentum and z is invalidated and has to be remade. The effects on the flavour distribution from this are small, but it introduces a correlation between z and p_t for hadrons.

After a hadron has been accepted, p_z and E for it are found according to

$$p_z = \tfrac{1}{2}\left(z_{+i}W_{+(i-1)} - \frac{m^2_{ti}}{z_{+i}W_{+(i-1)}}\right), \qquad (10)$$

$$E = \tfrac{1}{2}\left(z_{+i}W_{+(i-1)} + \frac{m^2_{ti}}{z_{+i}W_{+(i-1)}}\right). \qquad (11)$$

The perhaps most known jet generation scheme, the Field–Feynman (FF) one [14], is similar to the model presented above. The major difference is in the longitudinal fragmentation. There an effective fragmentation function

$$f(z_+)\,dz_+ = \left(1 - a + 3a(1 - z_+)^2\right)dz_+\,, \qquad (12)$$

with $a = 0.77$ is used. Charm and heavier quarks are not included in the FF model, but are traditionally introduced by using a shape similar to eq. (12) or of the type

$$f(z_+)\,dz_+ = (1+b)z_+^b\,dz_+, \tag{13}$$

with $b \geq 0$ for the first rank meson (containing the heavy quark) and then the ordinary function afterwards. In our implementation of the FF scheme it is also possible to produce baryons, again not included in the FF recipe, according to our own model.

3.2. Hadron and diquark jets

Depending on the initial wavefunctions, the J- and I-quarks will stop at different positions along the string, expressed by x_J and x_I. As reasonable parametrizations of these probability distributions we choose

$$f_J(x_J)\,dx_J = 6x_J(1-x_J)\,dx_J \tag{14}$$

for baryon and diquark jets

$$f_{Ib}(x_I)\,dx_I = \frac{\theta(x_J - x_I)}{x_J}\,dx_I \tag{15}$$

for baryon jets (the θ function means that the I-quark always lies behind the J-quark) and

$$f_{Im}(x_I)\,dx_I = 2(1-x_I)\,dx_I \tag{16}$$

for meson jets. The corresponding positions in momentum space are given by $W_{+J} = x_J W_+$ and $W_{+I} = x_I W_+$.

Neglecting Γ-factors for the moment, the fragmentation function for a hadron jet is basically given by eq. (5). However, we do not expect any collinear gluons to be associated with the string piece between the L- and J-quarks, since these two separate at a rather late stage, after most gluon radiation has taken place. Hence, until the J-quark has been included in a baryon, eq. (1) will be used instead.

With the scaling variable z_{+i} chosen, it is possible to check the remaining $W_{+i} = (1 - z_{+i})W_{+(i-1)}$ against W_{+J} and W_{+I} to see if either the J-quark or I-quark or both should be included in the hadron to be formed. In a step when neither is included, the flavour fragmentation scheme of section 3.1 carries over unchanged. Let us then consider the modifications when including a J- or I-quark.

The J-quark may either be included in the first rank hadron together with the L-quark, or in a higher-rank hadron together with a remnant-quark from the L-quark jet fragmentation (in this case a remnant-antidiquark is not an acceptable alternative, if this happens the generation is started over). In addition a third quark will go into the hadron, either the I-quark or a quark created in the field behind the J-quark. The probability for these three quarks to go into a baryon is calculated using the ordinary SU(6) factors. Note that if the L-quark is included in the baryon, then the L- and J-quarks already are in a diquark state, so that the SU(6) factors on the average will be larger than for three quarks at random. The probability for the L- and J-quarks to stick together is thus enhanced approximately from 50 to 60%. If the SU(6) weighting fails, the complete jet is generated anew (but with the same x_J and x_I values).

An I-quark will always be assumed to lose any spin correlation with the rest of the original hadron. Hence, when the I-quark is included in a meson or a baryon, possibly together with the L- and/or J-quark, it will be treated precisely like an ordinary quark created in the field. The only exception is that if we are to combine it with a diquark created in the field no SU(6) weighting is performed, since we can not throw away the I-quark (in practice this shortcoming is not very significant). When the I-quark is included in the hadron, there is no ordinary remnant-flavour left. Therefore a new flavour (q, $\bar{q}$, qq, $\bar{q}\bar{q}$) is generated according to customary probabilities for pair production in the field and forms the starting point for the rest of the flavour chain. The kinematics for this is treated as if the I-quark and this new flavour were an ordinary $q'\bar{q}'$ pair coming out from a common vertex with $W_+ = W_{+i}$ (for a hadron produced in the ith step).

Pairs created in the field during the fragmentation are again assumed to have transverse momenta according to eq. (4). The L- and J-quarks, normally not given any p_t, may be given opposite and compensating p_t (corresponding to the relative

Fermi motion, which is expected to be smaller than the ordinary fragmentation p_t), and may also share a p_t (to be balanced elsewhere in the event) just like a leading quark. The I-quark together with its associated new flavour are given a p_t in the same way as q'q̄' pairs.

Finally, a weighting in Γ is performed as for ordinary quark jets, with one modification. The field changes polarity at the J-quark, so that for a q'q̄' pair created between the L- and J-quark the relevant invariant time should be calculated from the point where the J-quark stopped. The iteration formula of eq. (9) is hence replaced by

$$\Gamma_i = \left((1-z_{+i})W_{+(i-1)} - W_{+J}\right) \times \left(\frac{\Gamma_{i-1}}{W_{+(i-1)} - W_{+J}} + \frac{m_{ti}^2}{z_{+i} W_{+(i-1)}} \right) \quad (17)$$

for particles in front of the J-quark and

$$\Gamma_i = (1-z_{+i})W_{+(i-1)} \times \left(\frac{\Gamma_{i-1}}{W_{+(i-1)} - W_{+J}} + \frac{m_{ti}^2}{z_{+i} W_{+(i-1)}} \right) \quad (18)$$

for the particle containing the J-quark.

Within the program it is possible e.g. to require the LJ-diquark always to stick together and go into the first rank hadron. Iterative models of the type qq → hadron + qq' [24] are, however, not implemented. Field–Feynman fragmentation functions are available as for quark jets, but this is of course not a standard feature of the FF model.

3.3. Gluon jets

An "infinite energy" gluon jet in the Lund model consists of two string pieces joined at the tip, at the gluon itself. The two string pieces will break by the production of a $q_1\bar{q}_1$ and a $q_2\bar{q}_2$ pair, respectively (where one of q_1 and q_2 may represent an antidiquark). A hadron $q_1\bar{q}_2$ is thus formed at the gluon corner. For each of the q'q̄' pairs a $\bar{p}_t$ is defined as in eq. (4), which add vectorially to give the p_t of the hadron.

When the string is stretched, the gluon will lose its energy equally rapidly to the two string pieces, so that the W_+ on the two sides are $W_+^{(1)} = W_+^{(2)} = W_{+g}/2$. The first rank hadron will take fractions $z_+^{(1)}$, $z_+^{(2)}$ of this so that

$$(E+p_z)_{hadron} = z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)} = \left(z_+^{(1)} + z_+^{(2)}\right) W_{+g}/2. \quad (19)$$

The $z_+^{(i)}$ are distributed independently of each other according to eq. (5).

Finite field length corrections are given by the Γ_i factor from the two sides:

$$\left| g\left(\frac{\kappa\tau_1}{m_{tq1}}\right)\right|^2 \left| g\left(\frac{\kappa\tau_2}{m_{tq2}}\right)\right|^2 = \frac{\Gamma^{(1)}}{\Gamma^{(1)} + m_{tq1}^2} \frac{\Gamma^{(2)}}{\Gamma^{(2)} + m_{tq2}^2}. \quad (20)$$

Here a further degree of freedom for the $\Gamma^{(i)}$ is introduced, which is not specified by the $z_+^{(i)}$ alone. Defining $W_-^{(i)} = (E - p_z)^{(i)}$ and corresponding fractions $z_-^{(i)}$, the transverse mass m_t of the first rank hadron is given by

$$\left(z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)}\right)\left(z_-^{(1)} W_-^{(1)} + z_-^{(2)} W_-^{(2)}\right) = m_t^2 \quad (21)$$

which means that

$$0 < z_-^{(i)} W_-^{(i)} < \frac{m_t^2}{z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)}}, \quad i = 1, 2. \quad (22)$$

We will assume that $z_-^{(1)} W_-^{(1)}$ is uniformly distributed in the allowed range (the same will then apply to $z_-^{(2)} W_-^{(2)}$). The $\Gamma^{(i)}$ are then given by

$$\Gamma^{(i)} = \left(1 - z_+^{(i)}\right) W_+^{(i)} z_-^{(i)} W_-^{(i)}, \quad i = 1, 2. \quad (23)$$

What remains after the formation of the first rank hadron is an antiquark jet $\bar{q}_1$ with known $\bar{p}_t$, $E + p_z = (1 - z_+^{(1)}) W_+^{(1)}$ and $\Gamma^{(1)}$, and a correspondingly known quark jet q_2. The continued fragmentation of these jets wll then proceed as in two ordinary, independent quark jets.

Other gluon jet models advocated [25,26] and available here as options are ones where the gluon either fragments like a quark of random flavour (u, d, s, ū, d̄, s̄), possibly then with a somewhat softer fragmentation function, or like a quark–antiquark jet pair sharing the total energy according to the Altarelli–Parisi splitting function for g → qq̄.

(We do, however, not include the possibility of gluon jets with a radically different flavour content, as has been advocated e.g. in ref. [27].) Of course it is also possible to use the Field–Feynman fragmentation function in connection with the fragmentation of a gluon jet.

3.4. Finite jets and systems

The schemes above have to be complemented with a prescription for when to stop the jet generation. In our program this takes place when the remaining W_+ becomes less than e.g. 0.1 GeV so that no further hadrons with $p_z > 0$ may be generated. It must, however, be remembered that several of the particles created before this may well have large, negative p_z. For the study of scaling properties and "infinite energy" jets this doesn't matter. However, when generating jets in actual physical situations one could e.g. choose to keep all final particles with $p_z > 0$ or to keep all stable particles coming from primary hadrons with $p_z > 0$. We include the latter possibility as an option in the program.

It would with such cuts on momentum parallel to the respective jet axes be possible to generate systems of quark and gluon jets to simulate e.g. $q\bar{q}$, $q\bar{q}g$ or ggg events. Models of this kind would not conserve energy, momentum or flavour except as properties on the mean. Neither would they be Lorentz invariant. At high enough energies one would expect the errors to be small when interest lies mainly in the rather fast particles so that the joining of the jets in the centre does not enter. This is essentially the line followed in the Hoyer et al. [25] and Ali et al. [26] Monte Carlo programs, but with the addition of special routines that ensure energy, momentum and flavour conservation by suitable adjustments of the jets "post facto". The option to generate independent jets is also available in the present program, then with energy, momentum and flavour breaks preserved. In the following section we will, however, choose another approach to the question of generating jet systems.

4. Jet systems

In the Lund model, with quarks represented by endpoints of strings and gluons by kinks on strings, two basic jet configurations are possible. One is an open string with a quark and an antiquark in the ends and an arbitrary number of gluons in between: $q\bar{q}$, $qg\bar{q}$, $qgg\bar{q}$, etc. The other is a closed gluon loop: gg, ggg, etc. Any jet system may be built up by combining such basic configurations. Note that for systems with four or more jets a given setup of parton flavours and momenta will not uniquely specify the string configuration. In ref. [28] this problem is studied for some specific processes.

In the following we will study the simulation of the different jet systems. In addition to what has been discussed in the previous section, three questions will be of importance: how to join two jets, the kinematics at gluon corners and cuts against soft and collinear gluons.

4.1. Quark–antiquark jet systems

The simplest jet system is the $q\bar{q}$ event. Seen in the CM frame we have a quark q going out in the $+z$ direction and an antiquark $\bar{q}$ in the $-z$ direction, with $W_{+0} = W_{-0} = E_{\rm cm}$, the centre of mass energy.

Neither the Lund nor the Field–Feynman fragmentation function is completely symmetric, in the sense that the final result is different if a jet system is generated from right to left or from left to right. To overcome partly this limitation, we will at each step of the generation scheme allow a particle to be formed with equal probability on either side of the then remaining system. We will refer to these as right $(+z)$ or left $(-z)$ side hadrons, keeping in mind that this flavour and coordinate space ordering may look entirely different in momentum space.

The scaling function to be used is $f(z_+)$ for a right side hadron and $f(z_-)$ for a left side one. The scaling variable z_+ (z_-) may no longer take all values between 0 and 1, constraints coming from conservation of energy and momentum. The (non-optimal) constraints used are

$$\frac{m_\perp^2}{W_+ W_-} < z < 1 - \frac{m_\perp'^2}{W_+ W_-}. \tag{24}$$

The lower cut corresponds to the hadron with transverse mass $m_\perp$ taking all the $W_-(W_+)$ available, the upper to the presence of a remaining system which has to take some $W_+(W_-)$. As the minimum mass of such a system $q_1\bar{q}_2$ we take $m'_t = m_{q1} + m_{q2}$. Each hadron formed takes a fraction both of W_+ and W_-, thus if the ith hadron is formed on the right side

$$W_{+i} = (1 - z_{+i}) W_{+(i-1)}, \tag{25}$$

$$W_{-i} = W_{-(i-1)} - \frac{m_{ti}^2}{z_{+i} W_{+(i-1)}}. \tag{26}$$

In the Lund model, a matrix element factor $|g|^2$ according to eq. (3) will appear for each $q'\bar{q}'$ pair created. Hence we have to keep track of a Γ_+ on the right side and a Γ_- on the left side. These may be obtained recursively as in eq. (9), but with the difference that whereas a left-side hadron will take a part of the total W_+, it will not influence the value for Γ_+. Hence we need to keep track of a variable $\tilde{W}_+$ which only depends on how much $E + p_z$ right side hadrons carry away, so that in the formation of such a particle

$$\begin{aligned} \tilde{W}_{+i} &= \tilde{W}_{+(i-1)} - z_{+i} W_{+(i-1)} \\ &= (1 - \tilde{z}_{+i}) \tilde{W}_{+(i-1)}, \end{aligned} \tag{27}$$

where it is the thus-defined $\tilde{z}_{+i}$ that enters in eq. (9).

The separation-off of hadrons may go on as long as the energy of the remaining system is sufficiently large. At some point, when

$$(W_+ W_-)_{\text{remaining}} < W_{\min}^2, \tag{28}$$

it is decided that the next breakup will give the final two hadrons rather than a hadron and a remainder-system. Basically $W_{\min}$ should be determined so that a flat rapidity plateau is obtained at high energies. This roughly corresponds to an average $W_{\min}$ of 2.4 GeV with the Lund fragmentation scheme and 2.9 GeV with the Field–Feynman parametrization.

Ideally, each particle type by itself should give a flat rapidity plateau. In practice this is unattainable, but a marked improvement is obtained if $W_{\min}$ is made flavour-dependent. For a $q_i\bar{q}_j$ system which breaks by the production of a, possibly final, $q_n\bar{q}_n$ pair, $W_{\min}$ may be written

$$W_{\min} = \left(W_{\min}^0 + m_{qi} + m_{qj} + k m_{qn}\right)(1 \pm \delta). \tag{29}$$

Here $k = 2$ corresponds to the mass of the final pair being taken fully into account. Smaller values may also be considered, depending on what criteria are used to define the "best" joining.

