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**The Lund Monte Carlo for
Jet Fragmentation and e^+e^- Physics
– JETSET version 6.2**

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Abstract:

Models for jet fragmentation and particle decays in high energy physics are discussed. The string fragmentation and independent fragmentation schemes implemented in this paper can be applied to any process, once the initial parton configuration is known. For the case of e^+e^- annihilation, a program is presented which generates these configurations according to perturbative QCD and QFD. Apart from the physics simulation routines, there also exist routines that can be used in the study of the events generated. A detailed manual is given for the program, including a description of all subroutines, functions and commonblocks.

1. Introduction

Jet fragmentation, in its broadest sense, occurs anytime a high energy physics event involves the production of several hadrons. Indeed, most of the experiments, present or planned, at high energy physics laboratories like CERN, DESY, Fermilab, SLAC, Cornell, KEK or Serpukhov involve jet studies, either for their own sake or as a prerequisite for the "real" physics studies. The theory for strong interactions, QCD, in principle should give all the properties of jet fragmentation, but we do not know how to solve it. Further, an event often contains tens or hundreds of particles, each particle with three momentum degrees of freedom, plus additional flavour and spin quantum numbers. Therefore even a formal, maybe approximate solution might well turn out to be too complicated to evaluate explicitly.

The natural way out has been the introduction of phenomenological models for jet fragmentation, implemented in terms of computer programs that generate complete events, which can be directly compared with experimental data. For subprocesses involving high momentum transfers Q^2 , perturbation theory can be used to give the leading order behaviour. The generation of an event can therefore be subdivided into two steps. In the first step, a parton configuration is selected, using perturbative QCD results. In the second step, these partons are then allowed to fragment into hadrons, with unstable hadrons decaying further. All elements specific to the process under study are supposedly contained in the first step, whereas the fragmentation is assumed to occur according to rules independent of the primary process, "jet universality". Because of quantum mechanical effects, neither of the two steps is of a deterministic nature. A correct treatment would utilize amplitudes and thus contain interference terms; since these terms are unknown anyhow, at least for fragmentation, it is natural to choose a probabilistic approach. This approach readily lends itself to an implementation in terms of Monte Carlo computer programs. Ideally the events generated with these programs should not only give the same mean behaviour as experimentally observed events, but also contain the same degree of event-by-event fluctuations.

The first part of the present program contains the process-independent fragmentation and decay routines, whereas the second part deals specifically with the production of the initial parton configuration in e^+e^- annihilation

events. Other, similar applications programs exist for lepto-production [1], hadron collisions [2] and hadron-nucleus and nucleus-nucleus collisions [3]. The Lund Monte Carlo is therefore a useful tool in the exploration of jet universality questions, in that experimentalists can directly compare e.g. flavour production parameters determined from different fields of high energy physics.

A program like this may be used for different purposes. In one extreme, it may offer a guideline for reasonable "conventional" physics when planning a detector design, or help in estimating acceptance corrections for a given detector geometry. In the other extreme, Monte Carlo results may be compared with existing data in order to extract and study interesting physics. The user probably wants to obtain a "best estimate" without too much ado in the former case, whereas he/she may want to play around with different schemes and possibilities in the latter case, often even studying "crackpot" alternatives just to build up the physical intuition.

A word of warning may therefore be in place. The program description is fairly lengthy, and certainly could not be absorbed in one sitting. This is not even necessary, since all switches and parameters are provided with sensible default values, based on our best understanding of jet fragmentation. A new user can therefore disregard all the fancy options, and just run the program as it is, to gain some experience. Later on, the options that might seem useful can be tried out. No single user is ever likely to find need for more than a fraction of the total number of switches and parameters available, yet many of them have been added to meet special user requests.

At all times, however, it should be remembered that this program represents a model, not a theory. Some parameter values have been determined from experimental data, others are "informed guesses". Some parts of the model/program seem to be supported by the data, whereas the status of others is more uncertain. There are many areas that have not even been touched upon in the present program, Bose statistics effects on two-particle correlations, spin and polarization phenomena, the space-time distribution of secondary vertices from charm or K_S^0 decays, to name but a few. Furthermore, surprises should always be expected when performing a new experiment, why else do it?

A word about the relationship between the Lund model and the Lund Monte Carlo. The former is a model for the hadronization of a multiparton configuration. This model is provided as the standard string fragmentation option in the

Monte Carlo. However, for many details, the model provides exact answers that are so complicated as to be useless for programming purposes, while simpler considerations of model properties leads to the sensible but approximate algorithms actually used. On the other hand, the Monte Carlo also contains a number of program components that are not a part of the Lund model proper, but that are necessary or useful in order to explore the physical consequences of the Lund model, such as particle decay routines, matrix elements for initial parton configurations, event analysis routines, even alternative fragmentation schemes.

In particular, the present paper is a description of a program, not of a model. It is not intended as an introduction to or review of jet fragmentation issues, for this we refer e.g. to [4]. The more "theoretical" sections only indicate what kind of physics is included in the program, and how the pieces fit together. Further, what is presented is mostly the algorithms for the practical handling of simulation problems, rather than the underlying principles.

The outline of the paper is as follows. In section 2 the development of the Lund Monte Carlo is reviewed. Section 3 contains a description of the jet fragmentation models and section 4 details on particles and their decays. The program manual for the jet fragmentation routines is found in section 5. In section 6 the physics of e^+e^- annihilation is described, with the associated program manual to be found in section 7. A routine for low- p_T physics is described in section 8. Finally, section 9 contains advice on installing the program and a few examples on how to run it. A user who only wants to think of the program as a "black box" might want to start by reading section 9, and then go on to the relevant pieces of sections 5 and 7.

2. Update History

The Lund Monte Carlo is by now a fairly old and well established program, but has still been steadily improved on. The published descriptions of the general jet fragmentation routines [5] and e^+e^- and event analysis routines [6] are no longer fully relevant. Although the basic programming philosophy is unchanged, so that a user of the old program should have no problem understanding the new one, many specific extensions and changes have been made. For subroutine calls, these changes generally only implies that new possibilities have been added, with the old options working as before. Commonblocks, however, have

generally been expanded to accommodate an increased number of options, and several parameters have been regrouped in a more coherent order. There is therefore no explicit backwards compatibility to previous versions of the Monte Carlo. In view of this, it was deemed prudent to give a complete and self-contained description of all program components. As to the actual physics description, we will concentrate on the areas where major changes have been made, and only briefly summarize what has already been published.

The main change in physics compared to the old program is the introduction of a new scheme to generate string fragmentation [7]. For a parton configuration where all pairs have large invariant masses, results generally coincide with that of the old scheme, but the new one additionally can be used to describe the fragmentation when one or several parton pairs have small invariant masses, so long as the total invariant mass of each colour singlet system is large enough. Closely related to this change is the introduction of the so-called symmetric fragmentation function [8], which particularly implies that heavy quarks take a large fraction of the available jet energy. The model for baryon pair production has been extended so that also the possibility to produce pairs separated by one meson is allowed [9]. In independent fragmentation, the number of options for gluon jet fragmentation has been increased, and several different schemes for momentum conservation have been introduced [10]. The list of minor changes in the jet fragmentation routines includes an update of particle decay data, and introduction of an intermediate step where low mass jet systems are allowed to collapse into one or two particles.

In the e^+e^- routines, complete second order QCD matrix elements have been implemented [11]. Also initial state photon radiation is now included [12], if so desired. Parton shower development has been incorporated as an alternative to explicit matrix elements [13,14].

To a large extent, the program has been in a state of continuous development during all of its existence, with the official numbered versions nothing more than snapshots of this process. For the record, we below list the main versions with some brief notes

no	date	publ.	main new or improved features
1	Nov78	[15]	single quark jets
2	May79	[16]	heavy flavour jets
3.1	Aug79		two-jets in e^+e^- , preliminary three-jets
3.2	Apr80	[17]	three-jets in e^+e^- with full matrix elements,

3.3	Aug80	toponium + 3g decays softer fragmentation spectrum
4.1	Apr81	baryon production and diquark fragmentation, fourth generation quarks, larger jet systems
4.2	Nov81	low- p_T physics
4.3	Mar82 [5]	four-jets and QED structure in e^+e^- ,
	Jul82 [6]	event analysis routines
5.1	Apr83	new string fragmentation scheme, full 2 nd order QCD for e^+e^-
5.2	Nov83	momentum conservation schemes for independent fragmentation, initial state photon radiation in e^+e^-
5.3	May84	extended model for baryon production
6.1	Jan85	commonblocks restructured, parton showers
6.2	Sep85	error detection

Whereas version 4.3 (and earlier versions) by now should be considered obsolete, versions 5.2 or 5.3 are certainly adequate e.g. for present-day e^+e^- or leptoproduction physics. The main reason for a version 6.1, as opposed to calling it 5.4, was the need to consider the production of a large number of particles (over 1000) at very high energies, e.g. SSC or LHC, so that commonblocks and the K(1,1) code had to be changed, at which time the opportunity was taken to rearrange some of the other commonblock variables as well.

3. Jet Fragmentation

A detailed review of the Lund string model is available in [4], with subsequent developments documented in [7,10,9]. Therefore, only the schematic outline is presented in this section, with further details and references to be found in the publications above.

Subsections 3.1 and 3.2 are of a general nature, the first introducing the three main present-day schools of jet fragmentation, the second presenting some subjective pros and cons. In 3.3 the basic scheme for flavour generation is described, and in 3.4 the longitudinal fragmentation properties are discussed. Although presented in a string fragmentation framework, much of this material is applicable to independent fragmentation as well. The details for generating jet systems are described next, in 3.5 for string fragmentation, and in 3.6 for independent fragmentation. Finally, in 3.7 three

different topics are covered: the possibility of a more complicated string structure, the treatment of low-mass jet systems and the fragmentation of diquark and hadron jets.

3.1. Introduction to the Models

After a high energy interaction has taken place, a number of partons, i.e. quarks and gluons, are moving out from a (more or less) common origin. These partons are coloured objects, and therefore feel the strong confinement force. As the partons move apart, these forces are screened by the production of new quark-antiquark (or diquark-antidiquark) pairs, and the energy of the partons is subdivided among the colour neutral hadrons formed. For the Monte Carlo description of this process, three different approaches have been used extensively: independent fragmentation (IF), string fragmentation (SF) and cluster fragmentation (CF). We should emphasize, however, that dividing lines are not absolute, e.g. the model of Artru and Mennessier [18] (to the best of our knowledge the first true jet fragmentation Monte Carlo ever written) could be classified either as an SF or as a CF approach, depending on what characteristics are emphasized. Further, in this paper we do not consider models that do not recognize the standard perturbative QCD framework, e.g. the fire-string model of [19].

The string model is most easily illustrated for the production of a back-to-back $q\bar{q}$ jet pair, as obtained in e^+e^- annihilation [20]. As the partons move apart, the physical picture is that of a colour flux tube being stretched between the partons. The transverse dimensions of the tube are of typical hadronic sizes, roughly 1 fm. With the tube assumed to be uniform along its length, this automatically leads to a linear confinement picture, as is also supported e.g. by lattice QCD results. The most straightforward way, to obtain a Lorentz covariant and causal description of the massless relativistic string with no transverse degrees of freedom. The string formalism thus gives the energy and longitudinal momentum flow between the two outgoing partons. The string can be thought of as parametrizing the position of the axis of a cylindrically symmetric flux tube. We need not here specify the true nature of this tube. If it is something like a vortex line in a type II superconductor, then the properties are completely specified by a small core region, for which a one-dimensional string is a good approximation. The energy, on the other hand, is mainly stored in the larger region of falling field strength outside this

core. Other pictures are also possible, e.g. corresponding to an elongated bag structure. From phenomenology the string constant, i.e. the amount of energy per unit length, is known to be $\kappa \approx 1 \text{ GeV/fm} \approx 0.2 \text{ GeV}^2$. (The expression "massless" relativistic string is somewhat of a misnomer, κ effectively corresponds to a "mass density" along the string. Lorentz boost effects on this mass density have to be handled with some special care, however, since the string is an extended object, so that the definition of a string piece "at a given time" is Lorentz frame dependent.)

As the q and \bar{q} move apart, the potential energy stored in the string increases, and the string may break by the production of a new $q'\bar{q}'$ pair, so that the system splits into two colour singlet systems $q\bar{q}'$ and $q'\bar{q}$. If the invariant mass of either of these systems is large enough, further breaks may occur, and so on until only ordinary hadrons remain. Typically, a break occurs when the q and the \bar{q} ends of a colour singlet system are 2-5 fm apart in the $q\bar{q}$ rest frame. Each hadron is formed by the quark from one break and the antiquark from an adjacent break. The hadrons can therefore be arranged in a flavour chain, and numbered consecutively from one end of the jet system. This ordering is called rank [21]. Two nearest neighbours in rank thus have one quark-antiquark pair in common (this statement is modified somewhat by baryon production, see below).

The various $q'\bar{q}'$ breaks have a spacelike separation, i.e. they are causally disconnected, but two adjacent breaks are related by the requirement that the intervening hadron be on mass shell. The spacelike separation implies that the time ordering of the breaking vertices is Lorentz frame dependent and hence irrelevant. In a Monte Carlo procedure it is therefore convenient to consider the production of the hadron at, say, the q end first, and then the next closest one, etc. This gives an iterative structure to the jet fragmentation Monte Carlo, as follows. The pair $q_1\bar{q}_1$ closest to the q end is generated first, and the first rank hadron $q_1\bar{q}_1$ is formed. Starting from the remaining q_1 the next pair $q_2\bar{q}_2$ is chosen, and the second rank hadron $q_1\bar{q}_2$ can now be selected, leaving q_2 unpaired, and so on until the \bar{q} end is reached.

A main point of the SF scheme is that both a space-time and a momentum-energy description of fragmentation is obtained "for the price of one", since the two pictures essentially only differ by a change of scale given by the string constant κ . Obviously this is strictly true only in a classical string picture; in a correct quantum mechanical description the uncertainty relations would have to be taken into account [22].

In the string model, gluons correspond to energy and momentum carrying kinks on the string spanned between a quark and an antiquark end [23] or, in an "onium" decay, to kinks on a closed string polygon. The typical example is $e^+e^- \rightarrow q\bar{q}g$, where a string is stretched from the quark via the gluon to the antiquark. Whereas a quark or antiquark thus has one string piece attached to it, a gluon has two, corresponding to the double colour charge of a gluon.

The concept of independent fragmentation is more imprecise than that of string fragmentation. The main assumption is that, in the CM frame of an event, the fragmentation of the outgoing partons can be considered completely independently of each other. This makes for an extreme ease of implementation, which is probably the main reason why IF is the preferred choice of most model builders [24,25,26,27,28]. For each jet, an iterative scheme is assumed for the fragmentation, just as outlined above for SF, but without any related space-time picture. Within the IF framework details, such as gluon fragmentation properties or flavour, momentum and energy conservation, have been implemented differently by different authors.

If a parton shower picture is used, and if each final gluon is split into a $q\bar{q}$ pair (if not by the parton shower itself, then by brute force) a number of not-too-massive colour singlet clusters are obtained. In the cluster fragmentation schemes, each such cluster is assumed to decay isotropically (in its rest frame) into the observable hadrons. Again details vary. In some schemes [29,30] clusters are assumed to decay into two hadrons, with the relative probability for different decay channels given by phase space and spin counting factors, in other models [31] cluster decays are based on parametrizations of low energy data and may result in a variable number of particles. In later versions of CF, string fragmentation schemes are actually used to break heavy clusters into smaller clusters [30,31]. The border to a true string scheme is thus fairly flexible, and neither a parton shower approach (as opposed to using matrix elements) nor the arbitrary $q \rightarrow q\bar{q}$ splittings are a necessity for CF [32]. Transverse momenta for hadrons are assumed to be generated by the cluster decays rather than by the tunneling mechanism invoked in SF.

3.2. Status of the Models

An evaluation of the relative merits of the various fragmentation schemes is obviously a very subjective matter. Keeping in mind that the author is biased, the following comments may still be useful.

In an $e^+e^- \rightarrow q\bar{q}$ event, the SF model predicts that the region between the q and \bar{q} jets should be less populated than the regions between g and q or g and \bar{q} [33], because the former region does not contain any string pieces whereas the latter two do. Such a "string effect" was originally observed by the JADE collaboration [34] and has later been confirmed by other groups [35]. It can not be explained within the framework of any of the standard IF models. From a theoretical point of view, IF models also suffer from the disease that the fragmentation prescriptions are Lorentz frame dependent, with the CM frame of the event taking a very special and unphysical importance. A related weakness is that, if combined with a parton shower approach, IF is not stable with respect to collinear gluon radiation: the multiplicity from the fragmentation of two collinear partons, sharing the energy, is larger than that of a single parton with the full energy. Further, conservation of flavour, momentum or energy does not follow automatically from the IF approach, but has to be imposed post facto.

It should be noted, however, that a generalization of the string model exists, in which separate "gluon-type" and "quark-type" strings are used [36]. This scheme has almost all the nice properties of ordinary SF, and still gives results similar to the IF approach in some limits, specifically almost symmetric three-jet events. The experimental observation of string effects puts a constraint that the gluon-type string constant has to be at least a factor 1.5 larger than the quark-type one. Unfortunately, this scheme is exceedingly difficult to implement correctly, and nobody has even tried; what is offered in this program is only a very first rough draft based on already existing program components.

The problems noted with IF deal mainly with the study of low-momentum particles between the jets or with what happens when two outgoing partons are separated by a small angle. For the study of reasonably high-momentum particles in well separated jets, IF has turned out to be very useful. Even for well separated jets, however, the strong coupling constant value needed to describe the data depends on model details, specifically the momentum conservation scheme adopted.

Initial CF models soon ran into problems, in that occasionally a parton shower produces a fairly high-mass cluster which, if allowed to decay isotropically, give results in disagreement with the data. This is remedied by having an intermediate step where large-mass clusters are broken into smaller ones, using information on colour field ("string") directions. With this improvement, cluster models based on coherent branching showers (see section 6.3) give a nice description of string effects [34,35]. A conceptual problem is that the amount of baryon production is very sensitive to the parton shower cutoff in models where cluster decay is determined by phase space factors. Models where clusters have no net baryon number and decay isotropically have anyhow been ruled out by recent TPC data on baryon-antibaryon correlations [37]. One way out would be to allow $g \rightarrow q\bar{q}g$ splittings in addition to the $q\bar{q}$ ones. The main purported advantage over SF and IF models, that phase space factors give the particle flavour composition without the use of any free parameters, would then probably be lost. Furthermore, the high z behaviour of particle spectra, as observed by HRS [38], is inconsistent with a picture where each cluster decays into (at least) two hadrons. A solution could be to associate a low-mass cluster with a single hadron; this again would bring CF closer to SF. Finally, from a theoretical point of view, CF models where $g \rightarrow q\bar{q}$ breakups are always enforced in the end are unstable against the emission of soft gluons, in that e.g. a $q\bar{q}$ event with one single soft g gives two low-mass clusters moving apart, with nothing in between, whereas the same $q\bar{q}$ event without the g normally would have been allowed to break into several clusters [32]. In practical terms, this means that the mean multiplicity in an event typically increases when the amount of gluon emission is decreased in the lower shower cutoff.

The string model has done well in all the areas above, and generally seems to provide a very good picture of the overall event structure in e^+e^- . The model is safe with respect to collinear or soft gluon emission, whereas copious perturbative $g \rightarrow q\bar{q}$ branchings would be a problem for the reason outlined above (fortunately $g \rightarrow gg$ is the dominant branching mode for gluons). Surprisingly, some of the main features and predictions of the string model have recently been derived in a purely perturbative QCD approach [39], indicating that perhaps a "duality" exists between the two approaches. Obviously the SF model, as well as the IF and CF ones, lack the Bose correlations now observed in the data [40], although the model might be extended to include such effects [41]. The potential main area of trouble, so far as can be seen today, is particle flavour composition, specifically the

production rate for rare baryons, which seems to be higher in the data than can be easily accommodated in the string model [42].

3.3. Flavour Properties of Jets

Consider a pair of q and \bar{q} partons moving apart. Between them a colour flux tube is stretched. In this field a $q'\bar{q}'$ pair, where the q' and \bar{q}' have no mass or transverse 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 (classically the q' and \bar{q}' will be moving along the two branches of a hyperbola, with the focus defining an effective breakup vertex, and with smallest distance between the two hyperbola branches $2m_T/\kappa$). Quantum mechanically, the quarks may be created in one point and then tunnel out to the classically allowed region. The production probability for this tunneling process will be proportional to

$$\exp(-\pi m_T^2/\kappa) = \exp(-\pi p_T^2/\kappa) \exp(-\pi p_T^2/\kappa) \quad (1)$$

The factorization of the transverse momentum and the mass terms leads to a flavour-independent Gaussian spectrum for the p_T of $q'\bar{q}'$ 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. In a perturbative QCD framework, a hard scattering is associated with gluon radiation, and further contributions to what is naively called fragmentation p_T comes from unresolved radiation. Therefore the mean p_T observed experimentally is somewhat higher than obtained with the formula above. Effectively the radiation has a non-Gaussian shape but, when combined with the ordinary fragmentation p_T , the overall shape is very close to Gaussian, and is parametrized correspondingly in the program.

The formula also implies a suppression of heavy quark production $u : d : s : c \approx 1 : 1 : 0.3 : 10^{-11}$. Charm and heavier quarks are hence not expected to be produced in the soft fragmentation. The suppression of $s\bar{s}$ production is left as a free parameter, but the experimental value agrees well with theoretical prejudice.

The simplest scheme for baryon production is that, in addition to quark-antiquark pairs, also antidiquark-diquark (colour triplet-antitriplet) pairs occasionally are produced in the field [43]. 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. Due to the large uncertainty in the definition of diquark masses, the tunneling formula can not be used directly to predict the expected rate of diquark production. Rather, from data a relative probability for diquark to quark production is determined to $qq : q = 0.09 : 1$, corresponding to a typical nonstrange diquark mass around 420 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 more general framework for baryon production is the so-called popcorn one [9], in which diquarks as such are never produced, but rather baryons appear from the successive production of several $q'\bar{q}'$ pairs. The picture is the following. Assume that the original q is red r and the \bar{q} is \bar{r} . Normally a new $q_1\bar{q}_1$ pair produced in the field would also be rr , so that the $q_1\bar{q}_1$ towards the q end and vice versa, and two separate colour singlet systems $q_1\bar{q}_1$ and $q_2\bar{q}_2$ are formed. Occasionally, the $q_1\bar{q}_1$ pair may be e.g. gg (g =green), in which case there is no net colour charge acting on either q_1 or \bar{q}_1 . Therefore, the pair can not gain energy from the field, and normally would exist only as a fluctuation. If q_1 moves towards q and \bar{q}_1 towards \bar{q} , the net field remaining between q_1 and \bar{q}_1 is $\bar{b}b$ (b =blue, $g+r=\bar{b}$ if only colour triplets are assumed). In this central field, an additional $q_2\bar{q}_2$ pair can be created, where q_2 now is pulled towards $q\bar{q}_1$ and \bar{q}_2 towards $q\bar{q}_1$, with no net colour field between q_2 and \bar{q}_2 . If this is all that happens, the baryon B will be made up out of q_1 , q_2 and some q_4 produced between q and q_1 , and \bar{B} of \bar{q}_1 , \bar{q}_2 and some \bar{q}_5 , i.e. the B and \bar{B} will be nearest neighbours in rank and share two quark pairs. Specifically, q_1 will gain energy from q_2 in order to end up on mass shell, and the tunneling formula for an effective q_1q_2 diquark is recovered.