The $1 \pm \delta$ factor signifies a smearing of the $W_{\min}$ value, e.g. $1 \pm \delta$ randomly distributed between 0.8 and 1.2, to avoid an abrupt and unphysical cutoff in the invariant mass distribution of the final two hadrons. Still, this distribution will be somewhat different from that of any two adjacent hadrons elsewhere. Due to the cut in eq. (28) there is no tail up to very high masses; there are also fewer events close to the lower limit, where the two hadrons are formed at rest with respect to each other.

For the two final hadrons the respective masses and transverse momenta and the remaining W_+ and W_- are known (flavour and $\bar{p}_t$ properties of the final $q_n\bar{q}_n$ pair are as for the other $q'\bar{q}'$ pairs created in the field, except that for q_n an antidiquark the SU(6) checks for matching flavours can only be done with respect to one of the adjacent $q'\bar{q}'$ pairs). If $W_+ W_-$ is too small, no kinematically allowed solution will exist, in which case we reject all previous steps and start all over again. Otherwise two possible solutions exist, one in which the right side hadron moves to the right in the CM frame of the two hadrons, and one in which it moves to the left. The probability for the latter, reverse, ordering is smaller for two adjacent hadrons elsewhere in the chain, hence a corresponding behaviour is put in by hand for the final two hadrons. A good parametrization is

$$P_{\text{reverse}} = \tfrac{1}{2} - a\left(1 - \frac{m_{t1} + m_{t2}}{(W_+ W_-)^{1/2}}\right)^b, \tag{30}$$

where m_{t1} and m_{t2} are the transverse masses of the final two hadrons and W_+ and W_- corresponding remaining quantities. We choose $a = 0.32$ and $b = 0.5$ in the Lund scheme and $b = 0.8$ with the Field–Feynman parametrization.

The recipe above will conserve energy, momentum and flavour at each step of the generation process. The result will agree with the single quark jet recipe for the fast particles on either side while we obtain a smooth joining of the two jets in the centre. It is, however, important to remember that no scheme of this kind can be made entirely consistent.

The scheme as discussed so far allows for an initial $q\bar{q}$ pair and the production of new quark–antiquark or antidiquark–diquark pairs in the colour field between them. However, just as in section 3.2, this can be extended to diquark or hadron jets. J- and I-quarks from the right-moving initial hadron are given positions W_{+J} and W_{+I}, while those from the left-moving hadron are given positions W_{-J} and W_{-I}. These quarks are included in the hadrons which, during the fragmentation, take the corresponding portions of the string. Normally a central flavour chain is stretched between the two I-quarks. For lack of something better to do, when a flavour is generated in association with one I-quark, the corresponding antiflavour is associated with the other I-quark, and in between ordinary breakups are allowed to take place. If, however, most of the energy has been used up before the I-quarks are included in hadrons, it may be that the two I-quarks end up in adjacent hadrons. In that case no central flavour chain is necessary, and the kinematics is handled as were the I-quarks coming from a common vertex.

A rather freestanding part of the program, only implemented for simple two-jet systems, is a simulation of the transverse momentum effects from soft gluons, as discussed in section 2.3. The central region in pseudorapidity space is divided into a number of bins with a width around $\Delta y = 1$. In each bin the gluons are summed up to one effective gluon with p_t according to [9]

$$\frac{d^2P}{d^2p_t} = \frac{1}{2\pi} \frac{a}{p_t^{2-a} M^a} \theta\left(M^2 - p_t^2\right), \tag{31}$$

where

$$a = \frac{4}{3\pi} \bar{\alpha}_s \, dy, \tag{32}$$

$$M = W\left[e^{|y|} + \min\left(\frac{W}{M_0}, \frac{W^2}{2M_0^2} e^{-|y|}\right)\right]^{-1}. \tag{33}$$

Here $\bar{\alpha}_s$ is the effective strong coupling constant and M_0 gives the cutoff of the soft gluon region (in terms of the cutoffs to be introduced in section 4.3, $M_0^2 = 8m_a^2 \approx 8$ GeV^2). This $\bar{p}_t$ is then distributed among the particles around the gluon pseudorapidity and a recoil is taken up by the endpoints and distributed in proportion to the W_+ or W_- fractions. This procedure will conserve the momentum, i.e. the central soft gluon $\bar{p}_t$ is exactly compensated by the recoil, but the total energy will in our scheme not be conserved exactly (although the deviations are not very large). This breaking has been forced on us since the $\bar{p}_t$ contribution from a soft gluon on a hadron depends on the pseudorapidity range subtended by the hadron, while an exact calculation of this range requires that the total $\bar{p}_t$ is already known. What we in fact do is to add the soft gluon $\bar{p}_t$ as perturbations on an ordinary event and recalculate the energies of the hadrons after this. This option in the program may be necessary e.g. for a study of "primordial k_t" in leptoproduction, but in general a good representation of the data is obtained by an increase in the Gaussian p_t width and/or by giving the endpoint quark–antiquark pair opposite transverse momenta just like a quark–antiquark pair in the field (such an option is also available for two-jet events).

4.2. *The gluon kinks*

Assume an arbitrary jet system characterized by the parton momenta and an ordering of the partons along the string stretched between them. For the purposes of our generation scheme an alternative setup of kinematical variables is calculated. The direction of each outgoing parton is characterized by standard polar and azimuthal angles θ and ϕ. The transverse velocity of each string piece is called β. With respect to a given parton, a string piece attached to it is characterized by an opening angle α between the parton and the string (longitudinal) direction and an azimuthal angle χ of the string around the parton direction.

With these quantities defined, the treatment of each string piece may be done with the string along the z axis. Thereafter the string may be transformed to the correct position by 1) a Lorentz boost $+\beta$ along the x direction, 2) a rotation $-\alpha$ in polar angle, 3) a rotation $+\chi$ in azimuthal angle, 4) a rotation $+\theta$ in polar angle and 5) a rotation $+\phi$ in azimuthal angle. Here the set

$(\alpha, \chi, \theta, \phi)$ may, for a given string piece, be defined with respect to either of the two partons between which the string piece is spanned. In fact, we will come to use both these possible characterizations for different parts of a given string piece.

Again the gluon will, in our semiclassical scheme, lose its energy equally rapidly to both legs attached to it. This is so since, although the string piece actually drawn out by the gluon per unit time is proportional to cos α, this string piece moves with a transverse velocity $\beta = \sin\alpha$, so that the energy density per unit length is a factor $1/\cos\alpha$ higher than for a string at rest.

A string piece at rest along the z axis, as described above, is then characterized by the energy variables W_+ and W_-. The product $W_+ W_-$ is the invariant mass squared of the two partons between which the string piece is stretched, however with a factor 1/2 multiplying a gluon momentum, since this momentum is to be shared between two strings. The definition of what is the + direction is not unique (e.g. a change in definitions $\alpha \to \pi - \alpha$, $\chi \to \chi + \pi$ gives $W_+ \leftrightarrow W_-$). An arbitrary orientation along the string is chosen by hand, so that each gluon has one string piece "coming in", where the gluon defines the + direction (and $\alpha < \pi/2$), and one piece "going out", for which the same gluon defines the − direction (and $\alpha > \pi/2$). Note that this is different from section 3.3, where both string pieces had the gluon in the + direction.

For the study of the production of a first rank hadron at a specific corner, e.g. placed along the $+z$ direction, we will, however, choose a notation more consistent with the one in section 3.3. Let f for forwards denote the direction towards the gluon corner, i.e. the − direction in string 1 and the + direction in string 2, and b for backwards denote the direction away from the gluon corner. The requirements that the first rank hadron be on mass shell leads to a generalization of eq. (21):

$$A z_b^{(1)} + B z_b^{(2)} + C z_b^{(1)} z_b^{(2)} = D. \qquad (34)$$

Here A, B, C and D are functions of the $z_f^{(i)}$, $W_+^{(i)}$, $W_-^{(i)}$, $\alpha^{(i)}$, $\chi^{(i)}$, $p_x^{(i)}$ and $p_y^{(i)}$ of the two systems $i = 1, 2$. The complete expressions are to be found in the program. For the simplifying case when the transverse momenta $\bar{p}_t^{(i)}$ of the two quark–antiquark pairs are 0, we have (note that $\cos\alpha^{(1)} < 0$ and $\cos\alpha^{(2)} > 0$)

$$A = \left(z_f^{(1)} W_f^{(1)} - \frac{\cos\alpha^{(1)}}{\cos\alpha^{(2)}} z_f^{(2)} W_f^{(2)} \right) W_b^{(1)}, \qquad (35)$$

$$B = \left(z_f^{(2)} W_f^{(2)} - \frac{\cos\alpha^{(2)}}{\cos\alpha^{(1)}} z_f^{(1)} W_f^{(1)} \right) W_b^{(2)}, \qquad (36)$$

$$C = -\cos\alpha^{(1)} \cos\alpha^{(2)} \left(\tan^2\alpha^{(1)} - 2\tan\alpha^{(1)} \times \tan\alpha^{(2)} \cos\left(\chi^{(1)} - \chi^{(2)}\right) + \tan^2\alpha^{(2)} \right) \times W_b^{(1)} W_b^{(2)}, \qquad (37)$$

$$D = m^2. \qquad (38)$$

Eq. (34) describes an hyperbola in the $z_b^{(1)} - z_b^{(2)}$ plane, with the allowed region $0 \leq z_b^{(i)} \leq 1$. Also, to ensure that the leading hadron is not unreasonably soft, we reject sets of $z_f^{(i)}$, $\bar{p}_t^{(i)}$ such that solutions exist with $z_b^{(1)} + z_b^{(2)} > 1$. We will assume that the physical states are distributed uniformly along the hyperbola and select $z_b^{(i)}$ pairs accordingly. In the Lund scheme this will also define $\Gamma_f^{(i)}$ according to eq. (23) and the finite field length suppression factor in eq. (20). The momentum and energy of the first rank hadron is again given by expressions which in the special case of $\bar{p}_t^{(i)} = 0$ reduce to

$$p_x = -z_b^{(1)} W_b^{(1)} \sin\alpha^{(1)} \cos\chi^{(1)} + z_b^{(2)} W_b^{(2)} \sin\alpha^{(2)} \cos\chi^{(2)}, \qquad (39)$$

$$p_y = -z_b^{(1)} W_b^{(1)} \sin\alpha^{(1)} \sin\chi^{(1)} + z_b^{(2)} W_b^{(2)} \sin\alpha^{(2)} \sin\chi^{(2)}, \qquad (40)$$

$$E + p_z = -\left(z_f^{(1)} W_f^{(1)} + z_b^{(1)} W_b^{(1)} \sin^2\alpha^{(1)} \right) / \cos\alpha^{(1)} + \left(z_f^{(2)} W_f^{(2)} + z_b^{(2)} W_b^{(2)} \sin^2\alpha^{(2)} \right) / \cos\alpha^{(2)}, \qquad (41)$$

$$E - p_z = -z_b^{(1)} W_b^{(1)} \cos\alpha^{(1)} + z_b^{(2)} W_b^{(2)} \cos\alpha^{(2)}. \qquad (42)$$

A given jet system will, after the hadron around each gluon has been formed, essentially reduce to a number of simple $q\bar{q}$ jet systems, with remaining flavour and energy (W_+ and W_- of system, $\bar{p}_t$ at ends, Γ_+ and Γ_-) well known. These remnant-systems may be treated as described in section 4.1. A certain minimum energy is of course required for these systems, as is discussed in the next section. If these requirements are not fulfilled for a given setup of q′q̄′, z_+, z_- and $\bar{p}_t$, we start anew.

4.3. Physical cuts on event geometries

While single jets may be generated of any energy, since the scheme used for those is not required to conserve flavour or energy exactly, the same is not true for jet systems. A minimum energy will always be required in order to be able to produce any particles at all. There are also physically motivated cuts on soft and collinear gluons, as discussed in section 2.3. All these cuts are by necessity Lorentz invariant and can be discussed in terms of invariant masses.

The collinear singularity corresponds to the invariant mass of two partons joined by a string becoming small, so small that no particles may be produced from the energy in that string piece alone. The event shape then is very similar to a case when one parton is carrying the full energy and momentum, and any deviations should rather be considered as perturbations on this case. In actual practice, the way we treat a system is to cut off a first rank hadron at each gluon corner and then allow each remaining string piece to fragment into at least two hadrons. This makes for a straightforward generation sheme, whereas situations with e.g. only one hadron in a remaining string piece would require ad hoc routines, to shuffle energy back and forth at the gluon corners, in order to obtain exact energy and momentum conservation. But although the cuts presented below are somewhat harder than is theoretically required, they are still softer than the experimental resolution power of one jet into two, with the one exception of $\Upsilon \to \mathrm{ggg}$, which with our cuts almost always collapses to an effective two-gluon system.

The actual form of the cuts will differ for the three cases of a qq̄, a qg and a gg string piece. Let us introduce $m_a = 1$ GeV as an "average" hadron transverse mass in jet fragmentation, with $m_q + \frac{1}{2}m_a$ an estimate of the mass of a hadron containing q. Then for a qq̄ string piece, required to give at least two hadrons

$$M_{q\bar{q}}^2 = (p_q + p_{\bar{q}})^2 > (m_q + m_{\bar{q}} + m_a)^2. \tag{43}$$

A qg string piece will only obtain half the gluon energy; in addition the energy must suffice for "half" the particle at the gluon corner and two particles in the string piece remaining after this. An estimate including the average relative motion of the hadrons gives

$$M_{q\frac{1}{2}g}^2 = \left(p_q + \tfrac{1}{2}p_g\right)^2 > \left(m_q + \tfrac{5}{2}m_a\right)^2. \tag{44}$$

Correspondingly for a g_1g_2 string piece, with half the energy of each gluon, two "half" particles at the corners and two particles in between

$$M_{\frac{1}{2}g\frac{1}{2}g}^2 = \left(\tfrac{1}{2}p_{g1} + \tfrac{1}{2}p_{g2}\right)^2 > (4m_a)^2. \tag{45}$$

Effectively these formulae can be summed up as

$$M_{\mathrm{string}}^2 = (\epsilon_1 p_1 + \epsilon_2 p_2)^2 > (m_1 + m_2 + m_a)^2, \tag{46}$$

where $\epsilon_i = 1$ for a quark (diquark) but $= 0.5$ for a gluon, and $m_i = \frac{3}{2}m_a$ is used for a gluon.