Part of the time, several $b\bar{b}$ colour pair productions may take place between the q_1 and \bar{q}_1 , however. With two production vertices $q_2\bar{q}_2$ and $q_3\bar{q}_3$, a central meson \bar{q}_2q_3 may be formed, surrounded by a baryon $q_4q_1q_2$ and an antibaryon $\bar{q}_3\bar{q}_1\bar{q}_5$. We call this a BM \bar{B} configuration to distinguish it from the $q_4q_1q_2 + \bar{q}_2\bar{q}_1\bar{q}_5$ BB configuration above. For BM \bar{B} the B and \bar{B} only share one quark-antiquark pair, as opposed to two for BB configurations. The relative probability for a BM \bar{B} configuration is given by the uncertainty relation

suppression for having the q_1 and \bar{q}_1 sufficiently far apart that a meson may be formed in between. Strictly speaking, also configurations like $BMB\bar{B}$, $BMM\bar{B}$, etc. should be possible, but the probability for this is small in our model. Further, since larger masses corresponds to longer string pieces, the production of pseudoscalar mesons is favoured over that of vector ones. If only $B\bar{B}$ and $B\bar{B}$ states are included, and if the probability for having a vector meson M is not suppressed extra, two compensating errors are made (since a vector meson typically decays into two or more pseudoscalar ones).

Unfortunately, the resulting baryon production model has a fair number of parameters, which would be given by the model only if quark and diquark masses were known unambiguously. We have already mentioned the $s : u$ ratio and the $qq : q$ one; the latter has to be increased from 0.09 to 0.10 for the popcorn model, since the total number of possible baryon production configurations is lower in this case (the particle sitting between the B and \bar{B} is constrained to be a meson). Further parameters in the simple diquark model include the extra suppression of strange diquarks compared to nonstrange ones in addition to the ordinary $s : u$ ratio (this is because what appears in the exponent of the tunneling formula is m^2 and not m , so that the diquark and the strange quark suppressions do not factorize for a strange diquark), and the suppression of spin 1 diquarks relative to spin 0 ones. For the popcorn model, exactly the same parameters are needed to describe the $B\bar{B}$ configurations. For BMB configurations, the square root of a suppression factor should be applied if the factor is relevant only for one of the B and \bar{B} , e.g. if the B is formed with a spin 1 "diquark" $q_1 q_2$ but the \bar{B} with a spin 0 diquark $\bar{q}_1 \bar{q}_3$. Additional parameters include the relative probability for BMB configurations, which is assumed to be roughly 0.5 (with the remaining 0.5 being $B\bar{B}$), a suppression factor for having a strange meson M between the B and \bar{B} (as opposed to having a lighter nonstrange one) and a suppression factor for having a $\bar{s}s$ pair (rather than a $\bar{u}u$ one) shared between the B and \bar{B} of a $B\bar{B}$ configuration. Of the parameters above, $s : u$ and $qq : q$ have been determined from the data; the remaining have default values as given by our model estimates.

Many different baryon schemes are used in other Monte Carlo programs. Apart from cluster decay models [31,30], double independent quark pair production [44] and chain "decays" of the type $q \rightarrow B\bar{q}\bar{q}$, $qg \rightarrow B\bar{q}$ and $qq \rightarrow Mqq$ [45] may be mentioned.

A quark and an antiquark may combine to produce either a pseudoscalar or a vector meson. The production of higher resonances is neglected; from orbital angular momentum arguments this rate is anyhow assumed to be low in a string framework. From counting the number of spin states one would expect the relative probability for pseudoscalar : vector to be 1 : 3. This should be modified by wave function effects, as manifested e.g. in the mass splitting between pseudoscalar and vector states. Simple estimates [46] suggest that vector meson production should be suppressed, relative to the naive factor of 3, by the ratio of pseudoscalars to vector masses (or possibly some power thereof), so that a factor 3 is approached only for charm and heavier mesons. In the program we have chosen to use three different parameters, one for light nonstrange mesons, one for strange mesons and one for charm and heavier mesons.

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' .

A given quark-diquark pair (even with the three quarks produced "independently", effective diquark numbers can still be assigned to any pair of quarks) 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 higher resonances are neglected. Special care is necessary here since, in distinction to the meson case, different flavour combinations have different number of states available: for uuu only Δ^{++} , whereas uds may become either Λ , Σ^0 or Σ^{+} . A very important constraint is the fact that a baryon is a symmetric state of three quarks (neglecting the colour degree of freedom). When a diquark and a quark are joined 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 $SU(6)$ (flavour $SU(3)$ plus spin) 56-multiplet would become equally populated. 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. As in the case for mesons, one could imagine an explicit further suppression of the heavier spin 3/2 baryons. We do not expect it to be an important effect, since baryon mass splittings are much smaller than in the meson case.

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If a given quark-diquark combination is not accepted above, properly speaking both the quark and the diquark flavour should be chosen anew. This would become a tedious process, since also the hadron produced in the step before would have to be rejected. In practice only the last produced pair, be that the quark or diquark one, is rejected. The error introduced by this is small.

In the diquark model, a diquark is expected to have exactly the same transverse momentum distribution as a quark. For BMB configurations the situation is somewhat more unclear, but we have checked that various possibilities give very similar results. The option implemented in the program is to assume no transverse momentum at all for the $q_1\bar{q}_1$ pair shared by the B and \bar{B} , with all other pairs having the standard Gaussian spectrum with local momentum conservation. This means that the B and \bar{B} p_T 's are uncorrelated in a B \bar{B} configuration and (partially) anticorrelated in the B \bar{B} configurations, with the same mean transverse momentum for primary baryons as for primary mesons.

3.4. Longitudinal Fragmentation of Jets

We have described how a sequence of hadrons is formed when an original $q\bar{q}'$ pair moves apart: the production of $q'\bar{q}'$ pairs (where ' q' may also represent an antidiquark) $q_1\bar{q}_1$, $q_2\bar{q}_2$, $q_3\bar{q}_3$ etc. break the colour flux tube into hadrons $q\bar{q}_1$, $q_1\bar{q}_2$, $q_2\bar{q}_3$ etc. On the average the $q'\bar{q}'$ creation vertices will appear along a hyperbola of constant proper time, however with rather large fluctuations. This implies that the strict ordering in flavour, rank, only in the mean corresponds to the ordering in rapidity. With the transverse momentum p_T given by the tunneling mechanism, and the mass of the hadron determined by the flavour composition and spin structure, only one degree of freedom remains to be specified in the energy-momentum four-vector for each hadron.

For the original quark moving out along the +z axis and the \bar{q} along the -z one, it is convenient to use the lightcone variables $W_+ = E + p_z$ and $W_- = E - p_z$, related by

$$W_+ W_- = E^2 - p_z^2 = m_{T'}^2 = m^2 + p_x^2 + p_y^2 \quad (2)$$

The fragmentation scheme can then be formulated in terms of a probability distribution $f(z)$. The first z value chosen, z_1 , is the ratio of the hadron W_+ and the total W_+ of the $q\bar{q}'$ jet system. For hadron transverse mass $m_{T1}^2 = m_{T1}^2/(z_1 W_+)$ is the fraction of the total W_+ taken. This leaves $(1-z_1)W_+$ and $W_- - m_{T1}^2/(z_1 W_+)$ for the remainder-system. For the production of the second

hadron a new z_2 is chosen, with z_2 to be interpreted as the fraction of the remaining W_+ that is taken by the second hadron. This can be iterated to yield a sequence of z_i values, with remaining W_+ reduced by a factor $(1-z_i)$ in each step i. Note that the use of scaling in W_+ rather than in E or in p_z ensures that the fragmentation scheme becomes Lorentz covariant under boosts along the z axis.

Different shapes have been suggested for $f(z)$. The Field-Feynman [21] parametrization

$$f(z) = 1 - a + 3a(1-z)^2 \quad (3)$$

with default value $a = 0.77$ seems to be too strongly peaked at $z=0$ [47], instead a shape like

$$f(z) = (1+c)(1-z)^c \quad (4)$$

may be used. Heavier quark jets are generally assumed to have a harder fragmentation function, as suggested by charm and bottom data. A simple approximation would be

$$f(z) = (1+b)z^b \quad (5)$$

A suggestion based on old-fashioned perturbation theory is the "SLAC" or "Peterson" formula [48]

$$f(z) \sim \frac{1}{z \left[1 - \frac{1}{z} - \frac{\epsilon}{1-z} \right]^2} \quad (6)$$

where one expects $\epsilon = (m_0/m_q)^2$ with m_0 some reference scale and m_q the heavy quark mass.

All these possibilities, which are available as options in the program, suffer from the disease of not being left-right symmetric. With this we mean the following. Above we have described an iteration scheme for the fragmentation of a $q\bar{q}'$ jet system, starting at the q end of the system and stepping "left" towards the \bar{q} end. Alternatively we could have started at the \bar{q} end and iterated the other way, towards "right", instead. Whatever way we choose to do it, we would wish to obtain the same result on the mean. The use of iteration schemes at all is just a matter of convenience; as we have noted before: all $q'\bar{q}'$ production vertices are causally disconnected from each other. Since our iteration schemes have been derived under the assumption that there is much energy left, an iteration from the q end can not trivially be taken all the way to \bar{q} and vice versa. In the central rapidity plateau of a reasonably large jet system, however, there should be no artefact left to tell the direction of

iteration.

It turns out that it is possible to find algorithms which are left-right symmetric. For the case of fragmentation into clusters with variable masses, one answer was given by Artru-Mennenier [18]. For fragmentation into particles with given transverse masses, the most general possible answer is given in [8]. When the invariant mass of the system is large, this answer can be implemented in an iterative scheme. For the production of a hadron with a known transverse mass m_T , the shape of $f(z)$ is then

$$f(z) \sim \frac{1}{z} z^{\alpha} \left[\frac{1-z}{z} \right]^\beta \exp\left[-\frac{bm_T^2}{z}\right] \quad (7)$$

where the indices α and β corresponds to the flavours produced at the "old" and "new" $q'q'$ vertices that together define the hadron. There is in principle one free parameter α_0 for each flavour and a common b parameter. In the program we assume that all a 's are the same, so that the formula collapses to

$$f(z) \sim z^{-1} (1-z)^a \exp(-bm_T^2/z) \quad (8)$$

A good fit to experimental data can be obtained with the parameter values $a=1$ and $b=0.7 \text{ GeV}^{-2}$.

It should be noted that the explicit mass dependence in $f(z)$ implies a harder fragmentation function for heavier hadrons; the asymptotic behaviour of the mean z value for heavy hadrons is

$$\langle z \rangle \approx 1 - \frac{1+a}{bm_T^2} \quad (9)$$

The parameter values above, determined for ordinary hadrons, also seem to provide a good description for charm and bottom fragmentation.

For future reference we note that the derivation of $f(z)$ as a by-product also gives the probability distribution in invariant time τ of $q'q'$ breakup vertices. In terms of $\Gamma = (k\tau)^2$, this distribution is

$$P(\Gamma) d\Gamma \sim \Gamma^a \exp(-b\Gamma) d\Gamma \quad (10)$$

with the same a and b as above. In a given event, the connection between adjacent Γ values is given by the formula

$$\Gamma_i = (1-z_i) (\Gamma_{i-1} + m_{Ti}^2/z_i) \quad (11)$$

where Γ_{i-1} is the "old" and Γ_i is the "new" value obtained after taking a step z_i for the production of a hadron with transverse mass m_{Ti} . The initial values at the q and \bar{q} ends of the system are $\Gamma_0 = 0$.

The $f(z)$ formulae above, for the breakup of a system into a hadron and a remainder-system, strictly speaking only apply when the mass of the remainder-system is large. If used all the way, in a fragmentation chain that is started at the q end, the mass of the "last" hadron to be formed at the \bar{q} end would not be free, but be completely determined by whatever happened to be left after the production of the previous hadrons. This last hadron would thus not end up on mass shell. In theory it is known how to take such effects into account, but the resulting formulae are wholly unsuitable for Monte Carlo implementation. We have therefore chosen the following scheme. In each step of the fragmentation, a random choice is made whether to produce a hadron on the "right" q side or on the "left" \bar{q} one. In the former case the z value is interpreted as the fraction of remaining W_+ to be taken by the hadron, in the latter as fraction of remaining W_- . After each hadron is produced, the amount of W_+ and W_- remaining is updated. This process is allowed to go on as long as the energy of the remaining system is sufficiently large.

At some point, when $(W_+W_-) \text{ remaining} = W_{\text{rem}}^2 < W_{\text{min}}^2$ 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, and ideally this should apply for each particle type separately. This is unattainable in practice, but fair results can be 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

$$W_{\text{min}} = (W_{\text{min}0} + m_{qi} + m_{qj} + k m_{qn}) (1 \pm \delta) \quad (12)$$

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 of the q and the \bar{q} chain. The factor $1 \pm \delta$ signifies a smearing of the W_{min} value, 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 there will be 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 a system of heavy quarks a bit above threshold, like $b\bar{b}$ at 15 GeV, the formalism above underestimates the probability that the system fragments into two hadrons (since the algorithm is optimized for typical hadrons, with transverse masses around $0.5 - 1$ GeV). For these rare cases a special check is made by calculating the $\Gamma (= (k\tau)^2)$ value for the possible breakup vertex and

accepting the vertex with a probability given by (an approximation of) the integral of $P(\Gamma')$ between 0 and the Γ of the vertex.

For the two final hadrons the respective transverse masses, m_{T1} and m_{T2} , and the remaining W_{rem} are known. If W_{rem} is too small, no kinematically allowed solutions will exist, in which case we reject all previous steps and start all over again. Otherwise two possible solutions exist, one in which the $q_i \bar{q}_n$ hadron moves to the right (the q_i side) and $q_n \bar{q}_j$ towards the left (the \bar{q}_j side) in the CM frame of the two final hadrons, and one in which the reverse situation holds. The probability for the latter ordering is smaller for two adjacent hadrons elsewhere in the chain, hence a corresponding behaviour have to be put in by hand for the final two hadrons. A good parametrization is

$$\text{reverse} = \frac{1}{2} \left\{ \frac{m_{T1} + m_{T2}}{W_{rem}} d \right\} \quad (13)$$

where d is to be determined by a study of the typical behaviour of adjacent hadrons.

When baryon production is included, some particular problems arise. First consider $B\bar{B}$ situations. In the naive iterative scheme one already has a quark and is to choose a matching diquark flavour or the other way around. In either case the choice of the new flavour can be done taking into account the number of SU(6) states available for the quark-diquark combination. For a case where the final $q_n \bar{q}_n$ breakup is an antiquark-diquark one, the weights for forming $q_i \bar{q}_n$ and $q_n \bar{q}_j$ enter at the same time, however. We do not know how to handle this problem; what is done is to use weights as usual for the $q_i \bar{q}_n$ baryon to select q_n , but then consider $q_n \bar{q}_j$ as given (or the other way around with equal probability). If $q_n \bar{q}_j$ turns out to be an antidiquark-diquark combination, the whole fragmentation chain is rejected, since we do not know how to form corresponding hadrons. A similar problem arises, and is solved in the same spirit, for a $B\bar{B}$ configuration in which the B (or \bar{B}) was chosen as third-last particle. When only two particles remain to be generated, it is obviously too late to consider having a $B\bar{B}$ configuration. This is as it should, however, as can be found by looking at all possible ways a hadron of given rank can be a baryon.

The beauty and symmetry of the basic fragmentation scheme is thus slightly broken by the necessity for this joining of the two sides. In practice the errors are small to begin with, and with our procedure of generating the events from both ends inwards the place of joining varies from event to event,

further masking the errors. In particular, properties of high-momentum particles on either side of the event coincides with the naive formulae derived for "infinite-energy" jet systems.

3.5. String Fragmentation of Jet Systems

We have now discussed the SF scheme for the fragmentation of a simple $q\bar{q}$ jet system. In order to understand how these results generalize to arbitrary jet systems, it is first necessary to understand the string motion for the case when no fragmentation takes place. In the following we will assume that quarks as well as gluons are massless, but all arguments can be generalized to massive quarks without too much problem.

For a $q\bar{q}$ event viewed in the CM frame, with energy W , the partons start moving out back-to-back, carrying half the energy each. As they move apart, energy and momentum is lost to the string. When the partons are a distance W/k apart, all the energy is stored in the string. The partons now turn around and come together again with the original momentum vectors reversed. This corresponds to half a period of the full string motion; the second half the process is repeated, mirror-imaged. For further generalizations to multiparton systems, a convenient description of the energy and momentum flow is given in terms of "genes" [49], infinitesimal packets of the four-momentum given up by the partons to the string. Genes with $p_2 = E$, emitted from the q end in the initial stages of the string motion above, will move in the \bar{q} direction with the speed of light, whereas genes with $p_2 = -E$ given up by the \bar{q} will move in the q direction. Thus, in this simple case, the direction of motion for a gene is just opposite to that of a free particle with the same four-momentum. This is due to the string tension. If the system is not viewed in the CM frame, the rules are that any parton gives up genes with four-momentum proportional to its own four-momentum, but the direction of motion of any gene is given by the momentum direction of the genes it meets, i.e. that were emitted by the parton at the other end of that particular string piece. When the q has lost all its energy, the \bar{q} genes, which before could not catch up with q , start impinging on it, and the q is pulled back, accreting \bar{q} genes in the process. When the q and \bar{q} meet in the origin again, they have completely traded genes with respect to the initial situation.

A three-jet $q\bar{q}g$ event initially corresponds to having a string piece stretched between q and g and another between g and \bar{q} . Gluon four-momentum genes are thus flowing towards the q and \bar{q} . Correspondingly, q and \bar{q} genes are flowing towards the g . When the gluon has lost all its energy, the g genes continue moving apart, and instead a third string region is formed in the "middle" of the total string, consisting of overlapping q and \bar{q} genes. The two "corners" on the string, separating the three string regions, are not of the gluon-kink type: they do not carry any momentum.

If this third region would only appear at a time later than the typical time scale for fragmentation, it could not affect the sharing of energy between different particles. This is true in the limit of high energy, well separated partons. For a small gluon energy, on the other hand, the third string region appears early, and the overall drawing of the string becomes fairly two-jetlike. In the limit of vanishing gluon energy, the two initial string regions collapse to naught, and the ordinary two-jet event is recovered. Also for a collinear gluon, i.e. $\theta_{q\bar{q}} \gg 0$ (or $\theta_{q\bar{q}} \ll 0$) small, the stretching becomes two-jetlike. In particular, the q string endpoint first moves out a distance \bar{p}_Q/κ losing genes to the string, and then a further distance \bar{p}_g/κ , a first half accreting genes from the g and the second half reemitting them. (This latter half actually includes yet another string piece; a corresponding piece appears at the \bar{q} end, such that half a period of the system involves five different string regions.) The end result is, approximately, that a string is drawn out as if there had only been a single parton with energy $|\bar{p}_q + \bar{p}_g|$, such that the simple two-jet event again is recovered in the limit $\theta_{q\bar{q}} \rightarrow 0$. These properties of the string motion are the reason why the string fragmentation scheme is "infrared safe" with respect to soft or collinear gluon emission.

The discussions for the three-jet case can be generalized to the motion of a string with q and \bar{q} endpoints and an arbitrary number of intermediate gluons [7]. For n partons, whereof $n-2$ gluons, the original string contains $n-1$ pieces. Anytime one of the original gluons has lost its energy, a new string region is formed. As the extra "corners" on the string, created in pairs each time a gluon lost its energy, meet each other, old string regions vanish and new are created, so that half a period of the string contains $2n^2 - 6n + 5$ different string regions. Each of these regions can be understood simply as built up from the overlap of (opposite-moving) genes from two of the original partons, according to well specified rules.

In the limit that transverse momenta from tunneling are neglected, the four-momentum of any hadron produced within a region is given as a sum of fractions x_+ and x_- of the four-momenta of the two original partons whose genes make up the region (actually a gluon sends out half of its momentum into each of its two attached string pieces so, for contributions from gluon genes, x is defined with respect to half the gluon four-momentum). The x_+ and x_- values are constrained by the requirement that the hadron produced be on mass shell. A hadron may also be produced by the string breaking in two different regions. The resulting hadron will not correspond to a simple straight string piece, as used up till now, but if the hadron is on mass shell we do not care (see also below). Again the four-momentum can be given as a sum of fractions x of the different initial parton four-momenta.

The generalization of the left-right symmetry requirement to multiparton configurations is not unique. In particular, the z variable is only well-defined for simple two-jet systems. However, in each point of any string region, the definition of an invariant time τ or a $\Gamma = (\kappa\tau)^2$ is unique. The guiding assumption in our Monte Carlo approach will then be that the probability distribution in invariant time for the string to break at a given point should be independent of the shape of the string. In particular, the overall distribution of vertices in Γ should be given by eq. (10). An iterative scheme can now be formulated as follows. Start e.g. at the q end, with $\Gamma_0 = 0$. With flavours and transverse momenta chosen as usual, the transverse hadron mass m_{T1} may be found, and a value z_1 can be chosen according to $f(z)$. This time z_1 is not used directly to define the $E+p_z$ fraction taken, but is rather plugged into eq. (11) to yield a value Γ_1 . The position of the breakup vertex for the $q_1\bar{q}_1$ pair, and hence the four-momentum to be taken by the hadron, is now uniquely given by the intercept of two curves. One is the curve of fixed invariant time Γ_1 for the $q_1\bar{q}_1$ vertex, the other is that of fixed transverse mass m_{T1} for the hadron. With the first hadron found, the process may be iterated to yield a $q_2\bar{q}_2$, a Γ_2 , and finally the breakup vertex for $q_2\bar{q}_2$.

For the case of a simple two-jet system, the standard treatment is exactly recovered. In a general multijet configuration, however, occasionally the $q_i\bar{q}_i$ and the $q_{i+1}\bar{q}_{i+1}$ vertices need not be in the same string region. The new string region can then always be found by a simple search procedure, as follows. Assuming the breakup to take place in a given string region, the curves of constant invariant time and constant hadron mass always take the shape of hyperbolae in the x_+ and x_- variables of total gene four-momentum

taken by the hadron. The two equations can be solved to yield the x_+ and x_- values. If these both come out between 0 and 1 (or, more generally, whatever is left from the production of previous hadrons), then all is well and a solution has been found. If any of them becomes smaller than 0 or greater than 1, i.e. assumes an unphysical value, this must be because the correct solution is outside that particular region. Starting at the region of the $q_i \bar{q}_i$ vertex, a systematic search can then be carried out until the correct region for the $q_{i+1} \bar{q}_{i+1}$ vertex is found.

Some difficulties do arise, both in the basic longitudinal fragmentation scheme and because of the tunneling P_T . These are generally related to the fact that, in an entirely classical description, a single hadron can be described by a fairly complicated string configuration. Quantum mechanically, however, the hadron is only characterized by its total momentum (and spin). In particular, the introduction of small "negative" string pieces does allow for considerable simplifications in the fragmentation scheme. We have checked the stability of the resulting physical picture to the various basic assumptions and approximations.

A brief note on multigluon configurations, without any quark ends. Here the string forms a closed polygon, so a first string breaking has to be chosen by special methods, selecting a vertex according to the proper distribution in invariant time and at a random point along the string. From there on, however, everything will work as described above.

In conclusion, a multijet string is in many respects handled very similarly to a simple $q\bar{q}$ jet system. The choice of new $q'\bar{q}'$ flavours, resulting hadron type and transverse momentum is made the same way, and the fragmentation is carried out at random from both ends of the system, with the two final particles chosen to give a uniform joining of the jets. The details necessary in order to handle the flow of energy and momentum in a multiparton system are quite cumbersome, however.

3.6. Independent Fragmentation of Jet Systems

In IF models, the fragmentation of the different partons is assumed to take place independently of each other in the CM frame of the event. The fragmentation of each quark jet can be treated using the same iterative schemes as outlined above for the flavour and transverse momentum properties

of hadrons. With the $+z$ axis put along a jet direction, scaling in W_+ may also be defined in the same way, where the initial W_+ value is $E + p_z$ of the quark. Note, however, that a choice of a z value close to 0 corresponds to a particle moving backwards, i.e. in the $-z$ direction:

$$\begin{aligned} E &= \frac{1}{2} \left\{ z W_+ + \frac{m_T^2}{z W_+} \right\} \\ p_z &= \frac{1}{2} \left\{ z W_+ - \frac{m_T^2}{z W_+} \right\} \end{aligned} \quad (14)$$

For W_+ , the amount remaining before the hadron with transverse mass m_T is generated. In string fragmentation this problem is circumvented by the simultaneous conservation of W_+ and W_- , so that z values that use up more W_- than is available are not allowed. For a jet supposed to fragment independently of the rest of the system, no corresponding constraint exists. It makes sense to allow only the production of particles with $p_z > 0$ for a jet along the $+z$ axis. To explicitly forbid z values that give particles with $p_z < 0$ would destroy the invariance under longitudinal boosts inherent in the basic one-jet scheme. The most straightforward way out [21] is to allow all z values but then discard hadrons with $p_z < 0$. Note that flavour, transverse momentum and W_+ carried by these hadrons are "lost" for the forward jet. By considerations of two-jet kinematics, one can show that such a scheme indeed gives the right average jet energy when a symmetric fragmentation function is used and the jet energy is very large, but also in real life it is a good approximation. The jet longitudinal momentum is decreased, since the jet acquires an effective mass during the fragmentation procedure. For a two-jet event this is as it should, at least on the average, because also the momentum of the compensating opposite-side parton is decreased.

Within the IF framework, there is no unique recipe for how gluon jet fragmentation should be handled. One possibility is to treat it exactly like a quark jet [24,27], with the initial quark flavour chosen at random among u , \bar{u} , d , \bar{d} , s and \bar{s} , including the ordinary's quark suppression factor. Since the gluon is supposed to fragment softer than a quark jet, the fragmentation function may be chosen independently [24]. Another main option is to split the gluon into a quark and an antiquark one, again $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ according to ordinary fragmentation probabilities, and allow the two jets to share the total energy, e.g. according to the Altarelli-Parisi splitting function [25]. The fragmentation function could still be chosen independently, if so desired. Further, in either case the fragmentation P_T could be chosen to have a

different mean. One also has the freedom to give the original quark of the jet a transverse momentum with respect to the jet direction [21]. Some such effect could actually come from the recoil against soft or collinear gluon emission. All the possibilities above are available as options in the program, including one designed to more represent the high-energy behaviour of a well isolated gluon in the string model, which is to share the jet energy equally between two strings but have a leading hadron which may take energy from both string pieces.

An honest application of the IF tenets inevitably leads to the total flavour, momentum and energy not being conserved during the fragmentation process, and that is the standard approach taken in our program. In order to make the IF concept more palatable, however, different schemes for post facto conservation of the abovementioned properties have been devised. All these schemes are applied to primary hadrons, i.e. before secondary decays have been considered.

Little attention is usually given to flavour conservation, and we only offer one scheme. When the fragmentation of all jets has been performed, independently of each other, the net initial flavour composition, i.e. number of u quarks minus number of \bar{u} quarks etc., is compared with the net final flavour composition. In case of an imbalance, the flavours of the hadron with lowest three-momentum are removed, and the imbalance is reevaluated. If the remaining imbalance could be compensated by a suitable choice of new flavours for this hadron, flavours are so chosen, a new mass is found and the new energy can be evaluated, keeping the three-momentum of the original hadron. If the removal of flavours from the hadron with lowest momentum is not enough, flavours are removed from the one with next-lowest momentum, and so on until enough freedom is obtained, whereafter the necessary flavours are recombined at random to form the new hadrons. Occasionally one extra $q\bar{q}$ pair must be created, which is then done according to the customary probabilities.

Several different schemes for energy and momentum conservation have been devised. All of them assume that the event is given in its CM frame. One scheme [24] is to conserve transverse momentum locally within each jet, so that the final momentum vector of a jet is always parallel with that of the corresponding parton. Then longitudinal momenta may be rescaled separately for particles within each jet, such that the ratio of rescaled jet momentum to initial parton momentum is the same in all jets. Since the initial partons had net vanishing three-momentum, so do now the hadrons. The rescaling factors may be chosen such that also energy comes out right, by an interative procedure.

Details in this scheme may vary, thus the way we ensure vanishing net transverse momentum within each jet is to share the net p_T imbalance equally between all hadrons within the jet, with a more complex scheme used in [24], but the main point is the same: the directions of the initial partons are faithfully preserved by the jets. The price to be paid is that, on the average, energy tends to get shuffled from the high-momentum to the low-momentum jets.

A different procedure is the following [25]. Given the momentum imbalance \vec{P}_{imbal} and the total energy E_{tot} of the event after fragmentation, a boost vector $\vec{\beta} = -\vec{P}_{\text{imbal}}/E_{\text{tot}}$ is defined, such that the Lorentz boosted event has vanishing total momentum. Energy conservation can now be obtained by rescaling all particle three-momenta by a common factor, which may be found iteratively. This scheme generally tends to give a more faithful representation of the initial parton energies than the scheme above, but at the price of distorting the angles between jets. Again, these effects may be of a systematic nature; for three-jet events the angle between the two highest-momentum jets tends to be increased.

The number of possible schemes is infinite. In the program we have two further options. One is to split the necessary three-momentum compensation equally among all the hadrons, another is to split it in proportion to the longitudinal mass $(m^2 + p_L^2)^{0.5}$ of hadrons, with p_L defined with respect to the momentum imbalance direction. In both of these cases, energy is conserved by a common rescaling afterwards.

In summary, the basic IF scheme for a multiparton configuration, even when including an extra final step for flavour, momentum and energy conservation, is much easier to program than is the SF approach. However, it is not trivial to see how the IF assumption and the conservation schemes fit into an actual physical understanding of the fragmentation process.

3.7. Further Fragmentation Issues

As has been mentioned before, there is an approach [36] in which the existence of two different kinds of strings is assumed. The "quark string" is characterized by the ordinary string constant κ , whereas a "gluon string" is taken to have a string constant κ_g . If $\kappa_g > 2\kappa$ it is always energetically favourable to split a gluon string into two quark ones, and the ordinary Lund

string model is recovered. Otherwise, for a three-jet $q\bar{q}g$ event the three different string pieces are joined at a junction. The motion of this junction is given by the compositant of string tensions acting on it. In particular, it is always possible to boost an event to a frame where this junction is at rest. In this frame, much of the standard naive IF picture holds for the fragmentation of the three jets; additionally, a correct treatment would automatically give flavour, momentum and energy conservation. Unfortunately, the simplicity is lost when studying events with several gluon jets. In general, each event will contain a number of different junctions, resulting in a polytoped shape with a number of quark and gluons strings sticking out from a skeleton of gluon strings.

In order to have a first look what this kind of scheme might mean for three-jet events in e^+e^- , the following kind of very simplified treatment was devised, using the framework already provided by the independent fragmentation routines. It is assumed that all strings of the system come together in one single junction. The frame where this junction is at rest may then be found iteratively. It turns out that the iteration scheme is unstable when having a parton with (almost) vanishing momentum in the rest frame of the junction. Since such a parton anyhow would not affect the motion of the junction for long, the effective string tension is scaled down linearly for partons with momenta smaller than 2 GeV. When the rest frame of the junction has been found, all partons are fragmented independently in that frame. The products are boosted back to the CM frame for the (optional) conservation of flavour, momentum and energy.

Occasionally, whether using SF or IF, a jet system may have too small an invariant mass for the ordinary jet fragmentation schemes. This is particularly a problem when including parton showers, where two "nearby" $g + q\bar{q}$ splittings may give one small colour singlet subsystem isolated from other colour singlet jet systems. We have included an optional initial step, before the ordinary fragmentation is performed, to catch situations like that. First the jet system with lowest invariant mass, minus endpoint quark masses, is found. If this is too low for jet fragmentation, an attempt is made to split the system into two hadrons by producing a new $q'\bar{q}'$ pair (with $q' = \text{antidiquark allowed}$) to go with the existing endpoint flavours. If the sum of these hadron masses is smaller than the total invariant mass, a simple isotropic two-particle decay is performed. If not, the endpoint flavours are combined to give one single hadron. Next, the parton (or hadron) is found which, when taken together with the jet system, has the largest invariant

mass. A minimal transfer of four-momentum is then performed, which puts the hadron on mass shell while keeping the mass of the parton unchanged. With this done, one may again search for a low-mass jet system, and iterate the procedure above if need be.

In the discussion on the flavour structure of jets, a topic not covered was that of diquark and hadron jet fragmentation. The basic Lund model for these phenomena is given in [50] and has not been changed since (in particular, the relationship between that model and the "popcorn" model for baryon-antibaryon production has not been sorted out). The basic idea is as follows. For an initial diquark jet, left e.g. when a quark is kicked out of a target baryon, the two quarks will sometimes end up in the same hadron and sometimes not. The "leading" quark at the end of the string is called L, whereas the one which is sitting somewhere along the colour field is called J for junction, with the colour field changing direction at J. The relative position of the J-quark along the string, x_J , is given by a probability function $f_J(x_J)$. An iterative scheme is started at the L-quark. In the step where the J-quark gets included a baryon is formed. Roughly 60% of the time this is at the first step, so that the LJ-diquark sticks together in the same hadron, but the rest of the time the baryon can be produced in the second, third, etc., step. This scheme was developed before the introduction of the symmetric fragmentation function, when the scaling variable could be obtained without any reference to the mass of the produced hadron. In the present scheme, a preliminary z value is found based on an average between the possible baryon and meson mass, which is used to determine whether the J-quark should be included or not. Once the hadron has been determined, the z value is rescaled to take into account the correct mass. The possibility of non-standard a and b values in eq. (8) is left open.

For the Lund low- P_T model, a similar scheme is used, where a baryon corresponds to three quarks sitting along the same single string, stretched over the whole event from one colliding hadron to the other, while a meson gives a quark and a antiquark along it. The most central of the baryon and meson quarks is called an I-quark. The probability distribution for J-quarks is given as before, and an additional probability distribution in scaled momentum x_I is introduced for the I-quark, with separate parametrizations for baryon and meson I-quarks. Again the fragmentation is started at the ends, and several of the L-, J- and I-quarks may or may not be included in the same hadron, depending on the sequence of z values for hadron production. Contrary to the case of a LJ-diquark sticking together, an I-quark is always assumed to lose all original spin correlations with the other quarks. When the I-quark on

one side is included, the flavour chain is closed, and therefore an extra flavour-antiflavour chain has to be stretched in the central region between the two I-quarks. The endpoint q'q' flavour of this pair is chosen according to customary probabilities, including diquark production.

4. Particles and their Decays

The particle classification and content is unchanged with respect to the one presented in the previous program description, with only minor changes in the decay treatment. The following description is therefore largely a somewhat shortened version of [5].

4.2. Masses

Quark masses are not particularly well defined, but the choice here is not critical for most applications in the program (where it is, as for tunneling probabilities, separate parameters are introduced anyhow). For the calculation of heavy hadron masses, and for quark masses needed e.g. in cuts on small systems, we introduce "constituent masses": $m_u = m_d = 0.325 \text{ GeV}$, $m_s = 0.5 \text{ GeV}$, $m_c = 1.6 \text{ GeV}$, $m_b = 5.0 \text{ GeV}$, $m_t = 40 \text{ GeV}$ and $m_h = 200 \text{ GeV}$. Constituent masses for diquarks are defined as the sum of the respective quark masses. The gluon is always assumed massless.

Particle masses, when known, are taken from [52]. From the constituent quark masses the masses of yet undiscovered mesons and baryons are built up by using formulae of the type [53]

$$m = m_0 + \sum_i m_i + k \sum_{i < j} \frac{\langle \bar{\sigma}_i \bar{\sigma}_j \rangle}{m_i m_j} \quad (15)$$

where the constants m_0 and k are fitted from known masses, treating mesons and baryons separately. The flavour neutral mesons, the "onia" of two heavy quarks, are defined individually.

The fourth generation lepton χ is assumed to have a mass 60 GeV, all neutrinos are assumed massless, $m_\nu = 94 \text{ GeV}$, $m_W = 83 \text{ GeV}$ and $m_H = 15 \text{ GeV}$; where the Higgs mass is chosen just to have something.

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

$$P(m) dm = \frac{1}{2\pi} \frac{1}{(m-m_0)^2 + \Gamma^2/4} dm \quad (16)$$

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 distribution may be a poor approximation, and should never be used for detailed studies of resonance production. It will, however, give a feeling for what mass smearing effects could mean.

4.1. Partons and Particles

Four generations of quarks and leptons are included in the program. The quarks are u , d , s , c , b , t , l (low, charge $-1/3$) and h (high, charge $+2/3$). Top has maybe been observed by UA1 [51] but so far the mass is highly uncertain. The quarks may appear singly or in diquark pairs, then with the quarks given in falling order ($l=u$, $2=d$, etc.) and with the spin as subscript. The list of partons also includes the gluon g .

From the quarks, the spin 0 and 1 mesons and spin 1/2 and 3/2 baryons 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. B_u^- (quarks b , \bar{u} , spin 0, charge -1), T_d^{*+} (quarks t , \bar{d} , spin 1, charge $+1$), C_{su}^+ (quarks c , s , u , total spin 1/2 with su in spin singlet, charge $+1$), T_{cu}^{*++} (quarks t , c , u , total spin 3/2, charge $+2$). New flavour neutral pseudoscalars are denoted by η , e.g. η_b^0 , while corresponding vector mesons are called ϕ , e.g. ϕ_t^0 . We also consider K_S^0 and K_L^0 as separate particles coming from the decay of K^0 and \bar{K}^0 .

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

4.3. 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 [52]. We normally assume that the momentum distributions are given by phase space. One exception is w and ϕ decays into $\pi^+ \pi^- \pi^0$. Here a matrix element of the form

$$|M|^2 = |\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|^2 \quad (17)$$

is used, with the \vec{p}_{π} the pion momenta in the rest frame of the decay. Another exception is the decay chain $PS_0 \rightarrow PS_1 + V + PS_2 + PS_3$, with PS representing pseudoscalar mesons and V a vector one. Here the decay angular distribution of V in its rest frame is

$$\cos^2 \theta_{02} d(\cos \theta_{02}) \quad (18)$$

A known shortcoming is that the matrix element for Dalitz decays $\pi^0, \eta \rightarrow \gamma e^+ e^-$ has not been implemented so far.

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

4.4. Weak Decays of Heavy Hadrons

The weak decay of a meson $Q\bar{q}'$ (or baryon $Qq'q''$) may, neglecting QCD corrections, go either as a "free" quark decay, $Q\bar{q}' \rightarrow q_1 \bar{q}_2 q\bar{q}'$ or $Q\bar{q}' \rightarrow l\nu_1 \bar{q}\bar{q}'$, or via quark annihilation, $Q\bar{q}' \rightarrow q_1 \bar{q}_2$ or $Q\bar{q}' \rightarrow l\nu_1$ (in the latter only $Qq'q'' \rightarrow q_1 q_2 q'$ 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 $h \rightarrow t \rightarrow b \rightarrow c \rightarrow s$ need be considered in free decays. There are some obvious cases where this might not hold, e.g. if the $t-t$ mass difference is smaller than the w mass but the $l-c$ difference is bigger than it. We have deliberately avoided such scenarios in choosing the default heavy flavour masses. Once masses and mixing angles have been chosen by the user, such a possibility could be included in the program.

Very heavy quarks, like the u and d of our program, are likely to decay into an on-mass-shell w plus the flavour one step down in the flavour decay chain. The decay of the w can then be treated in a later step. In principle the decay

angle of the w is not distributed completely at random, but we have not yet taken this correlation into account.

For decays of l and t the decay products are distributed according to the standard V-A matrix elements,

$$|M|^2 = (p_Q p_{l+})(p_V p_Q) \quad (19)$$

for a decaying spin +2/3 charge quark and

$$|M|^2 = (p_Q p_{V^-})(p_{l-} p_Q) \quad (20)$$

for a charge -1/3 one. Although given for semileptonic decays here, the matrix elements for hadronic decays are obtained by simple substitutions. The Q mass defined in the program to calculate hadron masses is a constituent one, whereas for the weak decay a current algebra one would be more relevant, so the possibility of a lower effective Q mass is left open. In principle the $q_1 \bar{q}_2$ pair is a colour singlet, since the pair comes from the W decay, and $q\bar{q}'$ is another colour singlet. There is a possibility for a colour rearrangement via a soft gluon exchange, so that the singlets become $q_1 \bar{q}'$ and $q\bar{q}_2$. These two possibilities are treated as different decay channels, with the latter one less probable by roughly a factor of ten, as suggested by CLEO $B \rightarrow J/\psi$ measurements [54].

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 (also for the high decays above) a single particle is formed from the flavour content, with a momentum vector given by 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. Rarely, the mass of the other colour singlet system (normally from the W decay) may be too low for jet fragmentation. If the spectator system has collapsed into one particle, the other system is also allowed to collapse, and the complete decay is reduced to a two-body one. If not, the decay is rejected and a new one is tried.

For semileptonic decays of charm and bottom, it is assumed that the spectator system always collapses into one hadron. Then one may substitute $Q \rightarrow H$ and $q \rightarrow h$ in the V-A matrix elements, where H is the heavy decaying hadron and h is the decay product hadron. A similar scheme is used for bottom hadronic decays. Normally the invariant mass of the remaining jet pair is too low for jet fragmentation, however, and a phase space model is used instead, as follows (see [5] for details). The multiplicity is distributed according to a Gaussian

with mean given as a logarithmic function of the invariant mass of the jet system, with some corrections for endpoint quark masses. New flavours are generated and combined into hadrons according to the same rules as for a string. If energetically possible, the hadrons are distributed according to phase space, if not the whole process is repeated.

For most charmed hadrons, hadronic decay branching ratios are unknown. Here we use the phase space model described above. For D^0 and D^+ a number of two-body decays are known, however, and have been explicitly included. They have been complemented by "educated guesses" for remaining two-particle channels (where ρ , K^* , etc. are counted as one single particle) and a phase space model for decays into three or more hadrons.

4.5. Other Decays

Leptonic decays of τ and the heavy lepton χ is performed with standard V-A matrix elements, eq. (20) with trivial substitutions. Hadronic decays of χ into a neutrino plus two jets is also handled similarly, with the two jets allowed to collapse into one single particle if the invariant mass is small. Two-body decays (neutrino plus meson) of τ are included with known or expected branching ratios, and our simple phase space model (preserving the correct neutrino spectrum as far as possible) is used for cases when two or more hadrons are produced.

For "onia" spin 1 resonances, decay channels into a pair of leptons are explicitly given. Hadronic decays are for J/ψ simulated using the phase space model, for Γ , ϕ_t and ϕ_1 into a pair of quark or gluon jets. The latter should properly be into three gluons; a routine for $\text{onia} \rightarrow q\bar{q}\gamma$ or $q\bar{q}\gamma$ is available separately (section 6.2). For spin 0 resonances, η_c decays are also according to phase space, whereas η_b , η_t and η_1 decay into two gluons, this time the correct leading behaviour. As mentioned above, the high quark is assumed to decay weakly, so for ϕ_h and η_h a random choice is made whether the h or \bar{h} is to decay (first). As already stated, in reality details depend on the actual mass pattern.

Decay probabilities for Z^0 and W^+ to quark and lepton pairs are given, but it should be remembered that gluon emission 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 in section 6.1 and in [1,2]. Also decay probabilities for a Higgs above the $b\bar{b}$ threshold, but still fairly light, are included. 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.

5. Description of the Jet Fragmentation Routines

What follows is the manual for the jet fragmentation routines, detailing subroutine and function calling sequences and commonblock structures. Subsection 5.1 contains the most important information of all, how the record of an individual event is stored in the commonblock LUJETS. Irrespectively of whatever other program components within the Lund Monte Carlo are used, this will always be where the result of an event generation call may be found. In 5.2 some basic routines are presented for defining an initial jet configuration and, optionally, letting it fragment. These are frequently called by the higher-level, process-dependent routines, and maybe not so often directly by the individual user. Subsection 5.3 contains routines for listing events as well as particle data, for rotating and boosting events, and for obtaining some information that can be derived from LUJETS. The description of the fragmentation routines in 5.4 is intended to give some overview of what is done here, but a user only need to know the LUJECM call. The commonblock LUDATI, described in 5.5, contains all the switches and parameters that allow the user to select exactly what should be done, if the default values are not satisfactory. Remaining commonblocks, containing particle masses, decay information and a few other things, are covered in 5.6.

In the description below (as well as in section 7), some frequently appearing concepts are denoted in shorthand. Thus ($D=...$) is used to signify default values given to switches and parameters in BLOCK DATA subprograms, (R) a commonblock variable that the user is allowed to read and may find useful information in, but should never change himself, and (I) a variable for purely internal program use.

5.1. The Event Record

Each new event generated is in its entirety stored in the commonblock LUJETS, which thus forms the event record. Here each jet or particle that appears at some stage of the fragmentation or 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 applications, extra lines may be used to represent other kinds of information.

The particle or parton species is given by the KF code, described below. For partons, a special IFL code also exists, which is used internally and as subroutine argument when no danger of confusion between partons and particles exist. This IFL code is 0=g, 1=u, 2=d, 3=s, 4=c, 5=b, 6=t, 7=l and 8=h, the two latter ones part of a hypothetical fourth generation. Diquark numbers lie between 11 and 88 and are of the form 10•IFL1 + IFL2, with IFL1>IFL2 for spin 1 and IFL1<IFL2 for spin 0 diquark. Antiquarks and antidiquarks are given with a - sign. From these codes, the KF code is derived by adding (or subtracting) 500, see below.

COMMON /LUJETS/ N,K(2000,2),P(2000,5)
 Purpose: to contain the event record, the complete list of all partons and particles in the current event.

N : number of lines in the K and P matrices occupied by the current event. N is continuously updated as the definition of the original configuration and the treatment of fragmentation and decay proceed. The individual parton/particle number, running between 1 and N, is called I.

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

KS : status code.

- = 0 : an undecayed particle or an unfragmented jet, the latter either being a single jet or the last one of a jet system.
- = 1 : an unfragmented jet, which is followed by more jets in the same colour singlet jet system.
- = 2 : a decayed particle or fragmented jet, with comment as =0.
- = 3 : a fragmented jet, with comment as =1.
- = 4 : original beam or target particle included for documentation purposes, but otherwise inactive.