The other cut, against soft gluons, is not so much dictated by a requirement that the program should work as that it should give sensible results. Imagine a gluon g, which with strings are attached to two partons 1 and 2, which may be either quarks or gluons. It is suitable to study the event in a frame where partons 1 and 2 go out in opposite directions and the g goes out perpendicularly to them. If the gluon is weak in that frame, it will rapidly lose its energy and only remain as a transverse exictation on the 1–2 string by the time the soft fragmentation sets in, giving a slightly increased average p_t but otherwise no significant effects. From our knowledge of Γ ($\propto \tau^2$) in qq̄ systems and remembering that a gluon loses energy twice as fast as a quark, we may choose the cut

$$E_g'^2 > 8m_a^2, \tag{47}$$

using the prime to denote energies in this frame. To obtain the form of the cut in the CM frame, we note that, neglecting parton masses

$$E_g'^2 = \frac{(2E_g'E_1')(2E_g'E_2')}{(4E_1'E_2')} = M_{g1}^2 M_{g2}^2 / M_{12}^2. \tag{48}$$

For nonzero parton masses the exact expression will become more complicated without adding anything significantly new, so we will always use the cut

$$M_{g1}^2 M_{g2}^2 / M_{12}^2 > 8m_a^2. \quad (49)$$

In summary, we have two kinds of cuts. For each parton leg there is a requirement of a minimum invariant mass and for each gluon corner a requirement of a minimum transverse momentum. There are, however, no cuts on the invariant mass between two partons not joined by a string.

5. Particles and their decays

In the present paper we include four generations of quarks and leptons by a straightforward extension of the standard model for weak and electromagnetic interactions. Whereas strong arguments speak for the existence of three complete generations, i.e. also including the so far undiscovered top quark, there is certainly no theoretical need for a fourth one. While no experimentalist wuld have to worry about new quark thresholds much above the Z^0 mass for some time to come, the possibility, however remote, of discovering them e.g. at LEP may require some studies, and it is with this in mind that a set of fourth generation (and top) masses has been chosen. These masses may of course easily be changed, however with the W mass as the upper practical limit, since the possibility of on-mass-shell W's in the weak decay of a heavier quark or lepton would change some of our assumptions.

5.1. Partons and particles

Eight quarks are included: u, d, s, c, b, t (top, charge +2/3), l (low, charge −1/3) and h (high, charge +2/3), with the latter three not yet discovered. These may appear singly or in diquark pairs, then with the quarks consistently given in falling order and with the spin as subscript, e.g. du_0 (d and u quarks in spin singlet) or $\bar{\mathrm{c}}\bar{\mathrm{s}}_1$ ($\bar{\mathrm{c}}$ and $\bar{\mathrm{s}}$ quarks in spin triplet). In addition we of course have the gluon g.

From the quarks the pseudoscalar and vector meson and spin 1/2 and spin 3/2 baryon multiplets are built up. For the rare charm baryons and all bottom, top, low and high hadrons standardized particle names are given by the quark content (in falling order), the hadron spin configuration and the charge, e.g. $\mathrm{B}_{\mathrm{u}}^-$ (quarks b, $\bar{\mathrm{u}}$, spin 0, charge −1), $\mathrm{T}^{*+}_{\mathrm{d}}$ (quarks t, $\bar{\mathrm{d}}$, spin 1, charge +1), $\bar{\mathrm{H}}_{\mathrm{u}}^0$ (quarks $\bar{\mathrm{h}}$, u, spin 0, charge 0), $\mathrm{C}_{\mathrm{su0}}^+$ (quarks c, s, u, total spin 1/2 with su in spin singlet, charge +1), $\mathrm{B}_{\mathrm{dul}}^0$ (quarks b, d, u, total spin 1/2 with du in spin triplet, charge 0) and $\mathrm{T}^{*++}_{\mathrm{cu}}$ (quarks t, c, u, total spin 3/2, charge +2). New flavour neutral pseudoscalar combinations are denoted by η, e.g. η_{b}, η_{l}, while corresponding vector mesons are called ϕ, e.g. ϕ_{t}, ϕ_{h}. We will also consider $\mathrm{K}_{\mathrm{S}}^0$ and $\mathrm{K}_{\mathrm{L}}^0$ as separate particles, coming from the "decay" of K^0 and $\bar{\mathrm{K}}^0$.

The three known lepton families e, μ and τ are complemented by a fourth, tentatively called λ. The other particles of the standard theory for weak and electromagnetic interactions are also included: γ, Z^0, W^+, W^- and the neutral Higgs H^0.

5.2. Masses

Quark masses are not particularly well defined, but fortunately the choice of quark masses is not critical for most applications in our program. For the calculation of heavy hadron masses and for quark masses occurring e.g. in cuts on small systems we introduce "constituent" masses

$$m_{\mathrm{u}} = m_{\mathrm{d}} = 0.325\ \mathrm{GeV},$$
$$m_{\mathrm{s}} = 0.5\ \mathrm{GeV}, \quad m_{\mathrm{c}} = 1.6\ \mathrm{GeV},$$
$$m_{\mathrm{b}} = 5.0\ \mathrm{GeV}, \quad m_{\mathrm{t}} = 20\ \mathrm{GeV},$$
$$m_{\mathrm{l}} = 40\ \mathrm{GeV}, \quad m_{\mathrm{h}} = 80\ \mathrm{GeV}.$$

Constituent masses for diquarks are defined as the sum of the respective quark masses. The gluon is always assumed massless (although a confined gluon has an effective, nonzero mass, we will never find any reason to introduce this).

From the constituent quark masses the masses of yet undiscovered mesons and baryons are built up by using formulae of the type [29]

$$M = m_0 + \sum_i m_i + k \sum_{i<j} \frac{\langle \bar{\sigma}_i \cdot \bar{\sigma}_j \rangle}{m_i m_j}, \quad (50)$$

i.e. one rather small constant term, a sum over constituent masses and a spin–spin interaction term for each quark pair in the hadron, where a set of constant m_0 and k are fitted from known masses for mesons and baryons separately. The flavour neutral mesons are also defined separately, since there in particular the constant term may differ compared to mesons with one heavy and one light quark (although we also include other hadrons with several heavy quarks in our particle list, the corresponding production rates are very low, so a minor mismatch there would not matter).

While constituent masses correspond to "dressed" quarks, the quark–antiquark or antidiquark–diquark pairs created in the field probably have masses more akin to the "current algebra" ones, at least in the initial stages relevant for the tunneling probability (eq. (2)) and the finite field length corrections (eq. (3)). Only mass values in the order of $\sqrt{\kappa/\pi}$ will be sensitive to the precise choice made, since here the tunneling probability is a rapidly varying function of the mass. Hence we choose a rather simple approach, to subtract a constant term (0.2 GeV) off the constituent quark masses to obtain the "current algebra" ones. For diquarks also a constant term (0.1 GeV) is subtracted, but in addition the spin–spin forces are taken into account as in eq. (50), with the same constant k as for baryons.

The fourth generation lepton λ is assumed to have a mass of 30 GeV, while all neutrinos are assumed massless. The Z^0 is given a mass of 94 GeV and the W a mass of 83 GeV, according to best present estimates [30]. The value of the H^0 mass is considerably more uncertain, but has tentatively been fixed at 15 GeV.

Particle masses as discussed so far have been sharp, i.e. with no mass broadening for short-lived resonances such as ρ, K^* and Δ. As an option we include, however, the possibility to distribute the masses according to a Breit–Wigner shape

$$P(M)\,\mathrm{d}M = \frac{\Gamma}{2\pi}\frac{1}{(M-M_0)^2+\Gamma^2/4}\,\mathrm{d}M, \qquad (51)$$

truncated at some value $|M-M_0|<\delta$, with δ arbitrarily chosen so that no problems are encountered in the decay chains. It should be emphasized that such a truncated but symmetric Breit–Wigner shape often is a poor approximation, and never should be used for detailed studies of resonance production. It will, however, give a feeling for what mass smearing effects could mean.

5.3. Strong and electromagnetic decays

The decays of hadrons containing the "ordinary" u, d and s quarks into two or three particles are known and branching ratios may be found in ref. [31]. We assume that the momentum distributions are given by phase space, except for ω and ϕ decaying into $\pi^+\pi^-\pi^0$. Here a matrix element of the form

$$|M|^2 = |\bar{p}_{\pi^+}\times\bar{p}_{\pi^-}|^2 \qquad (52)$$

is used, where the $\bar{p}_\pi$ are the momenta in the rest frame of the ω and ϕ, respectively.

Also a number of decays involving resonances of heavier hadrons, e.g. $\Sigma_c^0\to\Lambda_c^+\pi^-$ or $B_u^{*-}\to B_u^-\gamma$, are treated in the same way as the other two-particle decays.

5.4. Weak decays of heavy hadrons

The weak decay of a meson $Q\bar{q}$ (or baryon Qqq') may, neglecting QCD corrections, go either as "free" quark decay

$$Q\bar{q}\to q_1\bar{q}_2q_3\bar{q} \quad \text{or} \quad l\nu_l q_3\bar{q} \qquad (53)$$

or via quark annihilation

$$Q\bar{q}\to q_1\bar{q}_2 \quad \text{or} \quad l\nu_l \qquad (54)$$

(in the latter only $Qqq'\to q_1q_2q'$ is possible for a baryon).

The structure of the weak mixing between the families, as described in the Kobayashi–Maskawa model naively extended to four families, motivates a simplification so that only the decay chain $h\to l\to t\to b\to c\to s$ need be considered in free quark decays.

For charm mesons and baryons some semi-leptonic branching ratios are known, which have to be complemented with "educated guesses" on the composition of hadronic decays. For B and T mesons the relative probabilities for the different processes are given by Ali et al. [32], and we use their results here. Heavier hadrons, and also B and T baryons, are taken to decay exclusively in the "free" quark decay channels.

The quarks produced in the primary decay interact in the final state so that only hadrons come out. The momenta of the leptons in semileptonic decays are determined by the primary decay matrix element, but this is not so for hadrons. We expect that the quarks stretch out colour force fields between themselves, fields which then may fragment into new hadrons just like ordinary jet systems considered in section 4. However, in c and b decays we do not expect jet-like decays, in particular in view of the fact that in most cases more than two jets share the available energy. We therefore will choose a phase space kind of decay scheme for these hadrons, as follows.

For the nonleptonic decays of charm and bottom hadrons we expect the average multiplicity to grow logarithmically with the available energy, with somewhat more particles in free quark decays (eq. (53)). Hence we will assume

$$\langle n \rangle = \frac{n_{\mathrm{q}}}{4} + c_1 \ln\left(\frac{M - \sum m_i}{c_2} \right) = \frac{n_{\mathrm{q}}}{4} + c, \tag{55}$$

where M is the mass of the decaying hadron, m_i are the "current algebra" masses of the final state quarks and n_{q} is the number of quarks (or diquarks) in the final state. The constants c_1 and c_2 should be determined experimentally; a good representation of D and B meson decay multiplicities is obtained with $c_1 = 4.5$ and $c_2 = 1.05$ GeV. For convenience we use a Gaussian decay multiplicity distribution of the form

$$f_n(n)\,\mathrm{d}n = \exp\left(-\frac{(n - n_{\mathrm{q}}/4 - c)^2}{2c} \right) \mathrm{d}n \tag{56}$$

(n rounded off to nearest integer, $n \geq 2$, $n \leq 10$).

Once the multiplicity n of a decay has been determined, our model gives the flavour of the hadrons in a way very similar to the scheme discussed in sections 3 and 4. Consider e.g. a weak decay giving four primary quarks q_1, $\bar{\mathrm{q}}_2$, q_3 and $\bar{\mathrm{q}}$. A pair $\mathrm{q}_4\bar{\mathrm{q}}_4$ (here q_4 may also be an antidiquark as usual) is now created, with equal probability in either of the three colour fields associated with the Q decay products (whereas the spectator quark $\bar{\mathrm{q}}$ is assumed to be less energetic and not produce a jet of its own). The pair is pulled apart to give a hadron, either $\mathrm{q}_1\bar{\mathrm{q}}_4$, $\mathrm{q}_4\bar{\mathrm{q}}_2$ or $\mathrm{q}_3\bar{\mathrm{q}}_4$, leaving behind a new state with four quarks. This procedure is iterated $n-2$ times, the final two hadrons being obtained by a random combination of the quarks then left. The hadrons created according to this quark jet picture are then, however, following the arguments above, given momenta according to phase space [33] only.

For semileptonic decays of charm and bottom hadrons, the energy in the final state $\mathrm{q}\bar{\mathrm{q}}$ or qqq system is usually so low that at most one extra slow pion could be produced, which would hardly be discernible from pions produced in secondary decays. We therefore only take into account three-particle decays

$$\mathrm{H} \to \mathrm{h} l \nu_l, \quad l = \mathrm{e}, \mu, \tau. \tag{57}$$

Here H is the decaying heavy hadron and h is the product. Phase space only would not suffice here, since the $\mathrm{e}^{\pm}$ and $\mu^{\pm}$ will give rise to energy spectra reflecting the primary decay, little disturbed by final state interactions and secondary decays, contrary to the case for hadrons. Instead the momentum distribution is determined by a matrix element [34]

$$|M|^2 = (p_{\mathrm{H}} p_{l^+})(p_{\nu_l} p_{\mathrm{h}}) \tag{58}$$

if the decaying heavy quark Q is a charge $+2/3$ one and

$$|M|^2 = (p_{\mathrm{H}} p_{\bar{\nu}_l})(p_{l^-} p_{\mathrm{h}}) \tag{59}$$

if it is a charge $-1/3$ one.

For hadrons containing a t, l or h quark the decay scheme is simpler. Both in hadronic and semileptonic decays the decay products are distributed according to the relevant matrix element; eq. (58) or eq. (59), with $\mathrm{H} \to \mathrm{Q}$ and $\mathrm{h} \to \mathrm{q}$, i.e. with the spectator mass subtracted off. In effect one may wish to subtract a bit more than the spectator quark mass, to take into account that the energy available in the decay is really the Q "current algebra" rather than the constituent mass. In principle the $q_1\bar{q}_2$ pair in hadronic decays in eq. (53) is a colour singlet (since it comes from the W exchanged) and $q_3\bar{q}$ another colour singlet, but there is a certain probability for a colour rearrangement via soft gluon exchange so that the singlets become $q_1\bar{q}$ and $q_3\bar{q}_2$. We take this probability to be 1/2, corresponding to a complete loss of initial order, but this is a free parameter in the program. This way two or, for semileptonic decays, one well defined jet system is obtained. The system containing the spectator quark will often have a mass too small to allow it to fragment like a jet system. In these cases one single particle is formed with a momentum vector corresponding to the sum of the two quark momenta. Since the energy of this particle then will come out wrong, the momenta of the other jets or leptons in the decay are modified slightly to obtain total energy conservation. For hadronic decays where the invariant mass of the system not containing the spectator quark is too small, which is a rather rare occurrence, the choice is rejected and a new setup of quark momenta is found.

5.5. Other decays

The hadronic decays of the heavy τ lepton are treated as the hadronic decays of c and b hadrons, except that $n_q/4$ is replaced by $n_q/4 + n_p/2$ in eqs. (55) and (56), where $n_p = 1$ corresponds to the existence of a ν_τ in the final state. No particular care is thus taken with the ν_τ energy spectrum. For the leptonic decays, we use the relevant matrix element

$$|M|^2 = (p_\tau \cdot p_{\bar{\nu}_l})(p_l \cdot p_{\nu_\tau}). \qquad (60)$$

Correspondingly the decays of the hypothetical λ lepton is treated according to the same scheme as for top and heavier hadrons, but with the matrix element similar to eq. (60).