- = 5 : a virtually exchanged particle of the hard interaction, included for documentation purposes, but otherwise inactive.
 - = 6 : a continuation line, used to store extra information about hadron jets (J- and I-quarks).
 - = 7 : a continuation line, used to store extra information about colour flow, mainly for parton shower development.
 - = 8 - 9 : not used, but reserved for additional functions as continuation lines.
 - > 10 : used temporarily for internal administration.
 - KH : history code, normally the line number of the parent from which a particle stems. For fragmentation of a jet system using the Lund string scheme, the assignment of the produced particles to a specific jet within the colour singlet jet system is not meaningful, and what is given is the line number of one of the endpoint partons, the one sitting on the side from which the particle was produced. Normally KH=0 for the original partons/particles. In a LUEIT call, history information is normally lost, so that all KH are set to 0.
 - K(I,2) : contains the KF flavour code for the particle or jet of line I, except for KS>6, where it takes special meaning (use LULIST(3) and LULIST(4) for more detailed listings). A negative KF code, where existing, always corresponds to the antiparticle to the one listed here.
 - 0 blank, i.e. no entry of any kind
- | | | | | | |
|----|--------------------|----|-----------------------------|----|--------------------------------|
| 1 | Y | 31 | D ^{a+} | 61 | Δ ⁺⁺ |
| 2 | Z ⁰ | 32 | F ^{a+} | 62 | Δ ⁺ |
| 3 | W ⁺ | 33 | P ⁰ | 63 | Δ ⁰ |
| 4 | Higgs ⁰ | 34 | w | 64 | Δ ⁻ |
| 5 | Y/Z ⁰ | 35 | φ | 65 | Σ ^{a+} |
| 6 | | 36 | J/Ψ | 66 | Σ ^a 0 |
| 7 | e ⁻ | 37 | K ⁰ | 67 | Σ ^{a-} |
| 8 | v _e | 38 | K _L ⁰ | 68 | Ξ ^{a 0} |
| 9 | μ ⁻ | 39 | | 69 | Ξ ^{a -} |
| 10 | v _μ | 40 | | 70 | Ω ⁻ |
| 11 | τ ⁻ | 41 | p | 71 | Λ ^{a++} |
| 12 | v _τ | 42 | n | 72 | Λ ^{a+} |
| 13 | χ ⁻ | 43 | Σ ⁺ | 73 | Σ ^{a 0} |
| 14 | v _χ | 44 | Λ ⁰ | 74 | C ^{a+} |
| 15 | phasespace | 45 | Σ ⁻ | 75 | C _{SD} ^{a 0} |
| 16 | | 46 | Ξ ⁰ | 76 | C _{SS} ^{a 0} |
| 17 | π ⁺ | 47 | Ξ ⁻ | 77 | C _{cu} ^{a++} |

18 K^+ 48 Σ_c^{++} 78 $C_{c\bar{d}}^{++}$
 19 K^0 49 Σ_c^+ 79 $C_{c\bar{d}}^{++}$
 20 D^0 50 Σ_c^0 80 $C_{c\bar{s}++}$

21 D^+ 51 $C_{s\bar{u}}^+$ 81
 22 F^+ 52 $C_{s\bar{d}}^0$ 82
 23 π^0 53 $C_{s\bar{s}}^0$ 83 η_b
 24 η 54 $C_{c\bar{u}}^{++}$ 84 η_t
 25 η' 55 $C_{c\bar{d}}^+$ 85 η_1
 26 η_c 56 $C_{c\bar{s}}^+$ 86 η_h
 27 ρ^+ 57 Λ 87 Γ
 28 K^{*+} 58 Λ_c^+ 88 Φ
 29 K^{*0} 59 C_{su0}^+ 89 Φ_1
 30 D^{*0} 60 C_{sd0}^+ 90 Φ_h

91 - 100 free to use
 101 - 122 heavy pseudoscalar mesons
 123 - 144 heavy vector mesons

145 - 240 heavy spin 1/2 baryons ("I-like")
 241 - 292 heavy spin 1/2 baryons ("A-like")
 293 - 392 heavy spin 3/2 baryons

500 g 503 s 506 t
 501 u 504 c 507 1
 502 d 505 b 508 h
 511 - 588 diquarks in the form $500 + 10 \cdot IFL1 + IFL2$, where $IFL1$ and $IFL2$ are the two quarks in the diquark, with $IFL1>IFL2$ for spin 1 diquarks and $IFL1<IFL2$ for spin 0 ones. The most frequently used are

511 uu_1 521 $u\bar{d}_1$ 531 us_1
 512 $u\bar{d}_0$ 522 $d\bar{d}_1$ 532 ds_1
 513 us_0 523 $d\bar{s}_0$ 533 ss_1
 590 spectator flavour, remaining in heavy hadron ($KF>100$) when the heaviest quark is assumed to decay weakly. Used in decay channel specifications.

591 a random flavour chosen according to customary probabilities. Used in decay channel specifications.
 592 the antiflavour to the flavour given immediately before this, normally 591. Used in decay channel specifications.

601 - 688 extra information for diquark/hadron jets, given in continuation lines with $KS=6$, of the form $600 + 10 \cdot IFLJ + IFL1$. If the jet contains a J-quark, then $IFLJ$ is the IFL code for it, else $IFLJ=0$. Correspondingly $IFL1$ may represent an I-quark.
 ➤ 1000 used for continuation lines with colour flow information, i.e.

$KS=7$. May be used on the form $1000 + IA$, where IA is the line number of the "ancestor", i.e. the parton that initiated the shower.

$P(I,1) - P(I,5)$: normally contain momentum, energy and mass for the particle in line I , in units of GeV (with $c=1$). For $KS > 6$ (see $K(I,1)$) they take special meanings, as indicated below.

$P(I,1) : p_x$, momentum in x direction.

$RS = 6 : x_J$, i.e. position of J-quark.

$RS = 7 : z$ line number for colour mother.

$P(I,2) : p_y$, momentum in y direction.

$RS = 6 : n_x$, line number for particle containing J-quark.

$RS = 6 : n_t$, line number for anticolour mother.

$P(I,3) : p_z$, momentum in z direction.

$RS = 6 : x_I$, i.e. position of I-quark.

$RS = 7 : z$ line number for colour daughter.

$P(I,4) : E$, energy.

$RS = 6 : n_x$, line number for particle containing I-quark.

$RS = 7 : z$ line number for anticolour daughter.

$P(I,5) : m$, mass.

$RS = 6 : n_x$, not used.

$RS = 7 : z$ used internally for timelike parton showers.

5.2. Definition of Initial Configuration

With the use of the conventions described for the event record, it is possible to specify any initial jet/particle configuration. This task is simplified for a number of often occurring situations by the existence of the filling routines below. Several calls can be combined in the specification. In case one call is enough, the complete 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 if several calls are used, they should be made below. Some checks are made on the physical sensibility of the arguments, and in case of suspected error $MST(26)$ is set nonzero.

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 $LUEXC$

is called.

KF : particle flavour code.

PE : particle energy. If PE is smaller than the mass, the particle is taken to be at rest.

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

SUBROUTINE LU1JET(IP,IP1,IFL1,IFL2,IFL3,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 number 1 is used and LUEXC is called. If IP < 0, line -IP is used, with status code KS=1 rather than 0; thus a jet system may be built up by filling all but the last jet of the system with IP>0. If IFL1 or IFL2 nonzero, two lines will be used to define the jet, the second with status code KS=6.

IFL : flavour code for 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.

IFL : 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 LUEXC is called. If IP<0, lines -IP and -IP+2 are used, with extra colour connection information in -IP+1 and -IP+3, linking the two jets together, so that a parton shower can be generated by a LUSHOW call (with first two arguments -IP and -IP+2), followed by a LUEXC call, if so desired.

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 other two in lines IP+1 and IP+2. If IP=0, lines 1 through 3 are used and LUEXC 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 fraction taken by the i:th 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 other three in lines IP+1, IP+2 and IP+3. If IP=0, lines 1 through 4 are used and LUEXC is called.

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

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 i:th jet.

X12,X14 : $x_{ij} = 2P_i P_j / W^2$, 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).

5.3. Routines to Study an Event or Review Parameters and Particle Data

After a LUEXC call, the event generated is stored in the LUJETS commonblock, and whatever physical variable is desired may be constructed from this record. Via the functions KLU and PLU the values of some frequently appearing variables may be obtained more easily. Further, an event may be rotated, boosted or listed, parameters or particle data listed, and particle data modified.

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 and

decay.

= 3 : three times the total charge of remaining (stable) jets and 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), i.e. jet/particle status and history.

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

= 3 : three times jet/particle charge.

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

= 5 : generation number. Beam particles or virtual exchange particles 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 the 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 in a quark jet 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 and extra lines.

= 9 : jet IFL code for jets, but 1000 for particles and extra lines (not 0, since 0=g1).

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

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

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

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

= 14 : heaviest quark flavour/antiflavour (IFL code) in hadron, 0 for non-hadron.

= 1 - 4 : sum of P_x , P_y , P_z and E , respectively, for the stable remaining entries.

= 5 : invariant mass of the stable remaining entries.

= 6 : sum of electric charge of the stable remaining entries.

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. normally 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 $m_T^2 = m^2 + P_x^2 + P_z^2$.

= 12 : transverse mass m_T .

= 13 - 14 : polar angle θ in radians (between 0 and π) or degrees, respectively.

= 15 - 16 : azimuthal angle ϕ in radians (between - π and π) 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 momentum P .

= 19 : pseudorapidity $\eta = 0.5 \ln((p+p_z)/(p-p_z))$.

= 20 : momentum fraction $x = 2p/W$, where W is the 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, BEY, BEV, 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 \vec{B} of a Lorentz boost, such that a particle initially at rest will have $\vec{p}/E = \vec{B}$ afterwards.

Remark: all entries 1 through N corresponding to status codes KS<6 are affected by the transformation, unless lower and upper bounds are I=0, J= : properties referring to the complete event.

FUNCTION PLU(I,J)

Purpose: to provide various real-valued event data. Note that some of the options available (I>0, J=20-25), which are primarily intended for studies of systems in their respective CM frame, requires that a LUEXEC call has been made for the current initial parton/particle configuration, but that the latest LUEXEC call has not been followed by a LUROBO one.

explicitly given by MST(1) and MST(2).

SUBROUTINE LUEDIT(MEDIT)

Purpose: to exclude unstable or undetectable jets/particles from the event record; also to store spare copies of event (specifically initial parton configuration) that can be recalled to allow e.g. different fragmentation schemes to be run through with one and the same parton configuration.

MEDIT : tells which action is to be taken.

= 0 : lines with status code KS = 4, 5 or >8 are removed. The jets/particles remaining are compressed in the beginning of the LUJETS commonblock and the N value is updated accordingly. The event history is lost, thus all KH values are reset to 0.

= 1 : as =0, but in addition all jets/partices that have fragmented/decayed are removed. KS = 6 or 7 continuation lines are removed only if the corresponding jet has fragmented.

= 2 : as =1, but also all neutrinos are removed.

= 3 : as =2, but also all uncharged particles are removed, leaving only charged, stable particles (if jet fragmentation has been performed).

= -1 : all jets/partices in current event record are stored (as a spare copy) in bottom of commonblock LUJETS (is e.g. done to save original partons before calling LUEXEC). If not enough space is available in LUJETS, MST(26) is nonzero at return.

= -2 : jets/partices stored in bottom of event record with =-1 are placed in beginning of record again, overwriting previous information there (so that e.g. a different fragmentation scheme can be used on the same partons). Since the copy at bottom is unaffected, repeated calls with =-2 can be made.

= -3 : primary jets/partices in the beginning of event record are marked as not fragmented or decayed, and number of entries N is updated accordingly. Is simple substitute for =-1 plus =-2 when no fragmentation/decay products precede any of the original jets/partices.

SUBROUTINE LULIST(MLIST)

Purpose: to list an event, jet or particle data or current parameter values.

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, diquark the two quark flavours and spin, trailing A for

antiquarks and antidiquarks. Characters 5-7 are JET and the last one is F if the jet has 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 characters 5-7 contains a B for antiparticles and the value of the charge(++, +, 0, --) for particles not their own antiparticles. The final character is D for a particle that has 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. If KS>7, the K(I,2) value is printed as it is, and so is K(I,1). For the last two categories the customary momentum and energy information is of course replaced by the relevant information stored in the LUJETS commonblock.

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

= 2 : is equivalent to =0, except that the MST(3) lines following after line N are listed as they stand, i.e. without converting K(I,2) to flavour code, 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 KTP values, mass, width and maximum broadening. Each decay channel (TDC) 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 antiquark (KF=592).

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

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

= 10 : as =0, but the actual K(I,1) and K(I,2) numbers are listed together with the jet/particle name, and P(I,1) - P(I,5) are listed with more decimals.

= 11 : as =1, but expanded as for =10.

= 12 : as =2, but expanded as for =10.

= -1 : writes a header with program version number and last date of change; is mostly for internal use.

SUBROUTINE LUUPDA(MUPDA,LFN)

Purpose: to give the user the ability to update particle data, or to keep several versions of modified particle data for special purposes (e.g. charm studies).

MUPDA : gives the type of action to be taken.

= 1 : write a table of particle data, that the user then can edit at leisure. For ordinary listing of decay data, LULIST(3) should be used, but that listing could not be read back in by the program. For each particle 1-100, one line is written containing the KF flavour code (format 15), the number of decay channels (15), the KTY value (see KTY in LUDAT2) (I5), the mass value (F12.5), the mass width (F12.5) and maximum broadening (F12.5) and the particle name, excluding the charge (2X,A4). For lines above 100, the remaining entries in the KTY, mass, mass width and broadening columns are also given, although they do not refer directly to particle data, except that heavy flavour masses affect the corresponding particle masses. Also the number of decay channels is given for the corresponding group of heavy hadrons (see IDB), with a -1 to signify that the decay data are the same as for the previous group. After each KF line follows one line for each possible decay channel, containing the cumulative branching ratio (5X,F12.5), the MMAT code (see KDP) (I5) and the KF code for the decay products (4I5), with trailing 0:s if the number of decay products is smaller than 4.

= 2 : read in particle data, as written with =1 and thereafter edited by the user, and use this data subsequently in the current run. Reading is done with fixed format, which means that the user has to preserve the format codes described for =1 during the editing. In particular, the number of decay channels given on the first line for a particle must exactly correspond to the number of subsequent lines containing

decay channels.

= 3 : write current particle data as data lines, which can be edited into BLOCK DATA LUDATA for a permanent replacement of the particle data.

This option should never be used by the ordinary user.

LFN : the file number which the data should be written to or read from. The user must see to it that this file is properly opened for read or write.

5.4- The Physics routines

The physics routines form the 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. The actions that will be taken during a LUEXEC call can be tailored extensively via the LUDAT commonblocks, in particular by setting the MST values suitably.

SUBROUTINE LUPEP

Purpose: to rearrange parton shower endproducts (with KS=7 colour index lines) sequentially along strings; also to (optionally) allow small jet systems to collapse into two particles or one only, in the latter case with energy and momentum to be shuffled elsewhere in the event; also to perform checks that e.g. flavours of colour singlet systems make sense. May be called directly by the user before a LUEXEC call to check on possible errors, see MST(26).

Remark : in cases when one single particle is produced from a parton system, the momenta of the partons can not be corrected as for the particle. Beware that a piece of the event record then looks like four-momentum is not conserved, while the event as a whole does conserve it.

SUBROUTINE LUCONS(IP)

Purpose: to handle the fragmentation of a jet system according to independent fragmentation models or the simplified Montvay scheme, and implement energy, momentum and flavour conservation if so desired.

SUBROUTINE LUONEJ(IP)

Purpose: to generate the fragmentation of a single jet, e.g. as part of an independently fragmenting jet system.

SUBROUTINE LUSYSI(IP)

Purpose: to generate the fragmentation of an arbitrary colour singlet jet system according to the Lund string fragmentation model.

SUBROUTINE LUDECY(IP)

Purpose: to perform a particle decay.

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

Purpose: to generate a new quark or diquark flavour and to combine it with an existing flavour to give a hadron.

FUNCTION UIMASS(MMASS,KF)

Purpose: to give the mass for a particle or parton.

SUBROUTINE LUPTDI(IFL,PX,PY)

Purpose: to give transverse momentum, e.g. for a $q\bar{q}$ pair created in the field, according to independent Gaussian distributions in p_x and p_y .

SUBROUTINE LUZDIS(IFL1,IFL3,PR,Z)

Purpose: to generate the longitudinal scaling variable z in jet fragmentation.

SUBROUTINE LUFLY(KF,IFLA,IFLB,IFLC,RSP)

Purpose: to reconstruct the flavour content and spin of any hadron from its KF code. Is mostly used internally, but may be called directly as well.

KF : Particle flavour code.

IFLA, IFLB, IFLC : reconstructed quark flavours in descending order (i.e. heaviest quark first), with IFLC=0 for meson and all =0 for non-hadron.

Simplistic answers are given for the flavour mixing cases $\pi^0 \rightarrow \eta - \eta'$, $\rho^0 \rightarrow \omega$ and $K_S^0 \rightarrow K_L^0$.

KSP : particle spin classification.

= 0 : spin 0 meson.

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

= 4 : spin 3/2 baryon.

= -1 : non-hadrons, i.e. leptons, quarks, intermediate vector bosons, etc.

FUNCTION LUCHGE(KF)

Purpose: to give three times the charge for a particle or parton.

SUBROUTINE LUNAME(KF,CHAU)

Purpose: to give names in the form of character strings given the KF code of a parton or particle.

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 commonblocks.

5.5. The General Switches and Parameters

The commonblock LUDAT1 is, next to LUJETS, the one a user is most likely to access. Here he may control in detail what the program is to do, if the default mode of operation is not satisfactory.

COMMON /LUDAT1/ MST(40),PAR(80)

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) can be used to replace the ordinary lower and upper

limits (normally 1 and N) for the action of LUROBO, LUEDIT and LULST calls. Note that these switches are also used internally, so that they are reset to 0 (i.e. inactive) 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 function, i.e. how large a fraction of the energy available a newly-created hadron takes.

- = 1 : the Lund symmetric fragmentation function, see PAR(31) – PAR(37).
- = 2 : choice of some different forms for each flavour separately, including Field-Peynman and SLAC heavy flavour function, see PAR(41) – PAR(50).
- = 3 : hybrid scheme, where light flavours are treated with symmetric Lund (=1), but charm and heavier can be separately chosen e.g. according to the SLAC function (=2).
- = 0 : no jet fragmentation at all.
- = 1 : colour singlet parton systems are generated using the Lund string model, which provides explicit conservation of energy, momentum and flavour. For single jets all particles generated are kept. Single gluon jet fragmentation is done to approximate the properties of an isolated gluon in the Lund string case.
- = 2 : all jets are assumed to be independently fragmenting, and primary hadrons moving backwards with respect to the jet direction are removed. Gluon jet fragmentation is done to approximate the properties of an isolated gluon in the Lund string case.
- = 3 : as =2, but gluon is assumed to fragment like a random (u, d or s) quark or antiquark.
- = 4 : as =3, but longitudinal (see PAR(33) and PAR(49)) and transverse (see PAR(13)) momentum properties of quark or antiquark substituting for gluon may be separately specified.
- = 5 : as =2, but gluon is assumed to fragment like a pair of a quark (u, d or s) and its antiquark sharing the gluon energy according to the Altarelli-Parisi splitting function.
- = 6 : as =5, but longitudinal (see PAR(33) and PAR(49)) and transverse (see PAR(13)) momentum properties of quark and antiquark substituting for gluon may be separately specified.
- MST(6) : (D=0) energy, momentum and flavour conservation options, as well as switch for simplified Montvay scheme treatment, all for the case of independent fragmentation (MST(5)>2). Whenever momentum conservation is given below, energy and flavour conservation is also implicitly assumed.
- = 0 : no explicit conservation of any kind.
- = 1 : particles share momentum imbalance compensation according to their energy (roughly equivalent to boosting event to CM frame).
- = 2 : particles share momentum imbalance compensation according to their longitudinal mass with respect to the imbalance direction.
- = 3 : particles share momentum imbalance compensation equally.
- = 4 : transverse momenta are compensated separately within each jet,

- longitudinal momenta are rescaled so that ratio of final jet to initial parton momentum is the same for all the jets of the event.
- = 5 : only flavour is explicitly conserved.
- = 6 – 9 : as =1–4, except that above several colour singlet systems that followed immediately after each other in the event listing (e.g. $\bar{q}q\bar{q}'\bar{q}'$) were treated as one single system, whereas here they are treated as separate systems.
- = 10 : simplified Montvay scheme without energy, momentum or flavour conservation.
- = 11 – 14 : simplified Montvay scheme with momentum conservation as for =1–4.
- = 15 : simplified Montvay scheme with flavour conservation only.
- = -1 : independent fragmentation where also particles moving backwards with respect to the jet direction are kept (for single quark or Lund gluon jets this is already obtainable with MST(5)=1, here it can also be used e.g. for the different alternative gluon jet treatments given for MST(5) > 2).
- 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 KTP vector are given a mass according to a truncated Breit-Wigner shape.
- MST(9) : (D=0) use of parton/particle masses in filling routines (LUPART, LULJET, LU2JET, LU3JET, LU4JET).
- MST(10) : (D=1) structure of leading diquarks and hadron jet generation.
- = 0 : leading diquark always treated like a unit, i.e. both quarks go into same hadron. (Note that this has nothing to do with the production of baryon-antibaryon pairs in the field, where the probability of a diquark being split is given by PAR(5).)
- = 1 : L- and J-quarks may go into separate hadrons.
- = 2 – 3 : as =0–1, but stop generation for single jets when J- and/or I- quarks have all been included in hadrons. (This speeds up the generation when only the distribution of original quarks is of interest.)
- MST(11) : (D=0) generation of transverse momentum for endpoint quark(s) of

single quark jet or $q\bar{q}$ jet system (For multijet events no endpoint transverse momentum is ever allowed for).

- = 0 : no transverse momentum for endpoint quarks.
- = 1 : endpoint quarks obtain transverse momenta like ordinary $q\bar{q}$ pairs produced in the field (see PAR(14)); for two-jet systems the endpoints obtain balancing transverse momenta.

MST(12) : (D=1) treatment of colour singlet jet systems with low invariant masses.

- = 0 : no precautions are taken, meaning that problems may occur in LUSYSJ later on.
- = 1 : as described in section 3.7, small jet systems are allowed to collapse into two particles or, failing that, one single particle. Normally all small systems are treated this way, starting with the smallest one, but some systems would require more work and are left untrated; they include diquark-antidiquark pairs below the two-particle threshold and systems containing explicitly defined J- and/or I-quarks (KS=6 lines).

MST(13) : (D=10) maximum number of iterations in simplified Montvay scheme (MST(6) > 10) to find frame where string tensions balance. If no convergence has been obtained, jets are fragmented in overall CM frame, i.e. Montvay scheme is switched off for that event.

MST(14) – MST(18) : not used.

MST(19) : (D=1) writing of header (version number and last date of change) on output file.

- = 0 : not done.
- = 1 : header is written at first occasion, at which time MST(19) is set =0.

MST(20) : (D=6) file number to which all program output is directed. It is the responsibility of the user to see to it that the corresponding file is also opened for output.

MST(21) : (D=1) amount of information retained when parton shower branchings (with KS=7 colour index lines) are rearranged along strings (in LUPREP).

- = 0 : keep also the outdated original information (obviously with jets marked as fragmented).
- = 1 : remove KS=7 colour index lines and all jets that have been copied elsewhere during the rearrangement procedure (and are now KS=2 or 3). For MST(1) nonzero, jets with original line numbers < MST(1) are retained, but are marked as KS=4 documentation lines.
- = 2 : remove KS=7 colour index lines and all jets that have been copied elsewhere (i.e. not only KS=2 or 3, but also 4, 5 or 6), if followed

by a KS=7 line).

- = 3 : as =2, but also remove other jets that were not rearranged, but are still marked as fragmented or as documentation (i.e. KS=2, 3, 4 or 5).

MST(22) : (D=0) ordering in list of primary particles obtained with LUSYSJ call.

- = 0 : listing in the order they are generated, i.e. random from both ends.
- = 1 : ordered in rank along the string from one end to the other.
- = 2 : as =1, but for closed strings the artificial beginning point is shifted so as not to split a baryon-antibaryon pair of common origin.

MST(23) : (D=1) check on possible errors during program execution (managed by LUEXEC). Obviously no guarantee is given that all errors will be caught, but some of the most trivial user-caused errors may be found.

- = 0 : errors do not cause any immediate action, rather the program will try to cope, which may mean e.g. that it runs into an infinite loop.
- = 1 : parton/particle configurations are checked for possible errors, explanatory warnings are printed out for the first five errors and the corresponding events are not generated in full. After five errors the last event is printed and the execution is stopped. Also, a warning is printed the first five times MST(26) is nonzero in LUEXEC, after which no further messages are printed.
- = 2 : parton/particle configurations are checked for possible errors. The user should check MST(24) after each call and, if MST(24) is nonzero, decide on action to be taken and reset MST(24) before next event. No warning is printed. If a second error occurs before MST(24) has been reset, a message and the last event is printed, and the execution is stopped. If errors are frequent (and intended to be so), calling LUPREP beforehand and checking on MST(26) will save time.

MST(24) : (D=0) count of number of errors experienced to date. For MST(23)=2, the user should reset it to 0 after each error.

MST(25) : (R) type of latest error experienced; reason that event was not generated in full. Is reset at each LUEXEC call.

- = 0 : no error experienced.
- = 1 : not enough memory available in commonblock LUJETS.
- = 2 : unphysical flavour setup of parton system; may also be caused by erroneous K(I,J) codes.
- = 3 : not enough energy in jet system to be fragmented with string fragmentation.
- = 4 : not enough energy in jet system to be fragmented with independent fragmentation plus momentum conservation or simplified Montvay scheme.
- = 5 : no decay channels with sum mass smaller than the decaying particile

mass can be found.

= 6 : momentum, energy or charge was not conserved (even allowing for machine precision errors, see PAR(74)); is evaluated only after event has been generated in full, and does not apply when independent fragmentation without momentum conservation was used.

MST(26) : (R) advisory warning flag set in LUPART, LUJET, LU3JET, LU4JET, LU6JET(-1) or LU6PREP (which is also called from LU6EXEC) calls. A warning does not lead to any specific action being taken by the program, but obviously it signals a high probability that something will go wrong in a subsequent LU6EXEC call. Is reset to zero only when a warning is printed by LU6EXEC.

= 0 : no error experienced.

= 1 : not enough memory available in commonblock LUJETS.

= 2 : unphysical flavour setup of parton system; may also be caused by erroneous K(I,1) codes.

= 3 : not enough energy in jet system to be fragmented with string fragmentation.

= 4 : definition of kinematics in LU2JET, LU3JET or LU4JET is inconsistent; most likely the x variables are given values outside the kinematical region.

MST(27) - MST(29) : not used.

MST(30) : (D=2000) number of lines available in the commonblock LUJETS. Should always be changed if the dimensions of the K and P arrays are changed by the user, but should otherwise never be touched. Maximum allowed value is 10000.

MST(31) : (I) number of entries stored with LU6IT(-1) call.

MST(32) : (I) switch when generating gluon jet with options MST(5)=4 or 6.

MST(33) : (I) flavour of extra quark in popcorn baryon pair production.

MST(34) : (I) number of LU6EXEC calls in present run.

MST(35) : (I) number of warnings written for MST(26) nonzero in LU6EXEC.

MST(36) - MST(40) : not used.

PAR(1) : (D=0.10) is $P(q\bar{q})/P(q)$, the suppression of diquark-antidiquark pair production in the field compared to quark-antiquark production.

PAR(2) : (D=0.30) 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=0.4) is $(P(u\bar{s})/P(u\bar{d}))/P(s)/P(d)$, the extra suppression of strange diquark production compared to the normal suppression of strange quarks.

PAR(4) : (D=0.05) is $(1/3)P(u\bar{d}_1)/P(u\bar{d}_0)$, the suppression of spin 1 diquarks

compared to spin 0 ones (excluding the factor 3 coming from spin counting).

PAR(5) : (D=0.5) parameter determining relative occurrence of baryon production by BMB and by B \bar{B} configurations, roughly $P(BMB)/(P(B\bar{B})+P(B\bar{B})) \approx PAR(5)/(0.5+PAR(5))$.

PAR(6) : (D=0.5) extra suppression for having a s \bar{s} pair shared by the B and B \bar{B} of a BMB configuration.

PAR(7) : (D=0.5) extra suppression for having a strange meson M in a BMB configuration.

PAR(8) : (D=0.5) is the probability that a light meson (containing u and d quarks only) is produced with spin 1 (with 1-PAR(8) the probability for spin 0).

PAR(9) : (D=0.6) is the probability that a strange meson is produced with spin 1.

PAR(10) : (D=0.75) is the probability that a charm or heavier meson is produced with spin 1.

PAR(11) : (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 dynamic breaking implied by PAR(2), PAR(3), PAR(4), PAR(6) and PAR(7).

PAR(12) : (D=0.40 GeV) corresponds to the width in the Gaussian p_x and p_y transverse momentum distributions for primary hadrons.

PAR(13) : (D=1.) relative increase in transverse momentum in a gluon jet generated with MST(5)=4 or 6.

PAR(14) : (D=1.) relative increase in transverse momentum of the endpoint quark(s) of a single jet or a two-jet event generated with MST(11)=1.

PAR(15) : (D=0. GeV) gives the width of the Gaussian p_x and p_y distributions for the opposite transverse momentum given to the L- and J-quarks of a leading LJ-diquark.

PAR(16) : (D=1.) corresponds to an increase in the string constant with this factor for breakups close to a heavy quark (charm etc.), influencing the rate of s quark and baryon production and the mean transverse momentum.

PAR(17) : (D=1.) ratio of string constant in (hypothetical) gluon string to that in quark string, used for simplified Montvay scheme. Must be smaller than 2., or the ordinary Lund string would be recovered in nature.

PAR(18) : (D=2. GeV) minimum momentum of jet in simplified Montvay scheme, below which tension is assumed to decrease linearly, to roughly take into account that a very soft parton would be turned around before fragmentation anyhow.

PAR(19), PAR(20) : not used.

PAR(21) : (D=0.1 GeV) gives the remaining W_+ below which the generation of a single jet is stopped (it is chosen smaller than a pion mass so that no hadrons moving in the forward direction are missed).

PAR(22) : (D=1. GeV) is, with quark masses added, used to define the minimum of a jet system is stopped and two final hadrons formed. The three alternatives refer to MST(4)=1 through 3.

PAR(23) - PAR(25) : (D=1.1 GeV, 1.5 GeV, 1.1 GeV) are, together with quark masses, used to define the remaining energy below which the fragmentation of a jet system is stopped and baryon singlet jet system.

PAR(26) : (D=2.) represents the dependence on the mass of the final quark pair for defining the stopping point of the fragmentation. Is strongly correlated to the choice of PAR(23) - PAR(25).

PAR(27) : (D=0.2) relative width of the smearing of the stopping point energy.

PAR(28) - PAR(30) : (D=1.0, 0.6, 1.0) refers to the probability for reverse rapidity ordering of the final two hadrons, with transverse masses m_{T1} and m_{T2} , for a total remaining transverse mass W_{rem} : P(reverse ordering) = $0.5((m_{T1}+m_{T2})/W_{rem}) \text{PAR}(\dots)$. The alternatives refer to MST(4)=1 through 3.

PAR(31), PAR(32) : (D=1., 0.7 GeV $^{-2}$) give the a and b parameters of the symmetric Lund fragmentation function for MST(4)=1 (and MST(4)=3 for ordinary hadrons) $f(z) \sim (1/z)^a (1-z)^b \exp(-bm_T^2/z)$ where m_T is the transverse mass of the hadron.

PAR(33), PAR(34) : (D=1., 0.7 GeV $^{-2}$) give the a and b parameters as above for the special case of a gluon jet generated with MST(5)=4 or 6.

PAR(35), PAR(36) : (D=0.5, 0.7 GeV $^{-2}$) give the a and b parameters as above for the special case of a hadron or diquark jet before the J- and/or I-quarks have been used up.

PAR(37) : (D=1.0 GeV) average hadron mass used to obtain preliminary z value in the special case of a hadron or diquark jet before the J- and/or I-quarks have been used up.

PAR(38) - PAR(40) : not used.

PAR(41) - PAR(48) : (D=3•0.77, 5•0.) give four possible ways to parametrize the fragmentation function for MST(4)=2 (and MST(4)=3 for charm and heavier). The fragmentation of each flavour IFL may be chosen separately; for a diquark the flavour of the heaviest quark is used. With $c = \text{PAR}(40+\text{IFL})$ the alternatives are;

- $0 \leq c \leq 1$: Field-Feynman, $f(z) = 1-c+3c(1-z)^2$;
- $-1 < c < 0$: SLAC, $f(z) \sim 1/(z(1-1/z-(-c)(1-z))^2$;
- $c > 1$: power peaked at $z=0$, $f(z) \sim (1-z)^{(c-1)}$;
- $c < -1$: power peaked at $z=1$, $f(z) \sim z^{(-c-1)}$.

PAR(49) : (D=1.) replaces PAR(41) - PAR(43) for gluon jet generated with

MST(5)=4 or 6.

PAR(50) : (D=0.77) replaces PAR(41) - PAR(43) for a hadron or diquark jet before the J- and/or I-quarks have been used up.

PAR(51), PAR(52) : (D=1., 1.) gives the parametrization of the J-quark position in diquark and baryon jet fragmentation, $f(x_J) \sim \text{PAR}(51)(1-x_J) \text{PAR}(52)$.PAR(53), PAR(54) : (D=0., 1.) gives the parametrization of the I-quark position in meson jet fragmentation, $f(x_I) \sim x_I \text{PAR}(53)(1-x_I) \text{PAR}(54)$.PAR(55), PAR(56) : (D=0., 0.) gives a corresponding parametrization as above for the I-quark position in baryon jet fragmentation, with x_I replaced by x_I/x_J (since x_I is constrained by $x_I < x_J$ for baryon jets).

PAR(57), PAR(58) : not used.

PAR(59) : (D=0.09 GeV 2) effective cutoff in mass-square, below which partons may be recombined to simplify (machine precision limited) kinematics of string fragmentation.

PAR(60) : (D=0.01) effective angular cutoff in radians for recombination of partons, used in conjunction with PAR(59).

PAR(61) - PAR(70) : not used.

PAR(71) : (R) $\pi \approx 3.1415927$.PAR(72) : (R) $2\pi \approx 6.2831854$.

PAR(73) : not used.

PAR(74) : (D=0.001) relative error, i.e. nonconservation of momentum and energy divided by total energy, that may be attributable to machine precision problems (see MST(25)=6).

PAR(75) : (I) contains the total energy W of all first generation jets/particles after a LUEXEC call; to be used by the PUJ function for I>0, J=20-25.

PAR(76) - PAR(80) : not used.

5.6. Further Parameters and Data

The following commonblocks are maybe of a more peripheral interest, with the exception of the IDB array, which allows a selective inhibiting of particle decays, and PMAS(106), the top quark mass.

COMMON /LUDAT2/ KRTYP(120),PNAS(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 quarks according to 100 + IFL. Information is stored as KTYP(..) = KTYP1 + 10*KTYP2.

KTYP1 : particle/quark type (related to charge).

- = 0 : neutral particle its own antiparticle.
- = 1 : negative particle.
- = 2 : neutral particle not its own antiparticle.
- = 3 : singly positive particle.
- = 4 : doubly positive particle.
- = 5 : -1/3 charge quark.
- = 6 : 2/3 charge quark.

KTYP2 : 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*KTYP2-1 and 2*KTYP2.

KTYP(109) = KTYP(120) : not used.

PMAS(1) - PMAS(100) : particle masses for KF codes 1 - 100.

PMAS(101) - PMAS(108) : (D= 0.325, 0.5, 1.6, 5.0, 40., 60., 200. GeV) quark constituent masses stored in positions 100 + IFL. It is not recommended to touch the first four ones, since too low values (relative to the corresponding hadron masses, which are independently determined for IFL<4) could lead to infinite loops in the programs.

PMAS(109), PMAS(110) : not used.

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 and quark constituent masses, determine the mass splitting due to spin-spin interactions for heavy mesons and baryons, respectively. The latter factor is also used for the splitting between spin 0 and spin 1 diquarks.

PMAS(117) - PMAS(120) : not used.

PWID : store width information for particles (or quarks) assumed to have a mass broadening. For particles having a nonzero KTYP2 value in the KTYP vector, PWID(2*KTYP2-1) is the total width Γ of a symmetric Breit-Wigner shape and PWID(2*KTYP2) is the maximum deviation from the PMAS mass value at which the Breit-Wigner shape is truncated.

KFR : describe the correspondence between a given quark content (and particle spin) and the flavour KF code, and must never be touched.

CFR(1) - CFR(12) : give a parametrization of the $\bar{u}-\bar{d}-\bar{s}$ 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 $\langle \bar{u} \bar{d} \rangle$ 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 from spin effects.

CFR(36) - CFR(40) : not used.

COMMON /LUDAT3/ DPAR(20),IDB(120),CBR(400),KDP(1600)

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

DPAR(1) - DPAR(10) : give corrective factors to the weight calculations for multiparticle decays (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 phase space decays.

DPAR(14) : (0.003 GeV) minimum kinetic energy in decays (safety margin for numerical precision errors).

DPAR(15) : (D=0.5 GeV) mass which, in addition to the spectator quark or diquark mass, is not assumed to partake in the weak decay of a heavy quark in a hadron.

DPAR(16) - DPAR(20) : not used.

IDB : give the entry point into the particle decay data table. For stable particles IDB(..)=0, giving a possibility to selectively inhibit particle decays (also a value IDB(..)<0 is interpreted as corresponding to a stable particle, thus a change of sign can be used to switch off and on the decay of a particle alternatively). Arguments up to 100 refer to particle KF code, with heavy hadrons ($KF>100$) lumped together in position 76 + 5*IFL + KSP, with IFL the flavour of the heaviest quark and KSP spin classification as explained for LUIFL.

CBR : give cumulative branching ratios for the different decay channels.

KDP : contain the decay products in the different channels, with four positions 4*IDC-3 to 4*IDC reserved for each channel IDC. The decay products are given following the standard KF code for jets and particles.

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 the event record, with momentum distributed according to phase space.
- = 1 : ω and ϕ decays into three pions, eq. (17).
- = 2 : not used.
- = 3 : vector meson decays into two pseudoscalars, decay angle distributed according to eq. (18) if meson comes from decay of pseudoscalar meson into this vector plus another pseudoscalar.
- = 4 : not used.
- = 5 : quarks and particles are distributed according to phase space, but with last quark a spectator, i.e. sitting at rest with respect to the decaying hadron.
- = 6 : phase space production of hadrons from the quarks available.
- = 7 : as 6, but at least three hadrons to be produced (useful when the two-body decays are given explicitly).
- = 8 : as 6, but for onia resonances, with the option of modifying the multiplicity distribution separately.
- = 9 - 10 : not used.
- = 11 : weak decay matrix element for quarks and leptons, where the spectator system may collapse into one particle for a small invariant mass.
- = 12 : weak decay matrix element for quarks and leptons, where the spectator system is assumed to collapse into one particle from the onset.
- = 13 : as 12, but the quarks from the virtual W decay are converted to particles, according to phase space in the W rest frame, as in =6.

COMMON /LUDATA4/ CHAG(50),CHAF(100)
CHARACTER*4 CHAG,CHAF
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+TFL).

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.

CHAG(36) : status of entry (decayed/fragmented/beam/virtual).

CHAG(37), CHAG(38) : J- and I-quark information.

CHAG(39), CHAG(40) : not used.

CHAG(41), CHAG(42) : stable/unstable particle species.

CHAG(43) - CHAG(50) : not used.

CHAF : particle names (usually excluding charge) according to KF code.

6. e^+e^- physics

In sections 3-5 we have described general-purpose fragmentation and decay schemes. In the following sections, more specific problems will be considered, which loosely have been collected under the heading e^+e^- physics. The production of a primary jet configuration in e^+e^- continuum annihilation is covered in section 6.1, with resonance jet production discussed in 6.2. Both these sections utilize a matrix element approach, whereas the parton shower formalism is introduced in 6.3. Finally, a few routines for event analysis are presented in 6.4. The concepts in 6.3 and 6.4 may be applied to other areas of high energy physics, although the methods are usually particularly transparent in the e^+e^- annihilation case.

6.1. Annihilation Events in the Continuum

The description of e^+e^- annihilation into hadronic events involves a number of components: the s dependence of the total cross section and flavour composition due to QFD, jet production cross sections in perturbative QCD, angular orientation of events, effects of initial state polarization and initial state photon bremsstrahlung. Much of this material is already covered in [6], but new additions have been made, so for the sake of continuity we will repeat briefly some of the topics already covered, together with the new ones. Many of the published formulae have been derived for the case of massless outgoing quarks. For each of the components described in the following, we will begin by discussing the massless case, and then comment on

what is done to accommodate massive quarks.

In the standard theory, we have the following couplings (here illustrated for the first generation)

$$\begin{aligned} q_v &= 0, & v_v &= 1, & a_v &= 1, \\ q_e &= -1, & v_e &= -1 + 4 \sin^2 \theta_W, & a_e &= -1, \\ q_u &= 2/3, & v_u &= 1 - 8/3 \sin^2 \theta_W, & a_u &= 1, \\ q_d &= -1/3, & v_d &= -1 + 4/3 \sin^2 \theta_W, & a_d &= -1, \end{aligned} \quad (21)$$

with q the electric charge and v and a the vector and axial couplings to the Z^0 . The relative energy dependence of the weak neutral current to the electromagnetic one is given by

$$E(s) = \frac{1}{4 \sin^2 \theta_W} \frac{s}{s - m_Z^2 + i m_Z \Gamma_Z} \quad (22)$$

We have chosen $m_Z = 94$ GeV, $\Gamma_Z = 2.8$ GeV and $\sin^2 \theta_W = 0.217$. In principle, Γ_Z can be calculated from information on how many decay channels are open [55]; such an option is available.

Although the incoming e^+ and e^- beams are normally unpolarized, it is possible to have configurations in which they are polarized. We have included this latter possibility, following the formalism in [56]. Thus the incoming e^+ and e^- are characterized by polarizations \hat{P}^\pm in the rest frame of the particles

$$\hat{P}^\pm = P_T^\pm \hat{s}^\pm + P_L^\pm \hat{p}^\pm \quad (23)$$

where $0 < P_T^\pm < 1$ and $-1 < P_L^\pm < 1$, with the constraint

$$\hat{P}_T^{\pm 2} = P_T^{\pm 2} + P_L^{\pm 2} \leq 1 \quad (24)$$

Here \hat{s}^\pm are unit vectors perpendicular to the beam directions \hat{p}^\pm . To be specific, we choose a right-handed coordinate frame with $\hat{p}^\pm = (0, 0, -\pm 1)$ and standard transverse polarization directions (out of the machine plane for storage rings) $\hat{s}^\pm = (0, \pm 1, 0)$, the latter corresponding to azimuthal angles $\phi^\pm = \pm \pi/2$. As free parameters in the program we choose P_T^+ , P_L^+ , $P_T^- = (P_T^+ P_L^-)^{0.5}$ and $\Delta\phi = (\phi^+ + \phi^-)/2$.

In the massless QED case, the probability to produce a flavour f is proportional to q_f^2 , i.e. up type quarks are four times as likely as down type ones. In QED the corresponding probabilities are given by [55,56]

$$\begin{aligned} h_f^{(1)}(s) &= q_f^2 (1 - P_L^+ P_L^-) - 2 q_f v_f \text{Re}(f(s)) \{v_e (1 - P_L^+ P_L^-) - a_e (P_L^- P_L^+)\} \\ &\quad + (v_f^2 + a_f^2) |f(s)|^2 \{(v_e^2 + a_e^2)(1 - P_L^+ P_L^-) - 2 v_e a_e (P_L^- P_L^+)\} \end{aligned} \quad (25)$$

which depends both on the s value and on the longitudinal polarization of the e^+ and e^- beams in a nontrivial way.

The total cross section in QED is found to be

$$(\sigma_0)_\text{QED} = \frac{4\pi\alpha^2}{s} \sum_f h_f^{(1)}(s) = \frac{86.8 \text{ nb} \cdot \text{GeV}^2}{s} 3 \sum_f h_f^{(1)}(s) \quad (26)$$

(with the factor 3 coming from colour explicitly written out). Conventionally the lowest order muon pair QED cross section is scaled out to give R

$$R = 3 \sum_f h_f^{(1)}(s) = 3 \sum_f \frac{q_f^2}{s} \quad (27)$$

the latter equality valid for the unpolarized QED case. QCD corrections to this result are small

$$\sigma_1 = \sigma_0 (1 + \alpha_s/\pi) \quad (28)$$

in first order and

$$\sigma_2 = \sigma_0 \{1 + \alpha_s/\pi + (1.986 - 0.115 n_f) (\alpha_s/\pi)^2\} \quad (29)$$

in second order, here and henceforth using the $\overline{\text{MS}}$ scheme.

The first order expression for the running strong coupling constant is [57]

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \ln(Q^2/\Lambda^2)} \quad (30)$$

and the second order one is

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \ln(Q^2/\Lambda^2) + 6 \frac{153 - 19n_f}{33 - 2n_f} \ln(\ln(Q^2/\Lambda^2))} \quad (31)$$

where n_f is the number of active flavours, i.e. basically with $2m_q < w$, and Λ is a parameter of the theory. Conventionally, one takes the energy scale $Q^2 = W^2$ = s for first and second order perturbation theory formulae.

Neglecting QCD effects, the mass corrections are given in terms of the velocity of a quark, $v_q = (1 - 4m_q^2/s)^{0.5}$, with mass m_q , as follows. The vector quark current terms in $h_f^{(1)}$ (proportional to q_f^2 , $q_f v_f$ or v_f^2) are multiplied by a threshold factor $v_f^{(3-v_f^2)/2}$ while the axial vector quark current term (proportional to q_f^2) is multiplied by v_f^3 . While inclusion of quark masses in the QED formulae decreases the total cross section, first order QCD

corrections tend in the opposite direction [58]. Naively, one would expect one factor of v_q to get cancelled. So far, the options available are either to include threshold factors in full or not at all.

QCD corrections to the naive two-jet picture are very important. Three-jet events are copiously produced and four-jet events have also been observed. At present, we have two main approaches to the description of these events. One is the calculation of explicit matrix elements, which has been carried out up to second order, and thus covers the production of two-, three- and four-jet events. The other is the application of parton shower rules, which allows the production of an arbitrary number of jets. Each method has its advantages and disadvantages. For the distribution of three-jetlike events, matrix elements provide a very convenient description. However, when moving on to four-jet events, it turns out that the observed four-jet rate is roughly a factor of two higher than would have been expected, based on an α_s mostly determined by the three-jet rate (this is probably related to the choice of Q^2 scale [10]).