The J/Ψ and the η_c decay predominantly via gluons, but the energies are so low that no jet structure can result. We will instead use a simple phase space model, with the same particle generation scheme as outlined for c and b hadron decays. The original $q\bar{q}$ pair needed in that formalism is taken just like any random flavour generated in jet fragmentation. The average multiplicity is not necessarily the same as in eq. (55), in fact we choose

$$c = c_1 \ln\left(\frac{M - \sum m_i}{c_2}\right) + c_3, \qquad (61)$$

with c_1 and c_2 as above and $c_3 = -1$ to obtain a smooth joining to a gg jet system at higher energies. For J/Ψ the leptonic channels are also included.

The higher η states ($\eta_b, \eta_t, \ldots$) decay predominantly into gg systems, which then fragment as usual. Corresponding vector meson states decay into ggg systems. The matrix element for this is implemented in ref. [10], which should be used for "onium" physics. Here they are just listed as decaying into two gluons. The Υ states form an unfortunate middle ground, too high for phase space models and too low for the development of three clear-cut gluon jets, and there is no simple solution to this within the Lund model. Since phase space models occasionally are used for comparison purposes, this is the decay given in the present paper. Obviously some admixture of, or complete replacement with, gg decays could also be tried.

Decay probabilities for Z^0 and $W^\pm$ to quarks and leptons are given, but it should be remembered that gluon bremsstrahlung will modify the simple two-jet picture of hadronic decays and that angular distributions usually are desired for comparisons with experiments. Such programs, where the exchange of γ/Z^0 or $W^\pm$ are explicitly taken into account for specific processes, are presented e.g. in refs. [10,11]. Also decay probabilities for the Higgs H^0 are included under the assumption that the H^0 mass is above the $b\bar{b}$ threshold. On the other hand the mass is probably so low that gluon radiation can be neglected. Since Higgs particles have no spin and thus decay isotropically in their CM frame, the problems of production and decay of H^0 completely separate, in contradistinction to the Z^0 and W cases.

6. The program components

Below we describe the different elements in the program. These basically are of three kinds:

1. physics subprograms for jet fragmentation and particle decays;
2. service subprograms for specifying initial jet/particle configuration and reading out the resulting event;
3. common blocks containing the event record, parameter values and particle data.

In any actual run, the main program is supplied by the user. Here he may

1. change default parameter values if desired;
2. specify initial jet/particle configuration;
3. have the resulting jet fragmentation and particle decay chain simulated;
4. study the event obtained.

No initializations are necessary (except for what is implied by the BLOCK DATA subprogram).

The program is written in FORTRAN 77. The only nonstandard feature is our use of a random number generator RANF giving numbers R with uniform probability distribution in the interval $0 < R < 1$. If a suitable random number generator is available under another name, a function RANF calling this generator should be created. Obviously, the compiler should not optimize RANF out of DO loops, etc. For LULIST we assume a standard output file with logical file number 6.

To avoid unnecessary name clashes and to help the user distinguish the commands to the Lund Monte Carlo, subroutine, function and common block names have been standardized. Hence almost all these names begin with LU, the exceptions being that real functions begin with UL and that the two functions KLU and PLU have K and P first to emphasize their relationship with these two matrices in the LUJETS common block.

6.1. Flavour codes and the event record

Each new event generated is in its entirety stored in the common block LUJETS, which hence forms the event record. Here each jet or particle that appears at some stage of the fragmentation and decay chain will occupy one line in the matrices. The different components in this line will tell which jet/particle it is, from where it originates, its present status (fragmented/decayed or not) and momentum, energy and mass for it. For some specific applications extra lines may be used to represent other kinds of information. Before specifying precisely how the event record is organized, we will comment on some components, in particular the jet/particle codes which also are used in other connections.

For the classification of jet and particle flavours two related codes exist, the IFL and the KF codes. Both assign integer numbers to the different objects in a unique way. Short lists for the most used codes are given in appendix A, and a complete documentation is available using LULIST.

The IFL code is used to characterize partons, i.e. gluons, quarks and diquarks. Quarks are given by numbers between 1 and 8, with $1 = \mathrm{u}$, $2 = \mathrm{d}$, $3 = \mathrm{s}$, $4 = \mathrm{c}$, $5 = \mathrm{b}$, $6 = \mathrm{t}$, $7 = \mathrm{l}$ and $8 = \mathrm{h}$, while $0 = \mathrm{g}$. Diquark numbers lie between 11 and 88 and are constructed by adding two quark numbers, one multiplied by 10, e.g. $11 = \mathrm{uu}_1$, $22 = \mathrm{dd}_1$. When combining two different quarks, the larger of the two possible numbers is used to represent the spin 1 combination and the smaller the spin 0 one, e.g. $21 = \mathrm{ud}_1$, $12 = \mathrm{ud}_0$. Antiquarks and antidiquarks are given by corresponding negative numbers, e.g. $-1 = \bar{\mathrm{u}}$, $-21 = \bar{\mathrm{u}}\bar{\mathrm{d}}_1$.

The KF code is used mainly to characterize particles: pseudoscalar and vector mesons, octet and decuplet baryons, leptons and intermediate vector bosons. As examples $1 = \gamma$, $7 = \mathrm{e}^-$, $9 = \mu^-$, $17 = \pi^+$, $18 = \mathrm{K}^+$, $41 = \mathrm{p}$. Again antiparticles, where existing, are given by corrresponding negative numbers, e.g. $-17 = \pi^-$.

For internal calculations and for specifying initial jet configurations the IFL code is used. However, in the event record, and also e.g. in decay data, jets and particles are mixed. In these cases the KF code is used, extended also to include jets. This is done by adding 500 to the IFL code for nonnegative IFL values and -500 for negative IFL, e.g. $500 = \mathrm{g}$, $501 = \mathrm{u}$, $521 = \mathrm{ud}_1$, $-501 = \bar{\mathrm{u}}$. Also, KF numbers larger than 600 are used in the event record to distinguish lines of extra information.

Another piece of information in the event record is the status code KS. Here 0 or 1 are used for jets/particles which have not fragmented/decayed, while 2 or 3 is used for those that have. Hence, initially the original jet/particle configuration will have KS 0 or 1, but as the fragmentation/decay proceeds, these will get 2 or 3 at the same time as the products appear with 0 or 1, so that in the end only stable particles remain with 0 or 1.

The use of four different values rather than two is to remove an ambiguity in the definition of colour singlet jet systems. In such a system, with the jets ordered the way the colour flux is assumed to go (for a gluon-only system the flow is taken to go on from the last jet to the first one to form a closed loop), all but the last one should have KS = 1 (which becomes 3 after fragmentation) to signify that the end of the system has not been reached. The last jet of a system, jets which are not assumed to form part of a system and particles all have KS = 0 (2 after fragmentation/decay). Without this convention, four consecutive gluons could either be treated as one colour singlet or as two.

Also other KS values are defined. To represent beam or target particles for documentation purposes, a code 4 should be used, while 5 fills the same function for virtually exchanged particles in the primary interaction. A line with KS = 6 is used to store extra information for hadron jets, while 7 indicates extra information for particles when using the soft gluon simulation option.

For each jet/particle, the line number of the immediate precursor (the parent) in the fragmentation/decay chain is stored. This way the complete event history can be studied. Note, however, that in the Lund model the relevant objects that fragment are not the partons but the strings between them. Hence a central particle (i.e. not containing any of the original partons) could be assigned to either of two jets. The actual jet number used in this case refers to the side of the string on which the particle was formed in the LUSYSJ routine. This number hence may be of little practical use, but in our belief reflects a basic uncertainty in nature.

COMMON/LUJETS/N, K(250,2), P(250,5)

N: is the number of lines in the K and P matrices occupied by the current event. N is continuously updated as definition of the original configuration and fragmentation and decays proceed.

K(I, 1): (KI) contains status and history information about the entry in the Ith line. It is of the form KI = 1000 × KS + KH, where KS is the status code outlined above and KH is the line number where the parent is stored (also see comment above). Note that KH = 0 for the original jets/particles, and also that all KH will be set 0 in LUEDIT calls.

K(I, 2): (KF) contains the KF flavour code for particles and jets, see above and appendix A.

P(I, 1), P(I, 2), P(I, 3): (PX, PY, PZ) the jet/particle momentum vector (p_x, p_y, p_z) in GeV/c.

P(I, 4): (PE) the jet/particle energy E in GeV.

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

Remark: for lines with extra information, KS = 6 or 7, P(I, 1)–P(I, 5) are given special meanings which differ from the ones used above.

For KS = 6, used in connection with hadron jets (corresponding to K(I, 2) between 601 and 688):

P(I, 1), (P(I, 2): x_J and line number for particle containing J-quark (0 if no J-quark).

P(I, 3), P(I, 4): ditto for I-quark.

P(I, 5): unused (set to 0).

For KS = 7, used in connection with soft gluon simulation (corresponding to K(I, 2) = 700):

P(I, 1), P(I, 2): z_+ and z_- coordinates for vertex to the right (+side) of particle.

P(I, 3), P(I, 4): ditto for vertex to the left (−side) of particle.

P(I, 5): unused (set to 0).

6.2. Definition of initial configuration

With the use of the conventions presented above, it is possible to specify any initial jet/particle configuration in the common block LUJETS. In general jets and particles may be mixed at will. Jets forming part of the same colour singlet system, however, should be ordered the way the colour flux is assumed to go. A single system may not consist of more than ten jets. Also, minimum invariant masses between two adjacent partons (i.e. partons connected with a string) are both physically motivated and necessary in order that the fragmentation routines should work. This demand is expressed in eq. (46). The further requirement of a minimum transverse momentum for each gluon with respect to the two adjacent partons, eq. (49), should also be fulfilled.

To simplify the specification of initial configuration, a few subroutines are available for standard tasks. Several calls can be combined in the specification. In case one call is enough, the whole fragmentation/decay chain may be simulated at the same time. At each call, the value of N is updated to the last line used for information in the call, so that if several calls are used, they should be made with increasing IP values, or else N should be redefined by hand afterwards.

SUBROUTINE LUPART (IP, KF, PE, THE, PHI)

Purpose: to add one particle to the event record.

IP: line number for the particle. If IP = 0, line number 1 is used and LUEXEC is called.

KF: particle flavour code.

PE: particle energy. If PE is smaller than the mass of the particle, e.g. PE = 0., the particle is taken to be at rest.

THE, PHI: polar and azimuthal angle for the momentum vector of the particle.

SUBROUTINE LU1JET (IP, IFL, IFLJ, IFLI, PE, THE, PHI)

Purpose: to add one quark, gluon, diquark or hadron jet to the event record.

IP: line number for the jet. If IP = 0, line 1 is used and LUEXEC is called. If IP < 0, line −IP is used, and the status code KS for this line becomes 1 instead of 0. Hence, although this routine is primarily intended for specifying independent jets, a jet system may be built up by filling all but the last jet of the system with IP < 0. If IFLJ or IFLI nonzero, two lines will be used to define the jet, the second with status code KS = 6 and meaning as described above.

IFL: flavour code for the leading quark, gluon or diquark.

IFLJ: flavour code for J-quark in leading diquark. IFLJ = 0 should be used for gluon or quark jets, and also for diquarks when the two quarks in it are assumed to be the J-quark with equal probability.

IFLI: flavour code for I-quark in hadron jet, IFLI = 0 if not a hadron jet.

PE: jet energy.

THE, PHI: polar and azimuthal angles for the momentum vector of the jet.

SUBROUTINE LU2JET (IP, IFL1, IFL2, ECM)

Purpose: to add a two-jet system to the event record.

IP: line number for the first jet, with second in line IP + 1. If IP = 0, lines 1 and 2 are used and LUEXEC is called.

IFL1, IFL2: flavour codes for the two jets.

ECM: (= W) the total energy of the system.

Remark: the system is given in the CM frame, with the first jet going out in the $+z$ direction.

SUBROUTINE LU3JET (IP, IFL1, IFL3, ECM, X1, X3)

Purpose: to add a three-jet system to the event record.

IP: line number for the first jet, with second in line IP + 1 and third in IP + 2. If IP = 0, lines 1 through 3 are used and LUEXEC is called.

IFL1, IFL3: flavour codes for the first and the third jet, while the middle one always is a gluon.

ECM: (= W) the total energy of the system.

X1, X3: $x_i = 2E_i/W$, i.e. twice the energy fractions taken by the ith jet.

Remark: the system is given in the CM frame, in the xz-plane, with the first jet going out in the $+z$ direction and the third one having $p_x > 0$.

SUBROUTINE LU4JET (IP, IFL1, IFL2, IFL3, IFL4, ECM, X1, X2, X4, X12, X14)

Purpose: to add a four-jet system (or, for IFL2 nonzero, two two-jet systems) to the event record.

IP: line number for the first jet, with the second in line IP + 1, third in IP + 2 and fourth in IP + 3. If IP = 0, lines 1 through 4 are used and LUEXEC is called.

IFL1, IFL2, IFL3, IFL4: flavour codes for the four jets (note that either both IFL2 and IFL3 are zero or none are).

ECM: ($= W$) the total energy of the system.

X1, X2, X4: $x_i = 2E_i/W$, i.e. twice the energy fraction taken by the ith jet.

X12, X14: $x_{ij} = 2p_ip_j/W^2$ i.e. twice the four-vector product of the momenta for jets i and j, properly normalized.

Remark: the system is given in the CM frame, with the first jet going out in the $+z$ direction and the fourth jet lying in the xz-plane with $p_x > 0$. The second jet will have $p_y > 0$ and $p_y < 0$ with equal probability with the third jet balancing this p_y (this corresponds to a random choice between the two possible stereoisomers).

6.3. Routines to study an event

After a call to LUEXEC, the event generated is stored in the LUJETS common block, as described above. Hence, whatever physical variable is desired may be constructed from the information stored there. Via the functions KLU and PLU the values of some frequently appearing variables may be obtained directly. Also some other facilities are available, to rotate or boost an event, to throw away unwanted jets/particles from the event record or to list an event or particle or jet data.

FUNCTION KLU (I, J)

Purpose: to provide various integer-valued event data. Note that some of the options available (in particular I > 0, J = 4–7) which refer to event history will not work after a LUEDIT call.

I = 0, J = : properties referring to the complete event.

= 1: N, total number of lines in event record.

= 2: total number of jets/particles remaining after fragmentation/decay.

= 3: three times the total charge of remaining (stable) jets/particles.

= 4: total number of jets in event, i.e. also those that have fragmented.

I > 0, J = : properties referring to the entry in line no. I of the event record.

= 1: K(I, 1) jet/particle status and history.

= 2: K(I, 2) jet/particle KF code.

= 3: three times jet/particle charge.

= 4: origin, i.e. position of parent (= KH).

= 5: generation number. Beam particles (KS = 4) or virtual particles (KS = 5) are generation 0, original jets/particles generation 1 and then 1 is added for each step in the fragmentation/decay chain.

= 6: line number of ancestor, i.e. predecessor in first generation (generation 0 entries are disregarded).

= 7: rank of a hadron in the jet it belongs to. Rank denotes an ordering in flavour space, with hadrons containing the original flavour of the jet having rank 1, increasing by 1 for each step away in flavour ordering. All decay products inherit the rank of their parent. Whereas the meaning of a first rank hadron is always well-defined, the definition of higher ranks is only unique for independently fragmenting quark jets. In other cases, rank refers to the ordering in the actual simulation.

= 8: particle KF code for particles, but 0 for jets, extra lines, etc.

= 9: jet IFL code for jets, but 1000 for particles, extra lines, etc. (not 0, since 0 = g!).

= 10: flavour KF code for jets/particles, but 0 for extra lines, etc.

= 11: flavour KF code for stable entries, 0 otherwise.

= 12: flavour KF code for stable entries excepting neutrinos, 0 otherwise.

= 13: flavour KF code for charged stable entries, 0 otherwise.

FUNCTION PLU (I, J)

Purpose: to provide various real-valued event data. Note that some of the options available (I > 0, J = 20–25) will not work if a LUROBO call is made after the LUEXEC one, and are primarily intended for studies of systems in their CM frame.

I = 0, J = : properties referring to the complete event.

= 1–5: sum of p_x, p_y, p_z, E and m, respectively, of the stable remaining entries.

= 6: ditto for the electric charge.

I > 0, J = : properties referring to the entry in line no. I of the event record.

= 1–5: P(I, 1)–P(I, 5), i.e. p_x, p_y, p_z, E and m for jet/particle.

= 6: electric charge q.
= 7: momentum squared $p^2 = p_x^2 + p_y^2 + p_z^2$.
= 8: momentum p.
= 9: transverse momentum squared $p_t^2 = p_x^2 + p_y^2$.
= 10: transverse momentum p_t.
= 11: transverse mass squared $m_t^2 = m^2 + p_x^2 + p_y^2$.
= 12: transverse mass m_t.
= 13–14: polar angle θ in radians or degrees, respectively.
= 15–16: azimuthal angle ϕ in radians or degrees, respectively.
= 17: true rapidity $Y = 0.5 \ln((E + p_z)/(E - p_z))$.
= 18: rapidity Y_π obtained by assuming that the particle is a pion when calculating the energy E, to be used in the formula above, from the (measured) momentum p.
= 19: pseudorapidity $\eta = 0.5 \ln(p + p_z)/(p - p_z))$.
= 20: momentum fraction $x_p = 2p/W$, where W is total energy of initial jet/particle configuration.
= 21: $x_F = 2p_z/W$ (Feynman-x if system is studied in CM frame).
= 22: $x_t = 2p_t/W$.
= 23: $x_E = 2E/W$.
= 24: $z_+ = (E + p_z)/W$.
= 25: $z_- = (E - p_z)/W$.

SUBROUTINE LUROBO (THE, PHI, BEX, BEY, BEZ)

Purpose: to perform rotations and Lorentz boosts (in that order, if both in the same call) of jet/particle momenta.

THE, PHI: standard polar coordinates θ, ϕ giving the direction of a momentum vector initially along the $+z$ axis.

BEX, BEY, BEZ: gives the direction and size $\bar{\beta}$ of a Lorentz boost, such that a particle initially at rest will have $\bar{p}/E = \bar{\beta}$ afterwards.

Remark: all entries 1 through N corresponding to status codes KS < 6 are affected by the transformations, unless lower and upper bounds are explicitly given by MST(1) and MST(2).

SUBROUTINE LUEDIT (MEDIT)

Purpose: to exclude unstable or undetectable particles from the event record.

MEDIT = : tells which entries are to be thrown away.
= 0: lines with status code KS 4 or larger are thrown away, i.e. beam or target particles, and lines with extra information.
= 1: in addition all jets/particles that have decayed/fragmented are thrown away.
= 2: also all neutrinos are thrown away.
= 3: all remaining uncharged entries are thrown away, leaving only charged, stable particles.

Remark: the jets/particles remaining are compressed in the beginning of the LUJETS common block and the value of N is updated accordingly. In a LUEDIT call the event history is lost, all KH = 0 afterwards.

SUBROUTINE LULIST (MLIST)

Purpose: to list an event, jet or particle data or current parameter values. The range of the listing may be limited from the default values by the use of MST(1) and MST(2).

MLIST = : determines what is to be listed.
= 0: gives a list of current event record: particles and jets with origin, current status, momentum, energy and mass. In a jet name, characters 1–4 represent the parton content: quarks U, D, S, C, B, T, L, H, gluon G, diquarks the two quark flavours and spin, A for antiquarks and antidiquarks. Characters 5–7 are JET and the last one is F for jets that have fragmented and blank otherwise. In a particle name, characters 1–4 contain a short form of the name, with a 0 sometimes added for particles that are their own antiparticles (π^0, ρ^0), while 5–7 contain a B for antiparticles and the value of the charge $(++, +, 0, -, --)$ for particles not their own antiparticles. Finally, character 8 is a D for particles that have decayed and blank otherwise. Beam and target particles are denoted by a B in position 8 and virtually exchanged particles by a V. Lines with extra information for J- and I-quarks give the J-quark flavour in positions 1–2 followed by JQ and the I-quark flavour in positions 5–6 followed by IQ. Lines with extra vertex information for soft gluon treatment are denoted by VERTEX. For the last two categories the customary momentum and energy information is of course

replaced by the relevant information stored in the LUJETS common block.

= 1: is equivalent to MLIST = 0, except that an extra line is added at the end. This line gives total charge, momentum, energy and mass of all stable entries, and hence serves as an easy check whether energy–momentum–flavour was conserved in the hadronization.

= 2: is equivalent to MLIST = 0, except that the MST(3) lines following after line N are listed as they stand, i.e. without converting K(I, 1) and K(I, 2) to flavour codes, etc. This may be used to store and display information not properly part of the event record.

= 3: provides a list of all particle and decay data used in the program. Lines with particle data contain the KF code, the particle and antiparticle (where appropriate) names, the KTYP values (for description see common block LUDAT2), mass, width and maximum broadening. Each decay channel (IDC) also gets one line, for particles 1–100 immediately following the particle data line, above 100 lumped together after each group of related particles. This line contains the decay channel number, matrix element type, branching ratio and decay products. The listing of the latter follows the same conventions for particle and jet names as outlined above, with three additional possibilities. SPECJET represents a spectator jet in the weak decay of a hadron (KF = 590), QRAJET a q jet (according to usual mixture) used in phase space models (KF = 591) and QBRAJET the corresponding $\bar{q}$ (KF = 592).

= 4: gives a list of all jet flavours. Each line contains the IFL and the KF flavour codes, the parton and antiparton name, the KTYP value, constituent and "current algebra" masses and width and maximum broadening.

= 5: gives a list of current parameter values for MST, PAR, FPAR and DPAR. This is useful to keep ceck of which default parameter values were changed in a given run.

6.4. The physics routines

The physics routines form a major part of the program, but once the initial jet/particle configuration has been specified and default parameter values changed if so desired, only a LUEXEC call is necessary to simulate the whole fragmentation and decay chain. We will therefore only give a rather brief overview.

SUBROUTINE LUEXEC

Purpose: to administrate the fragmentation and decay chain. LUEXEC may be called several times, but only entries which have not yet been treated (i.e. have KS 0 or 1) are affected by further calls. This may apply if more jets/particles have been added by the user or if particles previously considered stable are now allowed to decay.

SUBROUTINE LUONEJ (IP)

Purpose: to generate the fragmentation of a single jet: quark, gluon, diquark or hadron. Jets of course never appear alone, but it is sometimes a useful approximation. LUONEJ is also used to simulate models with independently fragmenting jets.

SUBROUTINE LUSYSJ (IP)

Purpose: to generate the fragmentation of an arbitrary colour singlet jet system consisting of up to ten jets, according to the Lund model. The only limitation is the requirement for certain minimum invariant masses for adjacent partons along the colour chain, as described above.

SUBROUTINE LUDECY (IP)

Purpose: to perform a particle decay, essentially in one of three ways:
according to particle table into fixed final states for ordinary hadrons;
according to a phase space model for charm and bottom;
into new jet systems for top and beyond.

SUBROUTINE LUIFLD (IFL1, IFL2, IFL3, IFL4, KF)

Purpose: to generate a quark or diquark flavour and to combine it with an existing flavour to give a hadron. Due regard should be taken to probabilities for u : d : s :diquark production, vector:pseudoscalar ratio for mesons, SU(6) factors for baryons, etc.

IFL1: existing flavour, quark or diquark, which is to be included in the hadron created.
IFL2: J-quark flavour to be included in hadron, 0 if no J-quark.
IFL3: I-quark flavour or, for final hadron (in the joining in the centre of e.g. a $q\bar{q}$ system), remaining flavour to be included in hadron, 0 if no such flavour. This means that when IFL3 $\neq 0$ the flavour content of the hadron is fully given by IFL1, IFL2 and IFL3 without the need for a new flavour IFL4.
IFL4: the new quark or diquark flavour generated, 0 if IFL3 $\neq 0$.
KF: the new hadron generated (from IFL1, IFL2, IFL3 and IFL4), if 0 signalling that SU(6) weighting for baryon including J-quark failed.
Note: a "diquark" may appear in three different situations:
i) a diquark created in the field, for which one of IFL1, IFL3 and IFL4 > 10 and IFL2 = 0;
ii) a LJ-diquark found in a baryon or diquark jet when the L- and J-quarks go into the first rank hadron, for which IFL1 > 10 is the LJ-flavour and IFL2 > 0 the J-flavour; or
iii) a baryon or diquark jet where the L- and J-quarks do not enter the same hadron, for which IFL1 < 10 is the remnant quark of the L-quark fragmentation and IFL2 > 0 the J-flavour.
If a SU(6) weighting fails in case i) a new flavour IFL4 is generated (no weighting is, however, performed if IFL3 is the diquark, since this corresponds to situations where we have no freedom left), while if it fails in case ii) or iii) we put KF = 0 to signal that the jet has to be generated anew. The SU(6) weights in case ii) are larger than in case iii) since in the former case two quarks already are in a diquark state.

FUNCTION ULMASS (MMASS, KF)
Purpose: to give the mass for a particle or parton.
MMASS = : determines the kind of mass to return.
= 0: particle masses or parton constituent masses, according to standard KF code, without any mass broadening.
= 1: ditto, but with mass broadening if allowed (see KTYP and MST(8)).
= 2: parton constituent masses, according to IFL code, with mass broadening if allowed.
= 3: parton "current algebra" masses, according to IFL code, with mass broadening if allowed.

SUBROUTINE LUPTDI (IFL, PX, PY)
Purpose: to give transverse momentum, e.g. for a quark–antiquark pair formed in the field, according to independent Gaussian distributions.
IFL: flavour of the quark stretching the field out of which the $q'\bar{q}'$ pair is created with a p_t to be simulated, the magnitude being given by PAR(7). The IFL value is of importance only when PAR(8) $\neq 1$. Also some special IFL values are implemented. If MST(10) = 1 and IFL = 93 then the leading quark in a single jet or the leading quarks in a $q\bar{q}$ event are assigned a p_t, for PAR(9) = 1 equal to the fragmentation p_t. While this p_t contribution is shared equally between the L- and J-quarks of a leading diquark, these quarks may also be given a relative momentum (corresponding to an internal Fermi motion), the magnitude of which is specified by PAR(10), and which is obtained by putting IFL = 94.

FUNCTION ULZDIS (IFL1, IFL3)
Purpose: to generate the longitudinal scaling variable z in jet fragmentation, either according to the Lund (except for the Γ-factor) or to an extended Field–Feynman recipe. Also to generate x_J and x_I in hadron jets.

SUBROUTINE LUIFLV (KF, IFLA, IFLB, IFLC, KSP)
Purpose: to give the quark content and spin for a particle with KF > 100.
KF: particle flavour code.
IFLA, IFLB, IFLC: quark flavours in decreasing order (i.e. heaviest quark first) with IFLC = 0 for meson.
KSP = :particle spin classification.
= 0: pseudoscalar (i.e. spin 0) meson.
= 1: vector (i.e. spin 1) meson.
= 2: spin 1/2 baryon with two lighter or two equal quarks in a spin 1 state ("Σ-like" baryons).

= 3: spin 1/2 baryons with two lighter quarks in a spin 0 state ("Λ-like" baryons).
= 4: spin 3/2 baryon.

FUNCTION LUCHGE (KF)
Purpose: to give three times the charge for a particle or jet flavour (the factor 3 is so that partons also are represented by integer numbers).

SUBROUTINE LUNAME (KF, CHAU)
Purpose: to give names, i.e. character strings corresponding to the KF code for particles, jets and lines with extra information.

FUNCTION ULANGL (X, Y)
Purpose: to calculate the angle from the x and y coordinates.

BLOCK DATA LUDATA
Purpose: to give default values for variables in the LUDAT common blocks.

6.5. Information in the common blocks

The four common blocks LUDAT1, LUDAT2, LUDAT3 and LUDAT4 contain a wealth of parameters and particle data. All are given sensible default values in the LUDATA subprogram, below indicated by (D = ...). These values may be changed by the user to modify the behaviour of the program. In some cases several parameters are interrelated, making their use somewhat more tricky.

COMMON/LUDAT1/MST(20), PAR(20), FPAR(40)
Purpose: to give access to a number of status codes and parameters which regulate the performance of the program as a whole.
MST(1), MST(2): (D = 0, 0, i.e. inactive) can be used to replace the ordinary lower and upper limits (normally 1 and N) for the action of LUROBO, LUEDIT and LULIST calls. Note that these parameters are also used internally, so that they are reset to 0 in LUEXEC calls.
MST(3): (D = 0) number of lines with extra information added after line N. Is reset to 0 in LUEXEC calls.
MST(4) = : (D = 1) choice of longitudinal fragmentation functions, i.e. how large a fraction of the energy available a newly-created hadron takes.
= 1: Lund scheme, i.e. flat fragmentation function + Γ factors + collinear gluon effects.
= 2: Field–Feynman parametrization extended also to heavier quarks (see FPAR(11)–(18)).
MST(5) = : (D = 1) choice of fragmetation scheme.
= 0: no jet fragmentation at all.
= 1: colour singlet jet systems are generated using the Lund model, for single jets all particles generated are kept.
= 2: all jets are assumed to be independently fragmenting, and primary hadrons moving backwards with respect to the jet direction are thrown away. Gluon jet fragmentation according to the Lund model for single gluon jets. No explicit energy–momentum–flavour conservation for jet systems.
= 3: as MST(5) = 2, but a gluon is assumed to fragment like a quark jet, with initial flavour u, d, s (or ditto antiquark) according to customary probabilities.
= 4: as MST(5) = 3, but if Field–Feynman fragmentation functions are used (MST(4) = 2) the gluon will fragment softer than an ordinary quark jet (see FPAR(19)).
= 5: as MST(5) = 2, but a gluon is assumed to fragment like a pair of a quark and an antiquark jet sharing the gluon energy according to the Altarelli–Parisi splitting functions, with quark flavour u, d, s according to customary probabilities.
MST(6) = :(D = 1) structure of leading diquarks and hadron jet generation.
= 0: diquarks always treated like a unit, i.e. both quarks go into same hadron.
= 1: L- and J-quark may go into separate hadrons.
= 2–3: as MST(6) = 0–1, but stop generation for single jets when J- and/or I-quarks have all been included in hadrons. (This speeds up hadron jet generation when only the distribu-

tion of original quarks is of interest.)