Further, in studies of the energy-energy correlation asymmetry, it has been shown by JADE [59] that a fairly low cutoff y_{cut} (to be introduced below) is necessary in order to describe the data, so that three- and four-jet events basically saturate the total cross section, which would indicate that higher order corrections are no longer negligible. Recently, studies by Mark II [60] (on the fragmentation functions of quark vs. gluon jets) indicate that even a low cutoff is not enough, whereas the data may be well described by parton showers. The weakness of parton shower approaches, on the other hand, is that the three-jet rate often comes out wrong, due to failures of the collinear approximations inherent in the formalism. The future probably will belong to some kind of hybrid schemes, where matrix elements give the dominant three-jet structure, but where subsequent parton branchings are then allowed. We have no such scheme to offer at the moment, rather this section will outline the matrix element description, which is the default option of the program, with parton showers discussed in section 5.3.

The lowest order process $e^+ e^- \rightarrow q\bar{q}$ is in first order QCD modified by the probability for the q and \bar{q} to radiate a gluon, i.e. by the process $e^+ e^- \rightarrow q\bar{q}g$. The matrix element for this is conveniently given in terms of scaled energy variables in the CM frame of the event, $x_1 = 2E_q/W$, $x_2 = 2E_{\bar{q}}/W$ and $x_3 = 2E_g/W$, where W is the total energy in the CM frame, i.e. $x_1 + x_2 + x_3 = 2$. For massless quarks the matrix element reads [61]

$$\frac{d\sigma}{dx_1 dx_2} = \sigma_0 \frac{\alpha_s}{\pi} \frac{2}{3} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \quad (32)$$

where the kinematically allowed region is $0 < x_i < 1$, $i = 1, 2, 3$.

The cross section in eq. (32) diverges for x_1 or $x_2 \rightarrow 1$ but, when first order propagator and vertex corrections also are included, a corresponding singularity with opposite sign appears in the $q\bar{q}$ cross section, so that the total cross section is finite, eq. (28). Physically, this cancellation corresponds to a difficulty to distinguish a single quark from a quark accompanied by a soft or collinear gluon. Specifically for QCD, where the experimentally observable entities are not quarks and gluons but hadrons, we expect the (average) properties of a $q\bar{q}g$ events to approach those of a $q\bar{q}$ one when the gluon becomes soft or collinear. This condition is fulfilled for the Lund string model, see section 3.5.

In a Monte Carlo program the problem of divergences may then be solved by imposing cuts, so that events with a hard gluon is generated according to the matrix element in eq. (32), but three-jet events with a soft or collinear gluon are lumped together with the two-jet ones. In the program, we have allowed two kinds of slightly different cuts. One is to require the smallest invariant mass between any two partons, m_{ij} , to be larger than some minimum mass, typically 2 GeV. The other is to require the smallest scaled invariant mass-squared $y_{ij} = m_{ij}^2/W^2$ between any two partons to be larger than some minimum value y_{cut} , by default 0.02. Only three-jet events which fulfill both these cuts are generated. The cut in invariant mass corresponds to the actual merging of nearby parton jets, i.e. where a treatment with two separate partons rather than one would be superfluous, and is expected to be roughly energy-independent. Something like the second cut is required, however, to see to it that the three-jet cross section does not exceed the total cross section as the energy is increased, and is thus more related to the limitations of fixed order perturbation theory than to our physical picture of jet production and fragmentation.

Two new event types are added in second order QCD, $e^+ e^- \rightarrow q\bar{q}gg$ and $e^+ e^- \rightarrow q\bar{q}q'\bar{q}'$. The four-jet cross section has been calculated by several groups [62, 63, 64], which agree on the result. We will use the formulae in [64], in which the angular orientation has been integrated out, so that five internal kinematical variables remain. These may be related to the ten variables $y_{ij} = m_{ij}^2/W^2 = (p_i + p_j)^2/W^2$ and $y_{ijk} = m_{ijk}^2/W^2 = (p_i + p_j + p_k)^2/W^2$ (where p_i are

the four-momenta), in terms of which the matrix elements are given. As in the $q\bar{q}g$ case divergences appear when some of the $y_{ij} \rightarrow 0$, which are removed by requiring that all $y_{ij} > y_{cut}$ with the same y_{cut} as for the three-jet case (and correspondingly for the additional minimum mass requirement).

Whereas the way the colour flux tube is stretched is uniquely given in $q\bar{q}g$ events, for $q\bar{q}gg$ events there are two possibilities: $qg_1g_2\bar{q}$ or $qg_2g_1\bar{q}$. A knowledge of quark and gluon colours, obtained by perturbation theory, will uniquely specify the stretching of the string, so long as the two gluons do not have the same colour. The probability for the latter is down in magnitude by a factor $1/N_C^2$, where $N_C = 3$ is the number of colours. One may either choose to neglect these terms entirely, or to keep them for the choice of kinematical setup but then drop them at the choice of string drawing [65]. We have adopted the latter procedure. Comparing the two possibilities, differences are typically 10-20% for a given kinematical configuration, and less for the total four-jet cross section, so from a practical point of view this is not a major problem.

In second order, the three-jet rate is affected both by virtual corrections and by four-jet events which fail the y_{cut} requirement above, and therefore should be classified either as three- or as two-jet events. This has been a subject of long-standing controversy: whereas everybody agrees on the virtual corrections, the question of how to project the kinematics of a "failed" four-jet event onto that of ordinary three-jet ones is not unambiguous. We discussed the situation in [10]; since then some further work on the subject has been done [66]. The conclusion reached there is that, whereas large parts of these corrections can be written in closed analytical terms, pieces remain that would have to be integrated numerically. Our choice of using the formulae of [11] is made mostly on the basis of simplicity; some corrections from finite terms are indeed missing. It has been argued [66] that an inclusion of these terms would lead to a somewhat lower α_s being required in order to fit the data.

For Monte Carlo applications, the various cross sections (first and second order three-jets, $q\bar{q}gg$ and $q\bar{q}g\bar{q}'$ four-jets) have been parametrized as a function of the y_{cut} value, excluding factors of α_s/π . Further, since virtual corrections to the three-jet rate may become negative in some pieces of phase space, the most negative ratio of virtual corrections to naive three-jet matrix element is also parametrized. All this has been performed with Monte Carlo integration once and for all. For given CM energy, Λ value and cutoff

parameters, the program will check that the total three- plus four-jet fraction is smaller than unity, and that the three-jet differential cross section is everywhere positive. If either of these conditions is not fulfilled, the effective y_{cut} value is increased and the checks are repeated.

For the first order formulae, modifications coming from the introduction of quark masses are well known, both how the phase space region in the (x_1, x_2) -plane is constrained and how the cross section inside this region is decreased. The mass corrections to the four-jet rate have been calculated [62] but are quite lengthy, and the virtual three-jet corrections can not be calculated with masses using present-day perturbation theory techniques. For second order results, we have therefore made use of the known three-jet phase space cut, together with four-jet phase space cuts based on one interpretation of the y_{ij} and y_{ijk} variables for the massive case, but left the matrix elements as such unchanged.

The angular orientation of a three- or four-jet event may be described in terms of three angles χ , θ and ϕ ; for two-jet events only θ and ϕ are necessary. From a standard orientation, with the q along the $+z$ axis and the \bar{q} in the xz plane with $p_x > 0$, an arbitrary orientation may be reached by rotations $+\chi$ in azimuthal angle, $+\theta$ in polar angle and $+\phi$ in azimuthal angle, in that order. Cross sections, including QED effects and arbitrary beam polarizations have been given for two- and three-jet events in [56,67]. We use the formalism of [56], with $\chi \rightarrow \pi - \chi$ and $\phi \rightarrow -(\phi + \pi/2)$. The resulting formulae are tedious, but straightforward to apply once the internal jet configuration has been chosen. Four-jet events are approximated by three-jet ones, by joining the two gluons of a $q\bar{q}gg$ event and q' and \bar{q}' of a $q\bar{q}q\bar{q}'$ event into one effective jet. This means that some angular asymmetries are neglected [62], but that weak effects are automatically included. It is assumed that the second-order three-jet events have the same angular orientation as the first order ones, some studies on this issue may be found in [68]. Further, the formulae normally refer to the massless case, only for the QED two- and three-jet cases are mass corrections available.

Initial state photon radiation has been included using the formalism of [12]. The main formula for the hard radiative photon cross section is

$$\frac{d\sigma}{dx_k} = \frac{\alpha_{em}}{\pi} \left(\ln(s/m_e^2) - 1 \right) \frac{1 + x_k^2}{x_k} \sigma_0(s') = (1-x_k)s \quad (33)$$

where x_k is the photon energy fraction of the beam energy, so that s' is the

reduced hadronic CM energy-squared, and σ_0 is the ordinary annihilation cross section at the reduced energy. In particular, choice of jet flavours should be done according to expectations at the reduced energy. The cross section is divergent both for $x_k \rightarrow 1$ and $x_k \rightarrow 0$. The former is related to the fact that σ_0 has a 1/s singularity for $s' \rightarrow 0$. The exact cutoff can here be chosen to fit the experimental setup. The latter is a soft photon singularity, which is to be compensated in the no-radiation cross section. A requirement $x_k > 0.01$ has therefore been chosen so that the hard-photon fraction is smaller than unity. In the total cross section, effects from photons with $x_k < 0.01$ are taken into account, together with vertex and vacuum polarization corrections (hadronic vacuum polarizations using a simple parametrization of the more complicated formulae of [12]).

The hard photon spectrum can be integrated analytically, also with the Z^0 pole and γ/Z^0 interference terms included, provided that no new flavour thresholds are crossed and that the $1+\alpha_s/\pi$ term in the cross section does not vary significantly over the range of allowed s' values. In fact, threshold effects can be taken into account by standard rejection techniques, at the price of not obtaining the exact cross section analytically, but only by an effective Monte Carlo integration taking place in parallel with the ordinary event generation. In addition to x_k , the polar angle θ_k and azimuthal angle ϕ_k of the photons are also to be chosen. Further, for the orientation of the hadronic system, a choice has to be made whether the photon is to be considered as having been radiated from the e^+ or from the e^- .

Final state photon radiation, as well as interference between initial and final state radiation, has been left out in this treatment. The formulae for $e^+ e^- \rightarrow \mu^+ \mu^-$ can not be simply translated for the case of outgoing quarks, since the quarks as such only live for a short while before turning into hadrons. Because of the lower charge of the e^+ and e^- , and because final state radiation photons normally will be buried in jets anyhow, we do not feel that this neglect is a major problem. Another simplification in our treatment is that effects of incoming polarized e^+ have been completely neglected, i.e. neither the effective shift in azimuthal distribution of photons nor the reduction in polarization is included. The polarization parameters of the program are to be thought of as the effective polarization surviving after initial state radiation.

6.2. Strong Decays of Onia Resonances

Many different possibilities are open for the decay of heavy JPC = 1-- "onia" resonances, see comments in section 4. Of special interest is the decays into three gluons or two gluons plus a photon, since these offer unique possibilities to study a "pure sample" of gluon jets. A routine for this purpose is included in the program. It was written at a time where the expectations were to find toponium at PETRA energies. If, as now seems possible, the toponium mass is around 80 GeV [51], then the lowest-order formulae (and even the four-jet formulae [60]) may not turn out to be very useful: due to the large colour charges, a significant amount of jet evolution, into multi-jet states, may be expected. The main application may therefore be for T .

The actual program has not been significantly changed compared to [6], except that the new string fragmentation scheme allows a relaxation of the cuts used. In principle, no cuts at all would be necessary for the gg decays, but for reasons of numerical simplicity we implement a y_{cut} cutoff as for continuum jet production, with all events not fulfilling this considered as (effective) gg events. For ggY events, the gg invariant mass is required to be at least 2 GeV.

6.3. Parton Showers

A parton shower approach provides an approximate treatment of multijet configurations, also for parton multiplicities where explicit matrix elements become too lengthy to be useful. In the program we have included a simple subroutine for parton shower evolution, which can be used directly from the $e^+ e^-$ continuum routines or from other programs (e.g., it is also used by the hadron physics program [2]). It should be emphasized that a number of problems remain unsolved in this approach, so results obtained with programs of this kind should always be considered as qualitative rather than quantitative predictions. In particular, for the $e^+ e^-$ case, the standard 3-jet rate is not reproduced exactly, so that an α_s determination by this program would deviate from the normal one, and explicitly depend on the maximum parton virtuality allowed. In this sense, the present implementation should be considered as preliminary.

Actually, the program contains two widely disparate options: one using a "conventional" parton shower approach developed by Kajantie and Pietarinen [13], the other one based on the "coherent" evolution scheme of Marchesini and Webber [14,30]. The code as such is obviously of our own doing, and in neither case do we claim exact agreement with the original paper. From a theoretical point of view, the "coherent" approach is more sound [70], but differences between the two are often small for practical applications. Also, both schemes have weaknesses when the lofty ideas are to be transformed into a working computer code. Many other parton shower algorithms exist, a few more may be found in [71,72,26,27,31].

A parton shower is based on the iterative use of the branchings $q \rightarrow qg$, $q \rightarrow gg$ and $g \rightarrow q\bar{q}$, as given by the Altarelli-Parisi evolution equations [73]:

$$\frac{dp}{dt} = \frac{\alpha_s(t)}{2\pi} \int_{z_{min}(t)}^{z_{max}(t)} p_{a \rightarrow bc}(z) dz \quad (34)$$

$$p_{a \rightarrow bc}(z) = \frac{z_{max}(t)}{z_{min}(t)} p_{a \rightarrow bc}(z) \quad (37)$$

Here the $p_{a \rightarrow bc}(z)$ are the Altarelli-Parisi splitting kernels, z gives the sharing of energy between b and c , and $t = \ln(m^2/\Lambda^2)$ is the evolution parameter. Starting at the maximum allowed mass for a , t may be successively degraded until a branching occurs. The products b and c may be allowed to branch in their turn, and so on. The parton branching is stopped when a parton mass is evolved below some minimum mass, i.e. $t_{min} = \ln(m_{min}^2/\Lambda^2)$. The probability that a parton does not branch between some initial maximum t and t_{min} is given by the Sudakov form factor

$$S_a(t) = \exp\left[-\int_{t_{min}}^t \frac{\alpha_s(t')}{2\pi} \int_{z_{min}(t')}^{z_{max}(t')} dz p_{a \rightarrow bc}(z)\right] \quad (35)$$

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

$$P_a(t_{max}, t) dt = S_a(t_{max}) \frac{d}{dt} \left\{ \frac{1}{S_a(t)} \right\} dt \quad (36)$$

The exact way in which to cut off the parton shower is uncertain. We have chosen to define effective parton masses, as $m_{eff,g} = m_{min}/2$, $m_{eff,q} = (m_{min}/2)^2 + m_q^2$, where $m_u = m_d = 0.325$, $m_s = 0.5$, $m_c = 1.6$ and $m_b = 5.0$ GeV are the ordinary quark masses. The minimum mass for a gluon to branch (into two gluons) is then $m_{min,g} = 2m_{eff,g} = m_{min}$ and for a quark to branch (into a quark plus a gluon) is $m_{min,q} = m_{eff,q} + m_{eff,g} > m_{min}$. These m_{eff} values are

used to define the allowed z range (see below), specifically the mass distribution $P_a(t_{max}, t)$ is assumed to be composed of a continuum above $m_{min,g}$ or $m_{min,q}$, plus a δ function (with weight $S_a(t_{max})$) at $m_{eff,g}$ or $m_{eff,q}$. In the end, the "stable" final partons are put on mass shell (mainly because the fragmentation routines assume that gluons are massless), but results for keeping the m_{eff} values are indistinguishable (at least for reasonable m_{eff} values).

We now specialize to the conventional shower approach. If z is chosen to be the lightcone variable along the jet axis (this is not a unique choice, in [72] the use of $E+|p|$ rather than $E+p_T$ is advocated), so as to obtain Lorentz covariance under longitudinal boosts, the transverse momentum p_T of the two decay products is given by

$$p_T^2 = z(1-z) \left\{ \frac{m_b^2}{z} - \frac{\frac{m_c^2}{z}}{1-z} \right\} \quad (37)$$

if z is the fraction taken by b and $1-z$ by c . If the two products are not assumed to branch further, one may choose $m_b = m_{eff,b}$ and $m_c = m_{eff,c}$ and obtain a constraint on the allowed z range from the requirement $p_T^2 > 0$. This can be plugged in as $z_{min}(t')$ and $z_{max}(t')$ in eq. (35), to give $S_a(t)$, which is used to determine m_a according to eq. (36).

In general, b and c are assumed to branch further, so that $m_b > m_{eff,b}$ and/or $m_c > m_{eff,c}$, and the truly allowed range in z is smaller. This obviously affects $S_a(t)$ and hence the choice of m_a . Since m_b and m_c are not determined until after the choice of m_a , the correct z range is not known, however. A number of different solutions to avoid this problem has been applied [26]. The perhaps most elegant is that of Kajantie and Pietarinen [13]. Whereas the normal approach is to have as basic step the choice of mother mass m_a and splitting variable z , with daughter masses m_b and m_c to be determined in subsequent steps, the Kajantie-Pietarinen approach assumes m_a known from a previous step and selects z , m_b and m_c . This is done according to the joint probability distribution

$$P_b(t, t_b) dt_b P_c(t_a, t_c) dt_c P_{a \rightarrow bc}(z) dz \theta(p_T^2) \quad (38)$$

$$\frac{d(\ln S_a(t_a))}{dt_a} = -\frac{\alpha_s(t_a)}{2\pi} \int dt_b P_b(t_a, t_b) \int_{t_{min}}^{t_a} dt_c P_c(t_a, t_c) \cdot$$

$$(39)$$

$$\int_0^1 dz P_{a \rightarrow bc}(z) \theta(p_T^2)$$

Since the integrals on the right hand side only require $S_b(t_b)$ to be known for $t_b < t_a$, the coupled integral equations for the Sudakov form factors of different flavours can be solved by starting at the cutoff mass and proceeding towards the highest virtualities that will be used. This has to be done in an initialization step, before any events can be generated.

To start the cascade, t_a is chosen according to $P(t \max, t_a)$. Thereafter t_b, t_c and z may be found according to eq. (38), and then b and c are allowed to split further, etc. For a pair of back-to-back jets, the two initial masses are required to add up to less than the total invariant mass, and the subsequent evolution will be with z corresponding to $E + P_L$ fraction for one jet and $E - P_L$ fraction for the other. A problem is that lightcone variables allow daughters to move backwards with respect to the direction of the mother, eq. (15), so there is a danger of double-counting the total amount of radiation [26, 72].

Another problem is that coherence effects [70] are neglected, specifically subsequent parton branchings are not strictly ordered in emission angle, as they ought to be. There is no straightforward way to introduce this ordering in the scheme above, since the Sudakov form factors would have to be functions both of the mass and the maximum allowed emission angle. Instead the coherent parton scheme follows that of Marchesini and Webber [14, 20].

In particular, Sudakov form factors are defined as a function of the combination $E^2 \xi \approx E^2 (1 - \cos\theta)$ rather than m^2 , i.e. the evolution parameter is $t = \ln(E^2 \xi / \Lambda^2)$. Here E is the energy of a parton and θ the opening angle between its decay products. Lightcone variables are not used, rather z refers to the sharing of energy. In particular, $z_{\min} = m_{\text{eff}}/b(E\xi^{0.5})$ and $z_{\max} = m_{\text{eff}}/c(E\xi^{0.5})$. Since the allowed range in z does not depend on the actual daughter masses, the Sudakov form factors are easily found and tabulated.

Events are studied in a frame where the two initial partons form an opening angle of 90° , i.e. $\xi_0 = 1$. With the energy E_a of one of these partons as given, $(E^2 \xi)_{\max} = E_a^2$ provides the starting value for the t evolution. From the selected t value ξ_a may be found. The simultaneously selected z value gives the sharing of energy, $E_b = zE_a$ and $E_c = (1-z)E_a$ (where the z min and z max values guarantee that $E_b > m_b$ etc.). Because of the requirement of ordering in

angle, the maximum virtualities of the daughters are $z^2 \xi_a$ and $(1-z)^2 \xi_a'$ respectively. These may now be degraded in virtuality to find $\xi_b < \xi_a$ and $\xi_c < \xi_a'$, etc. When all branchings have been handled, the actual invariant masses of the intermediate partons may be found, by moving backwards from the daughters to the mothers, using the relationship

$$m_2^2 = m_b^2 + m_c^2 + 2 E_b E_c \xi_2 \quad (40)$$

Obviously the relationship $\xi = 1 - \cos\theta$ is only strictly true for $m_b = m_c = 0$, eq. (40) is taken to be the exact definition of ξ . With all parton energies and invariant masses known, the reconstruction of the full kinematics is now straightforward, with the azimuthal angle at each branching chosen at random. After that, the event may be boosted e.g. to the CM frame, where the two initial partons are back-to-back.

One of the problems with the approach above is that, since one can integrate over the parton energies may be chosen by hand, the corresponding momenta depend on the ξ values generated, and hence the invariant mass of the jet system is not known beforehand. We have here chosen to give each of the two initial partons 0.7 times the desired CM energy in the frame where the opening angle is 90° .

The actual CM energy will then be a reasonably narrow distribution around the nominal value, and exact conservation is arranged by rescaling all final parton three-momenta by a common factor in the CM frame (cf. section 3.6). Another production is used in [14-30].

The Sudakov form factors depends on $\alpha_s(Q^2)$, and specifically on the choice of

scale. The conventional choice is here m_a , i.e. the mass square of the decaying parton. For consistency with the coherent choice below, we use $Q^2_{\text{conv}} = m^2/4$. The arbitrariness in the choice of the factor 4 may be pushed into the choice of Λ value. Specifically, Λ values determined by comparing data with matrix elements or with showers are bound to disagree due to the different Q^2 choices in the two cases. Studies of coherence effects [70] suggest that the p_T^2 of the daughters b and c should be more relevant than m_a^2 , so as an alternative we have $Q_{\text{coh}}^2 = z(1-z)m_a^2$, which coincides with Q_{conv}^2 for $z=1/2$. Note that we have not used the full expression for p_T^2 , e.g. eq. (36), since $p_T^2 \rightarrow 0$ is kinematically allowed but $a_s(Q^2)$ is divergent for $Q^2 = \Lambda^2$. For the coherent branching scheme, the usage of Q^2 scale is complicated by m^2 being unknown when the branchings are generated. Rather, eq. (40) is used to estimate

$$\frac{m^2}{a} \geq m_{eff,b}^2 + m_{eff,c}^2 + 2E_b E_c \xi_a \geq \frac{1}{2} \frac{m^2}{\min} + 2z(1-z)E_a^2 \xi_a \quad (41)$$

which is plugged into the expressions above.

When the string model is to be used for the subsequent fragmentation, the colour flow has to be kept track of. In parton showers of the kind outlined above, where only branchings $q \rightarrow qg$, $g \rightarrow gg$ and $g \rightarrow q\bar{q}$ are included, this is straightforward. For $q \rightarrow qg$ the gluon becomes a kink on the string ending at the q , for $g \rightarrow gg$ an additional string piece is stretched between the two gluons and for $g \rightarrow q\bar{q}$ the gluon kink is resolved into two string endpoint quarks. In e^+e^- annihilation the original $q\bar{q}$ pair is a colour singlet, but the shower formalism works equally well in cases where the two partons are not in a colour singlet state.