MST(7) = : (D = 1) particle decays.
= 0: all particle decays are inhibited.
= 1: particles declared unstable in the IDB vector are allowed to decay.

MST(8) = : (D = 0) particle masses.
= 0: discrete mass values are used.
= 1: particles registered as having a mass width in the KTYP vector are given a mass according to a truncated Breit–Wigner shape.

MST(9) = : (D = 0) parton/particle masses in filling routines (LUPART, LU1JET, LU2JET, LU3JET, LU4JET).
= 0: find masses according to mass tables as usual.
= 1: keep the mass value stored in P(I, 5), whatever it is. This may be used e.g. to describe kinematics with off-mass-shell partons.

MST(10) = : (D = 0) treatment of soft gluon effects in single jets or in two-jet $q\bar{q}$ events. Three-jet events, etc., are not affected by this, neither are single jets for MST(10) $\geqslant$ 2. Note that the choice made here also has some bearing on the value to choose for PAR(7).
= 0: no special soft gluon treatment.
= 1: endpoint quarks in single jets or $q\bar{q}$ systems are given transverse momenta, with the q and $\bar{q}$ of a $q\bar{q}$ system obtaining opposite and compensating $\bar{p}_t$. The magnitude of this p_t is normally the same as for the fragmentation p_t, but this can be modified with PAR(9).
= 2: a full treatment of soft gluon effects for $q\bar{q}$ jet systems, summing up the contributions from a number of soft gluons, see FPAR(31)–FPAR(34). The recoil effect is shared symmetrically between the two sides of the jet system (relevant e.g. for e^+e^- events).
= 3: as MST(10) = 2, but the recoil effect is only taken up in the forward (first jet filled e.g. in LU2JET) direction (relevant e.g. for leptoproduction events).

MST(11)–MST(20): unused at present.

PAR(1): (D = 0.075) is P(qq)/P(q), the suppression of diquark–antidiquark pair production in the field compared to quark–antiquark production.

PAR(2): (D = 0.3) is P(s)/P(u), the suppression of s quark pair production in the field compared to u or d pair production.

PAR(3): (D = 0.2) is (P(us)/P(ud))/(P(s)/P(d)), the extra suppression of strange diquark production compared to the normal suppression of strange quarks.

PAR(4): (D = 0.05) is (1/3)P(ud_1)/P(ud_0), the suppression of spin 1 diquarks compared to spin 0 ones (excluding the factor 3 coming from spin counting).

PAR(5): (D = 0.5) is the probability that a meson has spin 1 (1 − PAR(5) is probability for spin 0).

PAR(6): (D = 1) is an extra suppression factor multiplying the ordinary SU(6) weight for spin 3/2 baryons, and hence a means to break SU(6) in addition to the dynamical breaking implied by PAR(2), PAR(3) and PAR(4)).

PAR(7): (D = 0.44 GeV/c) corresponds to the width in the Gaussian p_x and p_y distributions for primary hadrons.

PAR(8): (D = 1) corresponds to a string constant a factor PAR(8) higher for breakups closest to a heavy quark (charm and beyond), influencing the rate of s quark and baryon production and the mean p_t.

PAR(9): (D = 1) gives, multiplied by PAR(7), the width of the Gaussian p_x and p_y distributions to be used for leading quarks in single jets or $q\bar{q}$ systems when simulating soft gluon effects (i.e. MST(10) = 1).

PAR(10): (D = 0) gives the width of the Gaussian p_x and p_y distributions for the opposite $\bar{p}_t$ given to the L- and J-quarks of a leading LJ-diquark.

PAR(11)–PAR(18): unused at present.

PAR(19): will after a LUEXEC call contain the total energy W of all first generation jets/particles, to be used by the PLU function for I > 0, J = 20–25.

PAR(20): π = 3.14159....

FPAR(1): (D = 0.1 GeV) gives the remaining W below which the generation of single jets is stopped (it is chosen $< m_\pi$ so that no hadrons moving in the forward direction are missed).

FPAR(2): (D = 1 GeV) is, with quark masses added, used to define the minimum allowable energy for a quark–antiquark jet system or subsystem (for antiquark one may of course also read diquark, etc.).

FPAR(3)–FPAR(4): (D = 1.0, 1.5 GeV) are, together with quark masses, used to define the remaining energy below which the fragmentation of a jet system is stopped. The two different alternatives refer to the Lund and the Field–Feynman fragmentation functions (see MST(4)).

FPAR(5): (D = 2) represents the dependence on the mass of the final quark pair for defining the stopping point of the fragmentation.

FPAR(6): (D = 0.2) relative width of the smearing of the stopping point energy.

FPAR(7): (D = 0.9) the maximum kinematical cuts allowed on the z-range in jet fragmentation.

FPAR(8): (D = 0.32) coefficient for asymmetry in the rapidity ordering of the final two hadrons.

FPAR(9), FPAR(10): (D = 0.5, 0.8) power in asymmetry in the rapidity ordering of the final two hadrons. The two values refer to the Lund and the Field–Feynman fragmentation functions (see MST(4)).

FPAR(11)–FPAR(18): (D = 3 * 0.77, 5 * 0.) gives the shape of the fragmentation functions in the Field–Feynman scheme for different quark flavours. With c = FPAR(10 + IFL) for a quark IFL (for diquarks, the heavier of the quarks is used), the fragmentation function is $f(z) = 1 - c + 3c(1-z)^2$ for $0 < c < 1$ and $f(z) = (1-c)z^{-c}$ for $c < 0$ (i.e. the smaller the c, the more peaked towards large z).

FPAR(19): (D = 1.) replaces FPAR(11)–FPAR(13) for the fragmentation of a quark jet representing a gluon (see MST(5) = 4).

FPAR(20): (D = 0.5) represents the softening of the z spectrum from collinear gluon effects expected in the Lund model, except for Γ-factors, giving the fragmentation function $f(z) = (1+c)(1-z)^c$ where c = FPAR(20) for a u or d quark fragmenting and successively smaller for heavier quarks.

FPAR(21), FPAR(22): (D = 1., 1.) is a parametrization of the J-quark position in diquark and baryon jet fragmentation, $f(x_J) = k x_J^a (1-x_J)^b$ with k a normalization constant, a = FPAR(21) and b = FPAR(22).

FPAR(23), FPAR(24): (D = 0., 1.) is a corresponding parametrization as above for the I-quark position in meson jet fragmentation, with x_J replaced by x_I.

FPAR(25), FPAR(26): (D = 0., 0.) is a corresponding parametrization as above for the I-quark position in baryon jet fragmentation, with x_J replaced by x_I/x_J (since x_I is constrained by $x_I < x_J$).

FPAR(27)–FPAR(30): unused at present.

FPAR(31) (D = 1.) is the maximum rapidity bin size used to sum up soft gluon contributions in terms of one effective gluon for each bin; i.e. when the total rapidity range considered is divided into a number of equally large bins, the bin size is chosen as large as possible with this constraint.

FPAR(32): (D = 2.8 GeV) corresponds to the M_0 mass scale used in matrix elements to separate hard gluons, explicitly taken into acount, from the soft ones. Here it denotes the upper limit for the soft gluon region to be summed up.

FPAR(33): (D = 1.) regulates how far out in rapidity soft gluon effects are to be taken into account, $\Delta y_{tot} = \ln(\text{FPAR(33)} W^2/M_0^2)$. (This is not a very sensitive parameter, since soft gluons at the edges give a small contribution to the total p_t of a particle.)

FPAR(34): (D = 0.2) represents the effective first order strong coupling constant $\alpha_s(Q^2)$ to use in the soft gluon region.

FPAR(35): (D = 1.) is the effective rapidity range over which the transverse momentum contribution from a soft gluon is felt.

FPAR(36)–FPAR(40): unused at present.

COMMON/LUDAT2/KTYP(120), PMAS(120), PWID(60), KFR(80), CFR(40)

Purpose: to give access to a number of particle/parton data and flavour treatment constants.

KTYP(1)–KTYP(108): gives particle/quark charge and mass width information. Arguments between 1 and 100 refer to particles according to KF code, between 101 and 108 to jets according to 100 + IFL.
Information is stored in form KTYP(...) = KTY1 + 10 × KTY2 where
KTY1 =: is particle/quark type (related to charge).
= 0: neutral particle its own antiparticle.
= 1: negative particle.

= 2: neutral particle not its own antiparticle.
= 3: positive particle.
= 4: doubly positive particle.
= 5: $-1/3$ charge quark.
= 6: $+2/3$ charge quark.
KTY2: is a consecutive numbering of all particles/quarks with a mass width, so that the relevant mass width information is stored in PWID in positions 2 × KTY2-1 and 2 × KTY2.

KTYP(109)–KTYP(120): unused at present.

PMAS(1)–PMAS(100). particle masses for particles with KF code 1–100.

PMAS(101)–PMAS(108): quark constituent masses stored in positions 100 + IFL.

PMAS(109), PMAS(110): unused at present.

PMAS(111), PMAS(112): amount subtracted from the constituent quark or diquark masses, respectively, to obtain the corresponding "current algebra" ones.

PMAS(113), PMAS(114): constant terms in the mass formulae for heavy mesons and baryons, respectively.

PMAS(115), PMAS(116): factors which, together with Clebsch–Gordan coefficients (see CFR(25)–CFR(35)) and quark constituent masses, determine the mass splitting due to spin–spin interactions for heavy mesons and baryons, respectively (the constant k of eq. (50) divided by m_u^2). The latter factor is also used for the splitting between spin 0 and spin 1 diquark masses.

PMAS(117)–PMAS(120): unused at present.

PWID(1)–PWID(60): store width information for particles (or quarks) assumed to have a mass broadening. For particles having a nonzero KTY2 value in the KTYP vector, PWID(2 × KTY2-1) is the total width Γ of a symmetric Breit–Wigner shape and PWID(2 × KTY2) is the maximum deviation from the PMAS mass value at which the Breit–Wigner shape is truncated.

KFR(1)–KFR(80): describe the correspondence between a given quark content (and particle spin) and the flavour KF code for hadrons, and are as such used in the two directions by LUIFLD and LUIFLV.

CFR(1)–CFR(12): give a parametrization of the $u\bar{u}$–$d\bar{d}$–$s\bar{s}$ flavour mixing for pseudoscalar and vector mesons.

CFR(13)–CFR(24): give flavour SU(6) weights for the production of a spin 1/2 or spin 3/2 baryon from a given diquark–quark combination.

CFR(25)–CFR(35): contain the quark spin–spin expectation values $\langle \bar{\sigma}_i \cdot \bar{\sigma}_j \rangle$ for pseudoscalar and vector mesons and spin 1/2 (Σ-like and Λ-like) and spin 3/2 baryons, used in the description of mass splittings of diquarks and heavy hadrons from spin effects.

CFR(36)–CFR(40): unused at present.

COMMON/LUDAT3/DPAR(20), IDB(120), CBR(300), KDP(1200)

Purpose: to give access to particle decay data and parameters.

DPAR(1)–DPAR(10): give corrective factors to the weight calculations for multiparticle decay (1–8 for 3–10-particle decay, 9 for ω and ϕ decay to three pions, 10 for semileptonic decays).

DPAR(11)–DPAR(13): give the primary multiplicity distribution in particle decays, specifically the constants c_1, c_2 and c_3 of eqs. (55) and (61).

DPAR(14): minimum kinetic energy in phase space decays.

DPAR(15): mass which, in addition to spectator quark or diquark mass, is not assumed to partake in the weak decay of a heavy quark (top and beyond) in a hadron.

DPAR(16): colour rearrangement probability in weak hadronic decays of heavy hadrons (top and beyond).

DPAR(17)–DPAR(20): unused at present.

IDB(1)–IDB(120): give the entry point into the particie decay data table. For stable particles IDB(...) = 0, giving a possibility to selectively inhibit particle decays. Arguments up to 100 refer to particle KF code, while heavy hadrons (KF > 100) are lumped together in position 76 + 5 × IFL + KSP, with IFL the flavour of the heaviest quark in the hadron and KSP spin classification as explained for LUIFLV.

CBR(1)–CBR(300): give cumulative branching ratios for the different decay channels IDC.

KDP(1)–KDP(1200): contain the decay products in the different channels, with four positions 4 × IDC − 3 to 4 × IDC reserved for each channel. The decay products are given follow-

ing the standard KF code for jets and particles (see appendix A).
In the first position, 4 × IDC − 3, an additional term of ±1000 × MMAT (with sign chosen equal to the decay product sign) is included with matrix element and other decay treatment information. Here MMAT = :
= 0: no special matrix element treatment, quarks and particles are copied directly to event record with momentum distributed according to phase space.
= 1: ω and ϕ decays into three pions.
= 2: phase space model for the production of particles from the quarks available, used e.g. for hadronic decays of charm and bottom.
= 3: semileptonic decays for charm and bottom (and leptonic for τ).
= 4: heavy (top and beyond) quark or lepton weak decay with quarks paired off into colour singlet systems.

COMMON/LUDAT4/CHAG(50), CHAF(100)
Purpose: to give access to character type variables.
CHAG(1): blank.
CHAG(2)–CHAG(18): antiquark, gluon and quark flavour names in positions CHAG(10 + IFL).
CHAG(19)–CHAG(22): some further codes related to jets.
CHAG(23)–CHAG(31): charge and particle/antiparticle distinction.
CHAG(32)–CHAG(35): spin classification for heavy hadrons (KF > 100).
CHAG(36): status of entry (decayed/fragmented/beam particle/virtual particle).
CHAG(37)–CHAG(40): J- and I-quark and vertex entries.
CHAG(41)–CHAG(50): unused at present.
CHAF(1)–CHAF(100): particle names (usually excluding charge) according to KF code.

7. Examples on how to use the program

The Lund Monte Carlo is very versatile, but the price to be paid for this is a large number of adjustable parameters and switches for alternative modes of operation. These are initially assigned sensible default values, so that the beginner need not worry about them. Neither need he worry about the detailed physics presented in sections 2–5. The Monte Carlo is built as a slave system, i.e. the user supplies the main program, and from this the Monte Carlo subroutines are called on to execute specific tasks, after which control is returned to the main program. Below we give some examples of what type of statements could appear in the main program.

A 10 GeV u quark jet going out along the $+z$ axis is generated with

```
CALL LU1JET(0, 1, 0, 0, 10., 0., 0.)
```

Note that such a single jet is not required to conserve energy, momentum or flavour, and that in addition the generation scheme may give rise to particles with large, negative p_z. If MST(5) = 2 primary hadrons with $p_z < 0$ will be thrown away automatically.