6.4. Event Analysis Routines

In [6] we described three routines for event analysis, one for sphericity and related measures, one for the thrust family of measures and one cluster algorithm for the reconstruction of a variable number of jets. Neither of these routines have been changed for the present program, so the principles are not repeated here. Two new routines of a similar nature have been added.

The first new routine is a cluster algorithm of the type now frequently used in hadron physics (although of less interest for e^+e^- physics, it was put here together with the other analysis routines). It assumes a given detector granularity, and groups nearby cells of transverse energy flow E_T into clusters. Compared to our other cluster algorithm, this one provides a much faster analysis for events with many particles, since the level of ambition is much lower: nearby particles are not assumed resolvable, further, not all particles are assigned to jets. In particular, this routine will not find the beam jets.

The routine works as follows. For a given detector grid in pseudorapidity and azimuthal angle, the total p_T of all particles hitting a cell is summed up to give the E_T for the cell. The cell with highest E_T is taken to be a jet initiator if it is above some threshold. A candidate jet is defined to consist of all cells which are within some given radius in the pseudorapidity-azimuth plane (counted between the center of the cells). If the summed E_T is above the required minimum jet energy, the candidate jet is accepted and all its cells

are removed from further consideration. If not, the candidate is rejected. The sequence is now repeated with the remaining cell of highest E_T , and so on until no single cell fulfills the jet initiator condition.

The other new routine is for calculation of Fox-Wolfram moments [74]. These moments H_1 , $1=0, 1, 2, \dots$, are defined by

$$H_1 = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{W^2} p_1(\cos\theta_{ij}) \quad (42)$$

where $\cos\theta_{ij}$ is the opening angle between hadrons i and j and $p_1(x)$ are the Legendre polynomials. To the extent that particle masses may be neglected, $H_0 = 1$. It is therefore customary to use scaled moments, $H_1 = H_1/H_0$.

7. Description of the e^+e^- Physics Routines

In this section the actual program routines for e^+e^- physics are introduced. The subsections 7.1-7.4 stand in a one-to-one correspondence with the subsections 6.1-6.4 above, with 7.5 covering the LUPDATE commonblock.

7.1. e^+e^- Continuum Event Generation

The only routine a normal user will call is LUEEVT. The other routines listed below, as well as LUSHOW (see section 7.3), are called by LUEEVT.

SUBROUTINE LUEEVT(IFL,ECM)

Purpose: to generate a complete $e^+e^- \rightarrow Y/Z^0 \rightarrow q\bar{q}, q\bar{q}g, q\bar{q}gg$ or $q\bar{q}q'\bar{q}'$ event according to the relevant QCD and QFD matrix elements. Optionally, parton shower evolution into an arbitrary number of jets may be used; this latter part of the program is still at a preliminary stage, and caution is advised.

IFL : flavour of events generated or, more generally, type of action to be taken.

= 0 : mixture of all allowed flavours according to relevant probabilities.
= 1 - 8 : primary quarks are only of the specified flavour IFL.

= 10 : print e^+e^- parameter values and event statistics.
= 11 : reset statistics.

ECM : total CM energy of system. Is dummy for IFL=10 or 11.

Remark: Each call generates one event, which is independent of preceding ones, with two exceptions. Firstly, if radiative corrections are included, the shape of the hard photon spectrum is recalculated only with each LUXTOT call, which normally is done only if IFL, ECM or MSTE(2) is changed. A change of e.g. the Z^0 mass in midrun has to be followed either by a user call to LUXTOT or by an internal call forced e.g. by putting MSTE(9)=3. Secondly, if parton shower evolution is requested, recalculation of the necessary Sudakov form factors is done only if necessitated by an increase in the ECM value. A change of parton shower switches or parameters in midrun has to be followed either by a user call to LUSHOW or by an internal call forced e.g. by setting MSTE(9)=3. Note that Sudakov form factor calculations are time-consuming, so the run should be organized to need as few as possible.

SUBROUTINE LUXTOT(IFL,ECM,XTOT)

Purpose : to calculate the total hadronic cross section, including quark thresholds, weak, beam polarization and QCD effects and radiative corrections. In the process, variables necessary for the treatment of hard photon radiation are calculated and stored.

IFL, ECM : as for LUREVT (IFL&E).

XTOT : the calculated total cross section in nb.

SUBROUTINE LURADK(ECM,MK,PAK,THEK,PHIK,ALPR)

Purpose: to describe initial state hard photon radiation.

SUBROUTINE LUXIFL(IFL,ECM,ECMC,IFLC)

Purpose: to generate the primary quark flavour in case this is not specified by user.

SUBROUTINE LUXJER(ECM,NJET,CUT)

Purpose: to determine the number of jets (2, 3 or 4) to be generated within the kinematically allowed region (characterized by CUT= γ_{cut}) in the matrix element approach, which is to be chosen such that all probabilities are between 0 and 1.

SUBROUTINE LUX3JT(NJET,CUT,IFL,ECM,X1,X2)

Purpose: to generate the internal momentum variables of a three-jet event, $q\bar{q}g$, in first or second order QCD.

SUBROUTINE LUX4JT(NJET,CUT,IFL,ECM,IFLN,X1,X2,X4,X12,X14)

Purpose: to generate the internal momentum variables for a four-jet event, $q\bar{q}gg$ or $q\bar{q}q'\bar{q}'$, in second order QCD.

SUBROUTINE LUXDIF(NC,NJET,IFL,ECM,CHI,THE,BHI)

Purpose: to describe the angular orientation of the jets. In first order QCD the complete QED or QFD formulae are used; in second order three-jets are assumed to have the same orientation as in first, and four-jets are approximated by three-jets.

FUNCTION ULALPS(Q2)

Purpose: to calculate the running strong coupling constant α_s as a function of the momentum transfer Q^2 , in first or second order QCD.

SUBROUTINE LUESTA(IFL,NJET,NC,ECM,MK,ECMC,NTRY)

Purpose: to collect and present event statistics, additionally to list e^+e^- parameter table.

IFL : flavour code or action request.

= 0 : unspecified flavour configuration.

= 1 - 8 : continuum event of specified flavour.

= 9 : onium event.

= 10 : print parameter table and event statistics.

= 11 : reset event statistics.

NJET : number of partons in jet system (2, -4 for $q\bar{q}q'\bar{q}'$) if it is to be distinguished from $q\bar{q}gg$.

NC : last line in commonblock LUJETS used for initial state.

ECM : total CM energy.

MK : 1 if radiative photon present, else 0.

ECMC : CM energy of hadronic system (i.e. excluding radiative photon).

NTRY : number of tries before acceptable event was found.

7.2. A Routine for Onium Decay

In LUONIA we have implemented the decays of heavy onia resonances into three gluons and two gluons plus a photon, which probably are the dominant non-backgroundlike decays of T and toponium (disregarding the subsequent gluon radiation), whereas weak decays are expected to dominate for any heavier onium states. In the present implementation, the orientation is according to QED alone, and higher order QCD corrections to jet production are not included.

LUONIA makes use of the two routines ULALPS and LUESTA described above.

SUBROUTINE LUONIA(IFL,ECM)

Purpose: to simulate the process $e^+e^- \rightarrow \gamma \rightarrow l^-$ "onium" resonance $\rightarrow ggg$ or $gg\gamma$.

IFL : the flavour of the quark giving rise to the resonance or, more generally, the action to be taken.

= 0 : generate ggg events alone.

= 1 - 8 : generate ggg and $g\gamma$ events in mixture determined by the charge-squared of flavour IFL. Normally IFL=5 or 6.

= 10 : print e^+e^- parameter values and event statistics.

= 11 : reset event statistics.

necessary for subsequent generation of showers, where QMAX gives the maximum (timelike) virtuality, i.e. mass, allowed for partons in subsequent generation. Once the initialization call has been made, the switches and parameters above can not be changed; if this is done without a subsequent new call with IP1=0, erroneous events are likely to be produced.

IP1 > 0, IP2 = 0 : generate timelike parton shower for the parton in line IFL in commonblock LUJETS, with maximum allowed mass QMAX. The z splitting variable is defined with respect to the +z axis, hence this should also be the jet axis. With only one parton at hand, one can not simultaneously conserve both energy and momentum, we here choose to conserve energy and transverse momentum, with longitudinal momentum (i.e. along z axis) not conserved.

IP1 > 0, IP2 > 0 : generate timelike parton showers for the two partons in lines IFL1 and IFL2 in the commonblock LUJETS, with maximum allowed mass for each parton QMAX. For shower evolution, the two partons are boosted to their CM frame, where the jet axis also defines the choice of splitting variable. Energy and momentum is conserved for the pair of partons, although not for each individually. One of the two partons may be replaced by a nonradiating particle, such as a photon or a diquark; the energy and momentum of this particle will be modified to conserve the total energy and momentum.

QMAX : for IP1=0, IP2=0 it gives the maximum mass (virtuality) that may be expected in subsequent calls, otherwise it gives the actual maximum mass of the radiating partons, i.e. the starting value for the subsequent evolution.

7.3. A Routine for Timelike Shower Evolution

The routine LUSHOW is a fairly freestanding piece of software, in the sense that it can be used to simulate timelike parton showers in a number of different processes, not just in e^+e^- annihilation. Because of the tree-like evolution of showers, the ordinary administrative framework is not sufficient. Rather, to each parton entry in the LUJETS commonblock, an extra line with KS=7 is attached with information about the colour flow, as outlined in the LUJETS description. In particular, in the P vector is stored from where the colour and/or anticolour of a given parton is coming and to where it is going. The partons which initiate the cascade and any other partons belonging to the same colour singlet system(s) must also be equipped with the same information. In LUPREP (called by LUJEC) the partons are rearranged sequentially along strings for the subsequent treatment. The conventional shower algorithm is based on the paper by Kajantie and Pietarinen [13] and the coherent one on the paper by Marchesini and Webber [14], but in neither case is an exact equivalence guaranteed.

SUBROUTINE LUSHOW(IFL,IP2,QMAX)

Purpose: to generate timelike parton showers, conventional or coherent. The performance of the program is regulated by the switches MSTE(11) - MSTE(16) and (for initialization output) MSTE(32) and parameters PARE(21) - PARE(24). Before showers can be generated, a special initialization call must be made, see below.

IP1 = 0, IP2 = 0 : initialize Sudakov form factors and other constants

The five routines LUSPHE, LUTHRU, LUCCLUS, LUCELL and LUFWO contains some tools for event analysis. All particles or partons present in the LUJETS commonblock which have KS<1 (i.e. $K(I,1)<2000$), i.e. which have not decayed or fragmented, are used for the event analysis (this also includes neutrinos!). To alter this, one may e.g. use LUEDIT or raise the KS value for the unwanted entries. Information about jet axes found with LUSPHE, LUTHRU, LUCCLUS or LUCELL are stored after the event proper in the LUJETS commonblock, but can be listed e.g. with LULIST(2). This information is overwritten if later another of the routines is called. Also, for all partices used in the

LUCUS analysis, the particle history code **KH** is overwritten by cluster assignment information.

SUBROUTINE LUSPHE(SPH,APL)

Purpose: to diagonalize the momentum tensor, i.e. find eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$ and corresponding eigenvectors. Momentum power dependence is given by PARE(30); default corresponds to sphericity, PARE(30)=1. gives measures linear in momenta.

SPH : $3 \cdot (\lambda_2 + \lambda_3)/2$, i.e. sphericity (for PARE(30)=2.).
 = -1. : analysis not performed because event contained less than two particles (or two exactly back-to-back particles, in which case the two transverse directions would be undefined).

APL : $3 \cdot \lambda_3/2$, i.e. aplanarity (for PARE(30)=2.).
 = -1. : as SPH=-1.

Remark: the lines N+1 through N+3 in LUJETS will, after a call, contain the following information:

```
K(N+i,1) = i, the axis number, i=1,2,3;  

K(N+i,2) = 0;  

P(N+i,1) - P(N+i,3) = the i:th eigenvector, x,y and z components;  

P(N+i,4) =  $\lambda_i$ , the i:th eigenvalue;  

P(N+i,5) = 0.
```

SUBROUTINE LUTHRU(THR,OBL)

Purpose: to find the thrust, major and minor axes and corresponding projected momentum quantities, in particular thrust and oblateness. The performance of the program is affected by MSTE(21), PARE(31) and PARE(34). In particular, PARE(31) gives the momentum dependence, with the default value corresponding to linear dependence.

THR : thrust (for PARE(31)=1.).
 = -1. : analysis not performed because event contained less than two particles.
 = -2. : remaining space in LUJETS (partly used as working area) not large enough to allow analysis.

OBL : oblateness (for PARE(31)=1.).
 = -1., -2. : as for THR.

Remark: the lines N+1 through N+3 in LUJETS will, after a call, contain the following information:

```
K(N+i,1) = i, the axis number, i=1,2,3;  

K(N+i,2) = 0;  

P(N+i,1) - P(N+i,3) = the thrust, major and minor axis, respectively, for
```

i = 1, 2 and 3;
 P(N+i,4) = corresponding thrust, major and minor value;
 P(N+i,5) = 0.

SUBROUTINE LUCUS(NJET,TGEN,DMIN)

Purpose: to reconstruct an arbitrary number of jets using a cluster analysis method based on particle momenta. The distance scale d join, above which two clusters may not be joined, is given by PARE(33). In general, d join may be varied to describe different "jet resolution powers"; the default value, 2.5 GeV, is fairly well suited for e⁺e⁻ physics at 30-40 GeV. Various options for the reconstruction are found in MSTE(22) and MSTE(23), whereas PARE(32) and PARE(34) influence more technical details (for events at high energies and large multiplicities, however, the choice of a larger PARE(32) may be necessary to obtain reasonable reconstruction times).

NJET : the number of jets reconstructed.
 = -1 : analysis not performed because event contained less than
 2*|MSTE(22)|+1 (normally 3) particles.
 = -2 : remaining space in LUJETS (partly used as working area) not large enough to allow analysis.

TGEN : generalized thrust, the sum of (absolute values of) parton momenta divided by the sum of particle momenta (roughly the same as multiplicity).
 = -1., -2. : as for NJET.

DMIN : the minimum distance d between two jets in the final jet configuration.

= 0. : when only one jet reconstructed.
 = -1., -2. : as for NJET.

Remark: the lines N+1 through N+NJET in the commonblock LUJETS will, after a call, contain the following information:
 K(N+i,1) = i, the jet number, with the jets arranged in falling order of momentum;

K(N+i,2) = the number of particles assigned to jet i;
 P(N+i,1) - P(N+i,) = momentum, energy and invariant mass of jet i, using the correct particle masses to define the latter two quantities.
 Also, for each particle I, 1*<=*N, which has been used in the analysis,
 K(I,1)=i, where i is the number of the jet the particle has been assigned to. Partons/particles not used in the analysis, i.e. with K(I,1)>20000, will not be affected by this.

SUBROUTINE LUORIE(MORI)

Purpose: to define a standard orientation of events following the analysis in either of the three preceding routines.

MORI : level of orientation.
 = 1 : rotate largest axis along z axis and second largest into xz plane.
 For LUCIUS it can be further specified to +z axis and xz plane with
 $x > 0$, respectively.
 = 2 : mainly intended for LUSPHE and LUTHU, this gives a further
 alignment of the event, following the one implied by =1. The "slim"
 jet, defined as the side ($z > 0$ or $z < 0$) with the smallest summed p_T over
 square root of number of particles, is rotated into the +z hemisphere.
 In the opposite hemisphere (now $z < 0$), the side $x > 0$ and $x < 0$ which has
 the largest summed $|p_z|$ is rotated into the $z < 0$, $x > 0$ quadrant.

SUBROUTINE LUCELL(NJET)

Purpose: to provide a simpler cluster routine more in line with what is currently used in the study of high- p_T collider events. A detector is assumed to stretch in pseudorapidity between -PARE(35) and +PARE(35) and be segmented in MSTE(24) equally large η (pseudorapidity) bins and MSTE(25) ϕ (azimuthal) bins. Transverse energy E_T for undecayed entries are summed up in each bin. All bins with E_T larger than PARE(36) are taken to be possible initiators of jets, and are tried in falling E_T sequence to check whether the total E_T summed over cells no more distant than PARE(38) in $(\Delta\eta^2 + \Delta\phi^2)^{0.5}$ exceeds PARE(37). If so, these cells define one jet, and are removed from further consideration. Contrary to LUCIUS, not all particles need be assigned to jets.

NJET : the number of jets reconstructed (may be 0).

= -2 : remaining space in LUJETS (partly used as working area) not large enough to allow analysis.

Remark: The lines N+1 through N+NJET in the commonblock LUJETS will, after a call, contain the following information:

$K(N+i,1) = i$, the jet number, with the jets arranged in falling order in E_T ;
 $K(N+i,2) =$ the number of particles assigned to jet i ;
 $P(N+i,1), P(N+i,2) =$ position in η and ϕ of the center of the jet initiator cell, i.e. geometrical center of jet;
 $P(N+i,3), P(N+i,4) =$ position in η and ϕ of the E_T -weighted center of the jet, i.e. the center of gravity of the jet;
 $P(N+i,5) =$ sum E_T of the jet.

SUBROUTINE LUFWO(H10,H20,H30,H40)

Purpose: to do an event analysis in terms of the Fox-Wolfram moments. The moments H_i are normalized to the lowest one, H_0 .

H10 : H_1/H_0 . Is =0 if momentum is balanced.
 H20 : H_2/H_0 .
 H30 : H_3/H_0 .
 H40 : H_4/H_0 .

= 2 : mainly intended for LUSPHE and LUTHU, this gives a further alignment of the event, following the one implied by =1. The "slim" jet, defined as the side ($z > 0$ or $z < 0$) with the smallest summed p_T over square root of number of particles, is rotated into the +z hemisphere. In the opposite hemisphere (now $z < 0$), the side $x > 0$ and $x < 0$ which has the largest summed $|p_z|$ is rotated into the $z < 0$, $x > 0$ quadrant.

COMMON /LUDATE/ MSTE(40),PARE(80)

Purpose: to give access to a number of status codes and parameters regulating the performance of the e^+e^- and event analysis routines.

MSTE(1) : (D=2) gives order in a_s of the matrix elements used for gluon emission in continuum events.

= 0 : only $q\bar{q}$ events are generated.

= 1 : $q\bar{q} + q\bar{q}g$ events are generated according to first order QCD.

= 2 : $q\bar{q} + q\bar{q}g + q\bar{q}qg + q\bar{q}\bar{q}g$ events are generated according to second order QCD.

= 3 : a parton shower is allowed to develop from an original $q\bar{q}$ pair, see MSTE(11).

= -1 : only $q\bar{q}g$ events are generated (within same matrix element cuts as for =1). Since the change in flavour composition from mass cuts or radiative corrections is not taken into account, this option is not intended for quantitative studies.

= -2 : only $q\bar{q}gg$ and $q\bar{q}q'\bar{q}'$ events are generated (as for =2). The same warning as for =-1 applies.

= -3 : only $q\bar{q}gg$ events are generated (as for =2). The same warning as for =-1 applies.

= -4 : only $q\bar{q}q'\bar{q}'$ events are generated (as for =2). The same warning as for =-1 applies.

MSTE(2) : (D=2) inclusion of weak effects (Z^0 exchange) for flavour production, angular orientation, cross sections and initial state photon radiation in continuum events.

= 1 : QED, i.e. no weak effects are included.

= 2 : QFD, i.e. including weak effects.

= 3 : as =2, but at initialization in LUXTOT the Z^0 width is calculated

from $\sin^2\theta_W$, α_{em} and Z^0 and quark masses (including bottom and top threshold factors for MSTE(3) odd), assuming three full generations, and the result is stored in PARE(7).

MSTE(3) : (D=7) mass effects in continuum matrix elements, in the form $MSTE(3) = M1 + 2*M2 + 4*M3$, where $Mi=0$ if no mass effects and $Mi=1$ if mass effects should be included. Here:

- M1 : threshold factor for new flavour production according to QFD result;
- M2 : gluon emission probability (only applies for $|MSTE(1)| \leq 1$, otherwise no mass effects anyhow);
- M3 : angular orientation of event (only applies for $|MSTE(1)| \leq 1$ and $MSTE(2)=1$, otherwise no mass effects anyhow).

MSTE(4) : (D=5) number of allowed flavours, i.e. flavours that can be produced in a continuum event if the energy is big enough. A change to 6 makes top production allowed above the threshold, etc. Also used as upper limit when checking the number of flavours in α_s .

MSTE(5) : (D=1) fragmentation and decay in LUEEVT and LUONIA calls.

- = 0 : no LUEEXEC calls, i.e. only matrix element treatment.
- = 1 : LUEEXEC calls are made to generate fragmentation and decay chain.

MSTE(6) : (D=1) angular orientation in LUEEVT and LUONIA.

- = 0 : standard orientation of events, i.e. q along $+z$ axis and \bar{q} along $-z$ axis or in xz plane with $p_x > 0$ for continuum events, and $g_1 g_2 g_3$ or $g_2 g_3$ in xz plane with g_1 or y along the $+z$ axis for continuum events.
- = 1 : random orientation according to matrix elements.

MSTE(7) : (D=0) radiative corrections to continuum events.

- = 0 : no radiative corrections.
- = 1 : initial state radiative corrections (including weak effects for $MSTE(2)=2$).

MSTE(8) : (D=2) calculation of α_s .

- = 0 : Fixed α_s value as given in PARE(3).
- = 1 : first order formula is always used, with Λ given by PARE(1).
- = 2 : first or second order formula is used, depending on value of $MSTE(1)$, with Λ given by PARE(1) or PARE(2).

MSTE(9) : (D=1) initialization of total cross section, radiative photon spectrum and Sudakov form factors in LUEEVT calls.

- = 0 : never; can not be used together with radiative corrections or parton showers.
- = 1 : cross section and radiative photon spectrum are calculated at first call and then whenever IFL or MSTE(2) is changed or ECM is changed by more than PARE(17). Sudakov form factors are calculated at first call and then whenever ECM exceeds limit of available form factors.

= 2 : cross section and radiative photon spectrum are calculated at each call; Sudakov form factors as =1.

= 3 : everything is reinitialized, but MSTE(9) is afterwards put =1 for use in subsequent calls.

MSTE(10) : not used.

MSTE(11) : (D=1) branching mode for timelike parton showers.

- = 0 : no branching at all.
- = 1 : conventional branching.
- = 2 : coherent branching.

MSTE(12) : (D=0) reserved for details of conventional branching.

MSTE(13) : (D=2) details of coherent branching (for MSTE(11)=2).

- = 0 : no momentum conservation, no randomized azimuthal angle.
- = 1 : no momentum conservation, randomized azimuthal angle.
- = 2 : momentum conservation, randomized azimuthal angle.

MSTE(14) : (D=1) choice of α_s scale for shower.

- = 0 : Fixed at PARE(3) value.
- = 1 : running with $Q^2 = z(1-z)m^2$ (natural choice for coherent showers).

MSTE(15) : (D=5) maximum flavour that can be produced in shower by $g + q\bar{q}$.

MSTE(16) : (D=50) number of Monte Carlo integration points used for each entry when calculating Sudakov form factor table for conventional branching (should be increased if higher accuracy is desired).

MSTE(17) - MSTE(20) : not used.

MSTE(21) : (D=42) regulates the behaviour of thrust analysis. $MSTE(21) = 10 * M1 + M2$, where:

- M1 : ($M1 > 1$) is the number of the fastest (i.e. with largest momentum) particles used to construct the (at most) 10 most promising starting configurations for the iteration;
- M2 : ($1 \leq M2 \leq 9$) is the number of different starting configurations above, which have to converge to the same (best) value before this accepted.

MSTE(22) : (D=1) the absolute value $|MSTE(22)|$ is the minimum number of clusters to be reconstructed by LUCCLUS. If $MSTE(22)$ is negative, the cluster directions already stored in LUJETS, in lines N+1 through N+NJET, are used as starting values for the iteration.

MSTE(23) : (D=1) distance measure used for assigning particles to clusters in LUCCLUS.

- = 1 : the same as the distance between clusters.
- = 2 : assign particles to the cluster with respect to which they have the

largest longitudinal momentum, i.e. as in "multiplicity".

MSTE(24) : (D=25) number of pseudorapidity bins that the range between -PARE(35) and +PARE(35) is divided into to define cell size for LUCCELL.

MSTE(25) : (D=24) number of azimuthal bins, used to define the cell size for LUCELL.

MSTE(26) - MSTE(29) : not used.

MSTE(30) : (D=1) documentation of continuum or onium events, in increasing order of completeness.

= 0 : only the fragmenting partons and the generated hadronic system are stored in the LUJETS commonblock.

= 1 : also a radiative photon is stored (for continuum events).

= 2 : also the original e^+e^- are stored (with KS=4).

= 3 : also the γ or γ/Z^0 exchanged for continuum events, the onium state for resonance events is stored (with KS=5).

= 4 : for parton showers (MSTE(1)=3) the complete parton evolution, including RS=7 continuation lines, is included.

MSTE(31) : (D=1) statistics saved in LUESTA and to be listed by a LUEEVT(10,0.) or LUONIA10,0.) call.

= 0 : none; only parameters in common LUDATE may be listed.

= 1 : parameters plus statistics on initial (parton) state.

= 2 : parameters plus statistics on initial and final (particle) state.

= -1 : only statistics on initial state.

= -2 : only statistics on final state.

MSTE(32) : (D=1) listing in LUSHOW(0,...) call, i.e. in initialization of parton showers.

= 0 : none.

= 1 : one line telling that initialization performed.

= 2 : full listing of Sudakov form factor table.

MSTE(33), MSTE(34) : not used.

MSTE(35) : (R) type of continuum event generated.

= 1 : $q\bar{q}$.

= 2 : $q\bar{q}g$.

= 3 : $q\bar{q}gg$ from Abelian (QED-like) graphs in matrix element.

= 4 : $q\bar{q}gg$ from non-Abelian (i.e. containing three-gluon coupling) graphs in matrix element.

= 5 : $q\bar{q}q'\bar{q}'$.

MSTE(36) : (I) check on need to reinitialize LUXTOT.

MSTE(37) - MSTE(40) : not used.

PARE(1) : (D=1.5 GeV) Λ value used in first order calculation of α_s .

PARE(2) : (D=0.5 GeV) Λ values used in second order calculation of α_s .
 PARE(3) : (D=0.2) fixed α_s value used when MSTE(8)=0 (or, for showers, MSTE(14)=0).
 PARE(4) : (D=0.0073) α_{em} = 1/137.
 PARE(5) : (D=0.217) $\sin^2\theta_W$, weak mixing angle in QFD.
 PARE(6) : (D=94. GeV) mass of Z^0 as used in propagators for QFD case.
 PARE(7) : (D=2.8 GeV) width of Z^0 as used in propagators for QFD case.
 PARE(8) : (D=0.02) Y_{cut} , minimum scaled invariant mass-squared of any two partons in 3- or 4-jet events; the main user-controlled matrix element cut.
 PARE(9) : (D=2. GeV) minimum invariant mass of any two partons in 3- or 4-jet events; a cut in addition to the one above, mainly of importance for the case of a radiative photon lowering the hadronic CM energy significantly.
 PARE(10) : (D=1. GeV) is used as a safety margin for small colour singlet jet systems, cf. PAR(22), specifically $q\bar{q}$ masses in $q\bar{q}q'\bar{q}'$ 4-jet events and gg mass in onium γgg events.

PARE(11), PARE(12) : (D=2.0.) longitudinal polarizations p_L^+ and p_L^- of incoming e^+ and e^- .
 PARE(13) : (D=0.) transverse polarization $p_T^+ = (p_T^+ p_T^-)^{0.5}$ with p_T^+ and p_T^- transverse polarizations of incoming e^+ and e^- .
 PARE(14) : (D=0.) mean of transverse polarization directions of incoming e^+ and e^- , $\Delta\phi = (\phi^+ + \phi^-)/2$, with ϕ azimuthal angle of polarization, leading to a shift in the ϕ distribution of jets by $\Delta\phi$.
 PARE(15) : (D=0.01) minimum photon energy fraction (of beam energy) in initial state radiation; should normally never be changed (if lowered too much, the fraction of events containing a radiative photon will exceed unity, leading to problems).
 PARE(16) : (D=0.99) maximum photon energy fraction (of beam energy) in initial state radiation; may be changed to reflect actual trigger conditions of a detector (but must always be larger than PARE(15)).
 PARE(17) : (D=0.2 GeV) maximum deviation of ECM from the corresponding value at last LUXTOT call, above which a new call is made if MSTE(32)=1.
 PARE(18) - PARE(20) : not used.

PARE(21) : (D=0.25 GeV) Λ value used in α_s for parton showers (see MSTE(14)).
 PARE(22) : (D=2. GeV) invariant mass cutoff m_{min} of parton showers, below which partons are not assumed to radiate.
 PARE(23) : (D=0.05) maximum allowed step size in ln of mass in Sudakov table (if the requested mass range can be covered with less than 100 steps, otherwise step size is found automatically).
 PARE(24) : (D=0.10) maximum allowed step size in ln of $z/(1-z)$ in integral of

Altarelli-Parisi splitting function (if the requested range can be covered with less than 100 steps, otherwise step size is found automatically).

PARE(25) : not used.

PARE(26) : (D=0.7) fraction of hadronic CM energy that is taken as maximum parton mass when calling LUSHOW from LUJEVT for shower evolution (i.e. QMAX=PARE(26)*ECM).

PARE(27) - PARE(29) : not used.

PARE(30) : (D=2.) power of momentum-dependence in LUSSPHE, default corresponds to sphericity, =1. to linear event measures.

PARE(31) : (D=1.) power of momentum-dependence in LUMRNU, default corresponds to thrust.

PARE(32) : (D=0.25 GeV) maximum distance d_{init} allowed in LUCLUS when forming starting clusters used to speed up reconstruction.

PARE(33) : (D=2.5 GeV) maximum distance d_{join}, below which it is allowed to join two clusters into one in LUCLUS.

PARE(34) : (D=0.0001) convergence criterium for thrust (in LUTHRU) or generalized thrust (in LUCLUS), i.e. when the value changes by less than this amount between two iterations the process is stopped.

PARE(35) : (D=2.5) defines maximum absolute pseudorapidity used in LUCELL.

PARE(36) : (D=1.5 GeV) gives minimum E_T for a cell to be considered as a potential jet initiator by LUCELL.

PARE(37) : (D=7.0 GeV) gives minimum summed E_T for a collection of cells to be accepted as a jet.

PARE(38) : (D=1.) gives the maximum distance in $(\Delta\eta^2 + \Delta\phi^2)^{0.5}$ from cell initiator when grouping cells to check whether they qualify as a jet.

PARE(39), PARE(40) : not used.

PARE(41) : (R) value of R, the ratio of continuum cross section to the lowest order muon pair production cross section, as given in massless QED (i.e. three times the sum of active quark charges-squared, possibly modified for polarization).

PARE(42) : (R) value of R, the ratio of continuum cross section to the lowest order propagator effects (for MSTE(2)=2).

PARE(43) : (R) value of R as PARE(42), but including QCD corrections as given by MSTE(1).

PARE(44) : (R) value of R as PARE(43), but additionally including corrections from initial state photon radiation (if MSTE(7)=1). Since the effects of heavy flavour thresholds are not simply integrable, the initial value of PARE(44) is updated during the course of the run to improve accuracy.

PARE(45) - PARE(48) : (R) absolute cross sections in nb as for the cases PARE(41) - PARE(44) above.

8. A Routine for low- τ_T Physics

PARE(49) : (R) current value of α_s .

PARE(50) : (R) current effective matrix element cutoff 'y_{cut}' as given by PARE(8), PARE(9) and the requirements of having non-negative cross sections for two-, three- and four-jet events.

PARE(51) : (R) value of CM energy ECM at last LUXTOT call.

PARE(52) : (R) current first-order contribution to the three-jet fraction; modified by mass effects.

PARE(53) : (R) current second-order contribution to the three-jet fraction; modified by mass effects.

PARE(54) : (R) current second-order contribution to the four-jet fraction; modified by mass effects.

PARE(55) : (R) current fraction of four-jet rate attributable to q \bar{q} q'q' events rather than q \bar{q} gg ones; modified by mass effects.

PARE(56) : (R) has two functions when using second order QCD. For a three-jet event, it gives the ratio of the second-order to the total three-jet cross section in the given kinematical point. For a four-jet event, it gives the ratio of the modified four-jet cross section, obtained when interference terms with not well defined colour flow are neglected, to the full unmodified one, all evaluated in the given kinematical point.

PARE(57) - PARE(59) : (I) used for cross section calculations to include mass threshold effects to radiative photon cross section. What is stored is basic cross section, number of events generated and number that passed cuts.

PARE(60) : (R) nominal fraction of events that should contain a radiative photon.

PARE(61) - PARE(64) : (I) give shape of radiative photon spectrum including weak effects.

PARE(65) : (I) contains 1.986-0.115n_f, n_f number of active flavours at last α_s call.

PARE(66) - PARE(69) : not used.

PARE(70) : (I) maximum virtuality Sudakov form factors have been initialized for.

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

In section 3.7 we outlined the Lund low- P_T model, as presented in [50]. In a hadron-hadron collision, one string is stretched from one end of the event to the other. The ordinary fragmentation routines are equipped to handle also the fragmentation of such a system, once the order of the quarks along the string is given. More specifically, what must be provided is L-, J- and I-quark flavours, plus spin for the LJ-diquark, the latter needed when the L and J enter the same hadron. This routine is here to provide that information, given the colliding hadrons.

The size of this routine is fairly limited, but it could not be made to fit logically anywhere else, and is therefore found separately here. While very successful in describing fixed target data [75], problems are encountered with understanding Collider data. It may be possible to extend the present model also to that case; in the hadron physics routines [2], however, we have chosen a somewhat different approach.

SUBROUTINE LULOPT(KF1,KF2,PE1,PE2)

Purpose: to simulate low- P_T hadronic reactions following the Lund model.

KF1, KF2 : particle codes for two incoming hadrons. The cases covered are 17 (π^+), 18 (K^+), 19 (K^0), 41 (p), 42 (n) and their antiparticles. PE1, PE2: energies of the two incoming hadrons, with no. 1 moving in the +z direction and no. 2 in the -z one. By putting a PE smaller than the corresponding hadron mass, the particle is taken to be at rest (fixed target).

Remark: the first two lines in commonblock LUJETS will contain the original hadrons, the next four information on the resulting jet system (two ordinary ones interleaved with two KS-6 continuation lines), and then follows the hadronic final state.

COMMON /LUDATH/ CHR(20),KHR(60)

Purpose: to contain information on the ordering of J- and I-quarks in the various allowed hadrons.

CHR : contains cumulative relative rates for the different L-, J- and I-quark arrangements of the incoming hadrons, beginning in position 1 for π^+ , 3 for K^+ , 5 for K^0 , 7 for p and 12 for n.

KHR : L-, J- and I-quark arrangement information, with three numbers corresponding to every CHR one. For a baryon the first gives LJ-diquark flavour, the second J-quark flavour (0 when it does not matter, e.g. for L=J) and the third I-quark flavour. For a meson the first in L-quark flavour, the second is empty (0) and the third is I-quark flavour.

9. Examples on How to Use the Program

The Monte Carlo program is built as a slave system, i.e. the user supplies the main program, and from this the various subroutines are called on to execute specific tasks, after which control is returned to the main program. Some of these tasks may be very trivial, whereas the "high-level" routines by themselves may make a large number of subroutine calls.

The program is written entirely in standard Fortran 77, and should run on any machine with such a compiler. The one nonstandard feature is the need for a random number generator returning numbers uniformly distributed between 0 and 1. Internally a function RLU is used for this purpose; this function is listed as last subroutine in the package, with a few examples how it can be interfaced to existing routines.

For most of the routines no initialization is necessary, except for the one implied by the presence of BLOCK DATA subprograms (there are three of them, LUDATA, LUEDAT and LUHDATA); these must be linked, however, which does not occur automatically with all loaders. The cases where some initialization may indeed be performed (depending on exactly which options are used), and hence events may have to be generated in some coherent fashion, are LUEvent (and some routines called by it), LUONTA and LUSHOW.

Apart from writing a header, printing error messages if need be, and responding to explicit requests for listings, all tasks of the program are performed silently. All output is directed to unit MST(20), by default 6, and it is up to the user to see to it that this unit is open for write.

The commonblock LUJETS, in which the event record is stored, has space for 2000 entries, which may include the initial jets (optionally with jet shower history), primary hadrons and all secondary decay chains. At high energies (SSC) even 2000 lines may not be enough; the program can without further ado be recompiled with any number up to 10000 lines in the LUJETS commonblock (at all its occurrences) if MST(30) is changed simultaneously.

A few sensitive pieces of code have been written in double precision, but for applications in the 40 TeV range (SSC) one is starting to come dangerously close to a point where (almost) all real variables ought to be in double precision on a 32 bit machine; conversely the use of double precision at all

is overkill when running on a 60 or 64 bit machine, but is included to have easily transportable code.

The Lund Monte Carlo is extremely versatile, but the price to be paid for this is a large number of adjustable parameters and switches for alternative modes of operation. No single user is ever likely to have need for more than a fraction of the options available. Since all these parameters and switches are assigned sensible default values, there is no reason to worry about them until the need arises.

9.1. The Jet Fragmentation Routines

What every user has to know something about is the commonblock LUJETS

```
COMMON /LUJETS/ N,K(2000,2),P(2000,5)
described in detail in 5.1, but briefly iterated here. The complete event record is stored in LUJETS. This normally includes the original jets, the particles these fragment into and the subsequent decay chains. The number N gives the number of lines (1 through N) in the K and P matrices that are actually used to store the current event. For line I, K(I,1) gives information about event history and current status. In particular, anything which has K(I,1) < 20000 represents a particle or jet that is either considered stable or has not yet been treated, whereas K(I,1) > 20000 corresponds to jets that have fragmented, particles that have decayed and an assortment of special purpose lines. K(I,2) gives a code for what parton or particle we are dealing with, e.g. 1=+, 7=-, 17=+, 41=K+, 501=u, 502=d. Antiparticles, where existing, are given by the negative number, -17=-, -41=-p, -501=t. This code is often referred to as KF code; in some subroutine calls dealing exclusively with jets, an IFL code is used, in which 0=q, 1=u, 2=d, -1=t, etc. but, when these jets get stored in LUJETS, +500 or -500 is automatically added. The P vector contains momentum information, with P(I,1), P(I,2) and P(I,3) giving the three-momentum, P(I,4) the energy and P(I,5) the mass; again special rules may apply if K(I,1) > 20000.
```

A general rule of thumb is that none of the physics routines (LUCONS, LUONEJ, LUSYSJ, LUDECY, etc.) should ever be called directly, but only via LUJEXEC. This routine may be called repeatedly for one single event. At each call only those entries that are allowed to fragment or decay, and have not yet done so, are treated. Thus

```
CALL LU2JET(1,1,-1,20.)
MST(5)=0
inhibit jet fragmentation
inhibit particle decay
inhibit pi^0 decay (IDB(23)>0 initially)
will not do anything
jets will fragment, but no decays
particles decay, except pi^0
nothing new can happen
pi^0:s decay
```

The program contains a number of checks that flavours specified for jet systems make sense, that the energy is enough to allow hadronization, that the memory space in LUJETS is enough, etc. If anything goes wrong that the program can catch (obviously that may not always be possible) an error message will be printed and the treatment of the corresponding event will be cut short. So long as no error messages appear on the output, it may not be worth the while to look into the rules for error checking, but if but one message appears, it should be enough cause for alarm to receive prompt attention.

```
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 rejected automatically.
```

In e.g. a leptoproduction event a typical situation could be a u quark going out in the +z direction and a ud 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 is 20 GeV and the boost beta=0.996 (corresponding to x_B = 0.045)

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

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

```

CALL LULJET(-1,1,0,0,223.15,0.,0.)
CALL LULJET(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  $(E-P_z) = m_p(1-x_B)$  to obtain the correct invariant mass for 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 LULJET(-1,1,0,0,223.15,0.,0.)
MST(9)=1
P(2,5)=0.938*(1.-0.045)
CALL LULJET(2,12,0,0,0.,0.,0.)
MST(9)=0
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{u} in the -z, +x quadrant. For three-jet, and particularly four-jet events, it is important to remember that not all setups of kinematical variables x lie within the kinematically allowed regions of phase space.

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 entries will be given. For string fragmentation these quantities should be conserved exactly (up to machine precision errors), and the same goes when running independent fragmentation with one of the momentum conservation options. (As noted in section 5.4, the action of LUPREP, with respect to very small jet systems collapsing into one single particle, does not seem to conserve energy or momentum, but actually these quantities are conserved in the event as a whole.) LULIST(1) gives a format that comfortably fits on an 80 column screen, the option LULIST(11) will give a bit more detailed information in a wider format. Also options 3 and 4 of LULIST are

useful for listing particle and parton data.

An event, as stored in the LUJETS commonblock, will contain the 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 the final particles, superfluous information may be removed with LUEDIT. Thus e.g.

```
CALL LUEDIT(2)
```

will leave you with the final charged and neutral particles (except neutrinos).

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.

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

The Field-Feynman jet model [21] is available in the program by changing the following values: MST(4)=2 (i.e. use the FF parametrization of longitudinal fragmentation functions, with the a parameter stored in PAR(41) - PAR(43)), MST(11)=1 (give endpoint quarks 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), PAR(8)=PAR(9)=0.5 (probability for meson to have spin 1) and PAR(12)=0.35 (width of Gaussian transverse momentum distribution). In addition only u, d and s single quark jets may be generated following the FF recipe. Various hybrid arrangements with using e.g. FF fragmentation functions to generate the fragmentation of a gluon jet are available, of course, but these may not be called FF "standard jets" (unfortunately this is one of the most misused terms in the business, a lot of people having adopted the term "FF fragmentation" for jet schemes of their own), but should be referred to as independent fragmentation models with this or that property.

A wide range of independent fragmentation options are implemented. In particular with MST(5)=3 a gluon jet is assumed to fragment like a random $u, \bar{u}, d, \bar{d}, s$ or \bar{s} jet, while with MST(5)=5 the gluon is split into a $u\bar{u}, d\bar{d}$ or $s\bar{s}$ pair of jets sharing the energy according to the Altarelli-Parisi splitting function. Whereas energy, momentum and flavour is not explicitly conserved in

independent fragmentation, a number of options are available in MST(6) to ensure this "post facto", e.g. MST(6)=1 will boost the event to ensure momentum conservation and then (in the CM frame) rescale momenta by a common factor to obtain energy conservation, whereas MST(6)=4 rather uses a method of stretching the jets in longitudinal momentum along the respective jet axis to keep angles between jets fixed.

If need be, new particles may be defined and used within the program. As an example, consider the production of a charged Higgs with mass 25 GeV which is assumed to decay to $c\bar{b}$ 40% and to $c\bar{s}$ 60% of the time.

```
COMMON /LUDAT2/ KTYP(120),PMAS(120),PWID(60),KFR(80),CFR(40)
COMMON /LUDAT3/ DPAR(20),IBD(120),CBR(400),KDP(1600)
COMMON /LUDAT4/ CHAG(50),CHAF(100)
```

CHARACTER*4 CHAG,CHAF

```
choose a free particle code (6)
specify a name
charge code for particle
particle mass
position of first decay channel
cumulative branching ratio...
... must increase up to 1
first decay channel products
KDP(4*351-3)=504
KDP(4*352-3)=504
second decay channel products
CALL LUPART(0,5,0.,0.,0.)
generate event
list it
CALL LULIST(11)
```

9.2. e^+e^- Physics

An ordinary e^+e^- annihilation event in the continuum, at a CM energy of 40 GeV, may be generated with

```
CALL LUVEVT(0,40.)
```

In this case a $q\bar{q}$, $q\bar{q}g$ or $q\bar{q}q'\bar{q}'$ event is generated according to second order QCD, including weak effects. Before a call to LUVEVT, however, a number of default values may be changed, e.g. MSTB(1)=1 to use first order QCD only or =3 to obtain parton shower evolution (this option is still slightly

preliminary), MSTE(2)=1 to have QED only, MSTE(4)=6 to allow $t\bar{t}$ production as well, MSTE(7)=1 to include initial state photon radiation (including a correct treatment of the Z^0 pole), PARE(2)=0.2 to change the second order Λ value, PARE(6)=93. to change the Z^0 mass or PARE(8)=0.015 to change the matrix element cutoff. If parton showers or initial state photon radiation is used, some restrictions apply to how one can alternate the generation of events at different energies or with different Z^0 mass etc. At the end of a run, a summary of what events have been generated can be printed out with

```
CALL LUVEVT(10,0.)
```

where the second argument is dummy.

The three-gluon or gluon-gluon-photon decay of a toponium resonance at 80 GeV may be simulated by a call

```
CALL LUONIA(6,80.)
```

Again LUONIA(10,0.) at the end of the run will print out statistics.

The routines for sphericity, thrust, cluster (2 different algorithms) and Fox-Wolfram moments may be called directly after the event generation

```
CALL LUVEVT(0,94.)
```

```
CALL LUCLUS(NJET,TGEN,DMIN)
```

and then all stable, final particles (including neutrinos!) are used in the analysis. With the use of LUEDIT it is possible to remove unwanted particles before the analysis.

A typical program for analysis of e^+e^- annihilation events at 100 GeV might then look something like

```
COMMON /LUJETS/ N,K(2000,2),P(2000,5)
COMMON /LUDAT1/ MST(40),PAR(80)
COMMON /LUDAT2/ KTYP(120),PMAS(120),PWID(60),KFR(80),CFR(40)
COMMON /LUDAT3/ DPAR(20),IBD(120),CBR(400),KDP(1600)
COMMON /LUDATE/ MSTB(40),PARE(80)
IDB(23)=0
MSTB(4)=6
PMAS(106)=45.
MSTB(7)=1
PARE(30)=1.
.....
initialize analysis statistics
```

put π^0 stable
allow top-antitop production
change top quark mass
include initial state radiation
use linear sphericity
other desired changes
initialize analysis statistics

```

DO 100 IEVENT=1,1000          loop over events
CALL LUVEVT(0,100.)           generate new event
IF(IEVENT.EQ.1) CALL LULIST(11)
CALL LUEDIT(2)
CALL LUSPHE(SPH,APL)
IF(SPH.LT.0.) GOTO 100
CALL LUORIE(1)
IF(IEVENT.EQ.1) CALL LULIST(12)
      ...
      CALL LUTHRU(THR,OBL)
      ...
100 CONTINUE
CALL LUVEVT(10,0.)
      ...
      END

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