In e.g. a leptoproduction event a typical situation could be a u quark going out in the $+z$ direction and a ud_0 target remnant essentially at rest. The simplest procedure is probably to treat it in the CM frame and boost it to the lab frame afterwards. Hence, if the CM energy $W = 20$ GeV and the boost $\beta = 0.996$ (corresponding to $x_{\mathrm{B}} \approx 0.045$)

```
CALL LU2JET(0, 1, 12, 20.)
CALL LUROBO(0., 0., 0., 0., 0.996)
```

The jets could of course also be defined and allowed to fragment in the lab frame with

```
CALL LU1JET(-1, 1, 0, 0, 223.15, 0., 0.)
CALL LU1JET(2, 12, 0, 0, 0.6837, 3.1416, 0.)
CALL LUEXEC
```

Note here that the target diquark is required to move in the backwards direction with $(E - p_z)_{\mathrm{qq}} \simeq m_{\mathrm{p}}(1 - x_{\mathrm{B}})$ to obtain the correct invariant mass of the system. This is, however, only an artefact of using a fixed diquark mass to represent a varying target remnant mass, and is of no importance for the fragmentation. If one wants a nicer-looking event record, it is possible to use the following

```
CALL LU1JET(-1, 1, 0, 0, 223.15, 0., 0.)
MST(9) = 1
P(2, 5) = 0.895
CALL LU1JET(2, 12, 0, 0, 0., 0., 0.)
MST(9) = 0
CALL LUEXEC
```

A 30 GeV u$\bar{\text{u}}$g event with $E_{\text{u}} = 8$ GeV and $E_{\bar{\text{u}}} = 14$ GeV is simulated with

```
CALL LU3JET(0, 1, -1, 30., 2.*8./30., 2.*14./30.)
```

The event will be given in a standard orientation with the u quark along the $+z$ axis and the $\bar{\text{u}}$ in the $-z$, $+x$ quadrant. Not all three-jet events can be simulated within the Lund scheme for gluon jet fragmentation; certain minimum invariant masses between the partons are necessary as described in section 4.3. The responsibility rests on the user not to make calls like e.g.

```
CALL LU3JET(0, 1, -1, 30., 0.5, 0.997)
```

for which $M_{\text{ug}} \approx 1.65$ GeV is definitely too small and which hence will lead to an infinite loop in the program.

It is always good practice to list one or a few events during a run to check that the program is working as intended. With

```
CALL LULIST(1)
```

all particles will be listed and in addition total charge, momentum and energy of stable particles will be given. For jet systems in the Lund scheme (MST(5) = 1) these should be conserved exactly. An example of the output from LULIST is given in appendix C. Also particle and parton data can be listed with LULIST.

An event, as stored in the LUJETS commonblock, will contain original jets and the whole decay chain, i.e. also particles which subsequently have decayed. This is useful in many connections, but if one only wants to retain e.g. the final state charged and neutral particles (except for neutrinos) this is done with

```
CALL LUEDIT(2)
```

The information in LUJETS may be used directly to study an event. Some useful additional quantities derived from these, such as charge and rapidity, may easily be found via the KLU and PLU functions. As an example, we take a run to study the π^+ total and longitudinal momentum in 20 GeV u$\bar{\text{u}}$ events.

```
    COMMON/LUJETS/N, K(250, 2), P(250, 5)
    (histogram booking)
    DO 100 IE = 1, 1000                      (loop over events)
    CALL LU2JET(0, 1, -1, 20.)               (generate events)
    IF(IE.LE.2) CALL LULIST(1)               (list first two events)
    CALL LUEDIT(3)                           (keep only charged stable particles)
    DO 100 I = 1, N                          (loop over particles in event)
    IF(K(I, 2).NE.17) GOTO 100               (skip everything but π+)
    PZ = P(I, 3)                             (longitudinal momentum read out directly)
    PA = PLU(I, 8)                           (absolute momentum found with PLU function)
    (fill PZ and PA in histograms)
100 CONTINUE
    (edit and output histograms)
    END
```

In the particle tables the following particles are considered as stable: γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K_L^0, p, $\bar{\text{p}}$, n, $\bar{\text{n}}$ and all neutrinos. It is, however, always possible to inhibit the decay of any given particle by putting the corresponding IDB value to zero, e.g. IDB(37) = 0 makes K_S^0 and IDB(57) = 0 Λ stable.

The Field–Feynman jet model [14] is available in the program by changing the following values:

MST(4) = 2 (i.e. use Field–Feynman parametrization of longitudinal fragmentation functions, with their a parameter stored in FPAR(11)–FPAR(13)), MST(10) = 1 (give endpoint quark p_t as quarks created in the field), PAR(1) = 0. (no baryon–antibaryon production), PAR(2) = 0.5 (= s/u ratio for the production of new $q\bar{q}$ pairs) and PAR(7) = 0.35 (σ, determining the width of the Gaussian transverse momentum distribution). In addition only u, d and s single quark jets may be generated following the FF recipe. Various hybrid arrangements using e.g. FF fragmentation functions in jet systems are of course possible, but then with the understanding that this no longer may be reproducible with another implemetation of the FF "standard jet".

Another important point where alternative schemes are available is the matter of gluon jet fragmentation, regulated by MST(5). The default value, MST(5) = 1, is the only alternative in which energy, momentum and flavour are conserved explicitly. If MST(5) ⩾ 2 jets are taken to be independently fragmenting. For MST(5) = 2 the Lund scheme for independent gluon jets is used, while e.g. MST(5) = 3 corresponds to treating a gluon jet just like a quark jet of random flavour and MST(5) = 5 to treating it like a quark and an antiquark jet sharing the total energy according to the Altarelli–Parisi splitting function. This will of course not make our program compatible with the Hoyer et al. [25] or the Ali et al. [26] Monte Carlos, where such schemes are used, but may sometimes be useful to check how much depends on this choice as compared to other differences between the programs.

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Appendix A

KF flavour codes

The KF code for particles, partons and various other objects is central for an understanding of the event record, but also for decay data, etc. Complete tables for particles and partons may be obtained with LULIST. Here we provide an overview of the codes. A negative KF code, where existing, always corresponds to the antiparticle (or antiquark, etc.) of the positive KF object, and is hence not included. Codes 5 and 15 are "quasiparticles" used for bookkeeping purposes.

0	blank, i.e. no entry of any kind		
1	γ	46	Ξ^0
2	Z^0	47	Ξ^-
3	W^+	48	Σ_c^{++}
4	H^0	49	Σ_c^+
5	γ/Z^0	50	Σ_c^0
6		51	C_{su1}^+
7	e^-	52	C_{sd1}^0
8	ν_e	53	C_{ss}^0
9	μ^-	54	C_{cu}^{++}
10	ν_μ	55	C_{cd}^+
11	τ^-	56	C_{cs}^+
12	ν_τ	57	Λ
13	λ^-	58	Λ_c^+
14	ν_λ	59	C_{su0}^+
15	phase space	60	C_{sd0}^0
16		61	Δ^{++}
17	π^+	62	Δ^+
18	K^+	63	Δ^0
19	K^0	64	Δ^-
20	D^0	65	Σ^{*+}
21	D^+	66	Σ^{*0}
22	F^+	67	Σ^{*-}
23	π^0	68	Ξ^{*0}
24	η	69	Ξ^{*-}
25	η'	70	Ω^-

26 η_c	71 Σ^{*++}_c
27 ρ^+	72 Σ^{*+}_c
28 K^{*+}	73 Σ^{*0}_c
29 K^{*0}	74 C^{*+}_{su}
30 D^{*0}	75 C^{*0}_{sd}
31 D^{*+}	76 C^{*0}_{ss}
32 F^{*+}	77 C^{*++}_{cu}
33 ρ^0	78 C^{*+}_{cd}
34 ω	79 C^{*+}_{cs}
35 ϕ	80 C^{*++}_{cc}
36 J/Ψ	81
37 K^0_S	82
38 K^0_L	83 η_b
39	84 η_t
40	85 η_l
41 p	86 η_h
42 n	87 Υ
43 Σ^+	88 ψ_t
44 Σ^0	89 ψ_l
45 Σ^-	90 ψ_h

91–100 free to use
101–122 heavy pseudoscalar mesons
123–144 heavy vector mesons
145–240 heavy spin 1/2 baryons ("Σ-like")
241–292 heavy spin 1/2 baryons ("Λ-like")
293–392 heavy spin 3/2 baryons

500 g	503 s	506 t
501 u	504 c	507 l
502 d	505 b	508 h

511–588 diquarks in the form $500 + 10 \times \text{IFL1} + \text{IFL2}$ where IFL1 and IFL2 are the IFL codes for the two quarks in the diquark, with $\text{IFL1} \geqslant \text{IFL2}$ for spin 1 diquarks and $\text{IFL1} < \text{IFL2}$ for spin 0 ones. The most frequently used ones:

511 uu_1	521 ud_1	531 us_1
512 ud_0	522 dd_1	532 ds_1
513 us_0	523 ds_0	533 ss_1

590 spectator flavour, remaining in heavy hadron ($KF > 100$) when the heaviest quark is assumed to decay weakly. When encountered in decay data, it signals that the spectator flavour of the hadron under consideration should be found and added to the decay product list.

591 a random flavour, chosen by using the same probabilities as when producing a quark–antiquark or diquark–antidiquark pair in the field, used as starting point in some phase space calculations.

592 the antiflavour to the flavour given immediately before this (normally 591).

601–688 extra information for diquark/hadron jets, given in the form $600 + 10 \times \text{IFLJ} + \text{IFLI}$. If the jet contains a J-quark, then IFLJ is the IFL code for it, else IFLJ is 0. Correspondingly IFLI may represent an I-quark.

700 extra vertex information for soft gluon treatment.

IFL codes, used only for quarks/diquarks/gluons, agree with the KF codes 500–588 if 500 is subtracted from these, so that e.g.

0 g	6 t	21 ud_1
1 u	7 l	22 dd_1
2 d	8 h	23 ds_0
3 s	11 uu_1	31 us_1
4 c	12 ud_0	32 ds_1
5 b	13 us_0	33 ss_1

Appendix B

A vocabulary of variable names

Although a complete standardization of variable names in the program has not been strived for, there still are some rules that have been kept in mind when constructing names. A knowledge of these might simplify any reading of the actual program. Below we give a list of frequently used name elements, where dots before and/or after indicates a preponderant use as suffix, prefix or anywhere in the name. Examples of complete variable names are given in parantheses.

.A	absolute value (KFA, PA).
ALP	α, angle at gluon corner.
BE.	β, direction and size of a Lorentz boost (Cartesian components BEX, BEY, BEZ).
.BR	brancing ratio in decay (CBR).
C.	cosine of angle (CTHE).
CHA.	character variable (CHAU).
CHI	χ, extra azimuthal angle e.g. at gluon corner.
.D.	related to particle decays (IDB, KDP).

ECM total energy of system in CM frame.
.F. related to jet fragmentation (FPAR).
.F initial flavour and energy values for jets according to event record (IFLF, WF).
.FR constants used in flavour treatment (KFR, CFR).
.G related to soft gluon effects (MG, DG).
GA. γ, the Lorentz factor in boosts (GA, GABEP).
GAM Γ-values (invariant time squared of breakup points) in jet fragmentation.
H. auxiliary kinematical variables, e.g. for hyperbola equation in gluon corners (HA, HSUM).
I. counter for position in event record and other related matrices (I, IP, IS).
.I related to I-quark in hadron jets (IFLI, WI).
IFL. quark/diquark/gluon flavour code (IFL1, IFLA).
J. counter for vector components (e.g. in momentum vector) or parts of jet system (J, JT).
.J related to J-quark in diquark or baryon jet (IFLJ, WJ).
KF. particle or jet flavour code.
KSP spin classification of hadrons.
KTY. particle charge, existence of antiparticle, finite mass width (KTYP).
L. general loop variable (rank in fragmentation LRK).
M. switch for alternative modes of operation in the program (MST, MLIST, MMAT).
N. number of e.g. jets/particles, often used as upper limit for loops (N, NP, NQ).
.O values of flavour and energy variables after particles at gluon corners have been formed, i.e. original values for single q jet or $q\bar{q}$ jet system treatment (IFLO, WO, PXO).
P. momentum and related variables (Cartesian components PX, PY, PZ, absolute value PA, energy PE, mass PM, longitudinal momentum PL, transverse momentum PT, transverse mass squared PR, sum of momenta PS).
.PAR parameter values (PAR, FPAR, DPAR).
PHI ϕ, standard azimuthal angle.
.PW power in expression (FPW, ZPW).
.Q. variables which specifically refer to quarks (PRQ, MQJ, NQ).
R. random numbers which have to be stored away for repeated use (RBR, RSAV).
S. sine of angle (STHE).
THE θ, standard polar angle.
W. energy variables $E \pm p_L$ for jets (W, WO, WJ).
WT. weights in matrix elements etc. (WT, WTMAX).
X. energy fraction variables in matrix elements, used to define initial jet configuration (X1, X12).
Z. scaling variables for the fraction of W taken by a particle in jet fragmentation (Z, ZO, ZG).

Appendix C

Example of an event listing

Example of an event generated with CALL LU2JET(0, 1, 12, 20.) and listed with CALL LULIST(1).

EVENT LISTING

I	ORI	PART/JET			PX	PY	PZ	E	M
1	0	U		JETF	0.000	0.000	9.987	9.992	0.325
2	0	DU	0	JETF	0.000	0.000	−9.987	10.008	0.650
3	2	L AM	0	D	0.088	−0.130	−7.993	8.072	1.116
4	2	K	+		0.330	−0.342	−0.810	1.061	0.494
5	1	RHO	+	D	0.545	0.034	1.442	1.722	0.766
6	2	RHO	B−	D	−0.066	0.635	1.096	1.482	0.766

EVENT LISTING (continued)

I	ORI	PART/JET	PX	PY	PZ	E	M
7	2	RHO0 D	−0.372	−0.109	−0.136	0.873	0.770
8	1	PI B−	0.188	0.241	1.481	1.518	0.140
9	1	PI +	−0.433	−0.038	3.892	3.918	0.140
10	2	OMEG D	−0.279	−0.291	1.028	1.354	0.782
11	3	N 0	−0.007	−0.062	−7.008	7.071	0.940
12	3	PI0 D	0.095	−0.068	−0.985	1.001	0.135
13	5	PI +	0.272	0.004	0.067	0.313	0.140
14	5	PI0 D	0.273	0.031	1.375	1.409	0.135
15	6	PI B−	0.135	−0.042	0.038	0.203	0.140
16	6	PI0 D	−0.201	0.676	1.058	1.279	0.135
17	7	PI +	0.150	−0.016	−0.238	0.315	0.140
18	7	PI B−	−0.522	−0.094	0.102	0.558	0.140
19	10	GAMM	0.166	0.111	0.513	0.551	0.000
20	10	PI0 D	−0.446	−0.402	0.515	0.802	0.135
21	12	GAMM	0.027	−0.092	−0.723	0.730	0.000
22	12	GAMM	0.067	0.024	−0.262	0.271	0.000
23	14	GAMM	0.119	0.073	0.784	0.797	0.000
24	14	GAMM	0.154	−0.043	0.591	0.612	0.000
25	16	GAMM	0.015	0.020	0.058	0.063	0.000
26	16	GAMM	−0.217	0.657	0.999	1.215	0.000
27	20	GAMM	−0.141	−0.084	0.210	0.267	0.000
28	20	GAMM	−0.305	−0.318	0.305	0.536	0.000
SUM:		1.000	0.000	0.000	−0.000	20.000	2.274

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TEST RUN OUTPUT

```
                    PARTICLE DATA TABLE

KF    PARTICLE    ANTIPART  KTYP      MASS      WIDTH      W-CUT
                IDC    MAT     B.R.   DECAY PRODUCTS

 7    E    -     E    B+       1      0.001

 8    NUE  0     NUE  B        2      0.000

 9    MU   -     MU   B+       1      0.106

10    NUMUO      NUMUB         2      0.000

11    TAU  -     TAU  B+       1      1.784
                23    (3)     17.0   NUE  B     E    -     NUTAO
                24    (3)     17.0   NUMUB      MU   -     NUTAO
                25    (2)     66.0   NUTAO      D    JET   UA   JET

12    NUTAO      NUTAB         2      0.000

13    CHI  -     CHI  B+       1     30.000
                26    (4)     11.0   NUE  B     E    -     NUCHO
                27    (4)     11.0   NUMUB      MU   -     NUCHO
                28    (4)     11.0   NUTAB      TAU  -     NUCHO
                29    (4)     34.0   UA   JET   D    JET   NUCHO
                30    (4)     33.0   CA   JET   S    JET   NUCHO

14    NUCHO      NUCHB         2      0.000

15    PHAS                     0      0.000
                31    (2)    100.0   QRA  JET   QBRAJET

16                             0      0.000

17    PI   +     PI   B-       3      0.140

18    K    +     K    B-       3      0.494

19    K    0     K    B        2      0.498
                32    (0)     50.0   KOS
                33    (0)     50.0   KOL

20    D    0     D    B        2      1.863
                34    (3)      5.0   E    B+    NUE  0     S    JET   UA   JET
                35    (3)      5.0   MU   B+    NUMUO      S    JET   UA   JET
                36    (2)     50.0   U    JET   DA   JET   S    JET   UA   JET
                37    (2)     40.0   S    JET   DA   JET
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21	D +	D	B-	3	1.868			
		38	(3)	16.0	E B+	NUE 0	S JET	DA JET
		39	(3)	16.0	MU B+	NUMU0	S JET	DA JET
		40	(2)	68.0	U JET	DA JET	S JET	DA JET
22	F +	F	B-	3	2.040			
		41	(3)	10.0	E B+	NUE 0	S JET	SA JET
		42	(3)	10.0	MU B+	NUMU0	S JET	SA JET
		43	(2)	50.0	U JET	DA JET	S JET	SA JET
		44	(2)	30.0	U JET	DA JET		
23	PI0			0	0.135			
		45	(0)	98.8	GAMM	GAMM		
		46	(0)	1.2	GAMM	E -	E B+	
24	ETA			0	0.549			
		47	(0)	38.2	GAMM	GAMM		
		48	(0)	30.1	PI0	PI0	PI0	
		49	(0)	23.7	PI +	PI B-	PI0	
		50	(0)	4.9	GAMM	PI +	PI B-	
		51	(0)	3.1	GAMM	GAMM	PI0	
25	ETAP			0	0.958			
		52	(0)	42.5	PI +	PI B-	ETA	
		53	(0)	23.1	PI0	PI0	ETA	
		54	(0)	29.8	GAMM	RHO0		
		55	(0)	2.7	GAMM	OMEG		
		56	(0)	1.9	GAMM	GAMM		
26	ETAC			0	2.970			
		57	(2)	100.0	QRA JET	QBRAJET		
27	RHO +	RHO	B-	33	0.766	0.148	0.400	
		58	(0)	100.0	PI +	PI0		
28	K* +	K*	B-	43	0.892	0.050	0.200	
		59	(0)	66.7	K 0	PI +		
		60	(0)	33.3	K +	PI0		
29	K* 0	K*	B	52	0.898	0.052	0.200	
		61	(0)	66.7	K +	PI B-		
		62	(0)	33.3	K 0	PI0		
30	D* 0	D*	B	2	2.006			
		63	(0)	55.0	D 0	PI0		
		64	(0)	45.0	D 0	GAMM		
31	D* +	D*	B-	3	2.009			
		65	(0)	64.0	D 0	PI +		
		66	(0)	28.0	D +	PI0		
		67	(0)	8.0	D +	GAMM		
32	F* +	F*	B-	3	2.140			
		68	(0)	100.0	F +	GAMM		

EVENT LISTING

I	ORI	PART/JET	PX	PY	PZ	E	M
1	0	B JETF	0.000	0.000	17.292	18.000	5.000
2	0	G JETF	-5.192	0.000	-3.007	6.000	0.000
3	0	BA JETF	5.192	0.000	-14.284	16.000	5.000
4	2	RHO + D	-1.528	0.860	-1.528	2.449	0.766
5	1	BD 0 D	-0.062	0.128	13.485	14.488	5.294
6	2	RHO B- D	-1.473	-0.970	-0.827	2.093	0.766
7	2	RHO + D	-0.485	0.588	1.274	1.671	0.766
8	2	ETAP D	-0.236	0.039	1.867	2.112	0.958
9	1	PI B-	-0.334	-0.164	0.043	0.400	0.140
10	2	RHO B- D	-0.173	-0.557	-0.800	1.252	0.766
11	3	BU *B+ D	4.289	-0.197	-12.117	13.918	5.335
12	2	RHO0 D	0.003	0.273	-1.397	1.619	0.770
13	4	PI +	-1.008	0.278	-1.182	1.584	0.140
14	4	PI0 D	-0.520	0.582	-0.347	0.865	0.135
15	5	D B D	0.175	-0.634	4.675	5.075	1.863
16	5	K B-	0.497	-0.273	1.325	1.524	0.494
17	5	PI +	0.014	0.301	0.700	0.775	0.140
18	5	D 0 D	-0.748	0.734	6.785	7.113	1.863
19	6	PI B-	-1.489	-0.887	-0.654	1.858	0.140
20	6	PI0 D	0.016	-0.083	-0.173	0.235	0.135
21	7	PI +	-0.492	0.655	0.730	1.106	0.140
22	7	PI0 D	0.006	-0.067	0.544	0.565	0.135
23	8	GAMM	-0.055	-0.160	0.384	0.420	0.000
24	8	RHO0 D	-0.181	0.199	1.483	1.692	0.770
25	10	PI B-	-0.238	0.088	-0.335	0.443	0.140
26	10	PI0 D	0.065	-0.645	-0.465	0.809	0.135
27	11	GAMM	0.027	0.019	-0.159	0.162	0.000
28	11	BU B+ D	4.262	-0.216	-11.958	13.756	5.294
29	12	PI +	-0.055	0.390	-0.324	0.529	0.140
30	12	PI B-	0.058	-0.116	-1.073	1.090	0.140
31	14	GAMM	-0.155	0.201	-0.048	0.258	0.000
32	14	GAMM	-0.365	0.382	-0.299	0.607	0.000
33	15	RHO B- D	0.233	-0.099	4.001	4.081	0.766
34	15	K +	-0.058	-0.535	0.674	0.994	0.494
35	18	OMEG D	-0.344	-0.036	1.433	1.669	0.782
36	18	K B D	-0.405	0.770	5.352	5.445	0.498
37	20	GAMM	0.064	-0.038	-0.147	0.165	0.000
38	20	GAMM	-0.047	-0.045	-0.026	0.070	0.000
39	22	GAMM	-0.033	-0.096	0.344	0.358	0.000
40	22	GAMM	0.040	0.029	0.200	0.206	0.000
41	24	PI +	-0.011	0.216	1.445	1.468	0.140
42	24	PI B-	-0.170	-0.017	0.037	0.224	0.140
43	26	GAMM	-0.023	-0.071	-0.019	0.077	0.000
44	26	GAMM	0.088	-0.574	-0.446	0.732	0.000
45	28	PI +	0.079	-0.020	-0.188	0.248	0.140
46	28	PI B-	0.177	0.036	-0.484	0.535	0.140
47	28	RHO + D	0.624	-0.164	-2.562	2.751	0.766

48	28	D* B	D	1.641	0.020	-4.095	4.847	2.006
49	28	OMEG	D	0.520	-0.087	-1.789	2.023	0.782
50	28	ETA	D	0.445	0.063	-1.290	1.472	0.549
51	28	ETA	D	0.664	-0.113	-1.385	1.635	0.549
52	28	PI0	D	0.112	0.048	-0.164	0.245	0.135
53	33	PI B-		0.083	-0.018	0.143	0.217	0.140
54	33	PI0	D	0.150	-0.081	3.858	3.864	0.135
55	35	PI +		-0.406	-0.137	0.875	0.984	0.140
56	35	PI B-		0.059	-0.002	0.468	0.492	0.140
57	35	PI0	D	0.003	0.103	0.090	0.192	0.135
58	36	K0L		-0.405	0.770	5.352	5.445	0.498
59	47	PI +		0.418	-0.005	-2.345	2.386	0.140
60	47	PI0	D	0.206	-0.159	-0.217	0.365	0.135
61	48	D B	D	1.475	-0.001	-3.725	4.419	1.863
62	48	PI0	D	0.166	0.021	-0.370	0.428	0.135
63	49	PI +		0.114	0.047	-0.110	0.217	0.140
64	49	PI B-		0.242	-0.287	-0.937	1.020	0.140
65	49	PI0	D	0.164	0.154	-0.742	0.787	0.135
66	50	PI +		0.115	0.043	-0.180	0.259	0.140
67	50	PI B-		0.011	-0.005	-0.366	0.392	0.140
68	50	PI0	D	0.319	0.026	-0.744	0.821	0.135
69	51	GAMM		0.741	-0.033	-1.079	1.310	0.000
70	51	GAMM		-0.077	-0.080	-0.306	0.325	0.000
71	52	GAMM		0.020	0.058	-0.133	0.147	0.000
72	52	GAMM		0.092	-0.010	-0.030	0.098	0.000
73	54	GAMM		0.094	0.024	1.534	1.537	0.000
74	54	GAMM		0.056	-0.105	2.324	2.327	0.000
75	57	GAMM		-0.019	0.036	-0.032	0.051	0.000
76	57	GAMM		0.022	0.067	0.122	0.141	0.000
77	60	GAMM		0.113	-0.040	-0.168	0.206	0.000
78	60	GAMM		0.093	-0.119	-0.049	0.159	0.000
79	61	OMEG	D	0.629	0.594	-2.377	2.647	0.782
80	61	K 0	D	0.847	-0.595	-1.348	1.771	0.498
81	62	GAMM		0.072	0.069	-0.242	0.262	0.000
82	62	GAMM		0.094	-0.049	-0.128	0.166	0.000
83	65	GAMM		0.085	0.017	-0.411	0.420	0.000
84	65	GAMM		0.079	0.137	-0.330	0.366	0.000
85	68	GAMM		0.140	-0.030	-0.452	0.474	0.000
86	68	GAMM		0.179	0.055	-0.292	0.347	0.000
87	79	PI +		0.377	0.186	-1.387	1.456	0.140
88	79	PI B-		0.062	0.085	-0.069	0.188	0.140
89	79	PI0	D	0.189	0.323	-0.921	1.003	0.135
90	80	K0S	D	0.847	-0.595	-1.348	1.771	0.498
91	89	GAMM		0.196	0.222	-0.698	0.759	0.000
92	89	GAMM		-0.007	0.101	-0.222	0.244	0.000
93	90	PI0	D	0.094	-0.233	-0.217	0.358	0.135
94	90	PI0	D	0.752	-0.362	-1.132	1.413	0.135
95	93	GAMM		-0.008	-0.012	-0.074	0.076	0.000
96	93	GAMM		0.103	-0.222	-0.142	0.283	0.000
97	94	GAMM		0.173	-0.055	-0.334	0.380	0.000
98	94	GAMM		0.580	-0.307	-0.797	1.032	0.000
	SUM:		0.000	-0.000	-0.000	-0.000	40.000	4.566

EVENT LISTING

I	ORI	PART/JET	PX	PY	PZ	E	M
1	0	DU OJETF	0.000	0.000	9.979	10.000	0.650
2	1	D JQU IQ	0.812	7.000	0.772	7.000	0.000
3	0	D JETF	-0.000	0.000	-9.995	10.000	0.325
4	3	SAIQ	0.000	0.000	0.734	6.000	0.000
5	3	K* 0 D	0.062	-0.065	-0.312	0.955	0.898
6	3	ETAP D	-0.433	0.069	-8.135	8.203	0.958
7	1	P +	0.042	-0.191	8.677	8.730	0.938
8	3	PIO D	0.107	0.048	0.777	0.798	0.135
9	1	OMEG D	0.221	0.138	-1.024	1.315	0.782
10	5	K +	-0.061	0.193	-0.038	0.535	0.494
11	5	PI B-	0.123	-0.258	-0.274	0.420	0.140
12	6	PI +	-0.086	0.097	-0.795	0.818	0.140
13	6	PI B-	-0.032	0.008	-2.480	2.484	0.140
14	6	ETA D	-0.315	-0.036	-4.860	4.901	0.549
15	8	GAMM	0.136	0.046	0.710	0.724	0.000
16	8	GAMM	-0.029	0.003	0.068	0.074	0.000
17	9	PI +	-0.124	0.015	-0.171	0.254	0.140
18	9	PI B-	0.032	0.183	-0.151	0.277	0.140
19	9	PIO D	0.313	-0.060	-0.703	0.783	0.135
20	14	PI +	-0.092	0.040	-1.430	1.440	0.140
21	14	PI B-	-0.121	0.103	-1.792	1.804	0.140
22	14	PIO D	-0.102	-0.179	-1.639	1.657	0.135
23	19	GAMM	0.034	0.035	-0.137	0.145	0.000
24	19	GAMM	0.280	-0.095	-0.566	0.638	0.000
25	22	GAMM	0.003	0.016	-0.037	0.041	0.000
26	22	GAMM	-0.105	-0.194	-1.601	1.616	0.000
	SUM:	1.000	0.000	0.000	-0.016	20.000	2.412

EVENT LISTING

I	ORI	PART/JET	PX	PY	PZ	E	M
1	0	U JETF	1.856	-10.580	8.053	13.429	0.325
2	0	UA JETF	10.958	-0.706	10.107	14.928	0.325
3	1	P +	-0.095	-1.249	1.096	1.910	0.938
4	2	PIO D	2.661	-0.255	2.171	3.447	0.135
5	1	N B	1.796	-5.256	4.836	7.425	0.940
6	1	RHOO D	0.972	-3.907	3.240	5.225	0.770
7	1	PIO D	1.267	-0.113	0.265	1.306	0.135
8	2	PI B-	6.213	-0.506	6.551	9.044	0.140
9	4	GAMM	0.447	-0.085	0.406	0.610	0.000
10	4	GAMM	2.214	-0.170	1.765	2.836	0.000
11	6	PI +	0.440	-1.553	1.752	2.387	0.140
12	6	PI B-	0.531	-2.353	1.488	2.838	0.140
13	7	GAMM	0.332	0.020	0.103	0.348	0.000
14	7	GAMM	0.935	-0.133	0.163	0.959	0.000
	SUM:	0.000	12.814	-11.286	18.160	28.357	2.298