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A MONTE CARLO PROGRAM FOR QUARK AND GLUON JET GENERATION

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Abstract:

Models for the generation of quark jets and of gluon jets are presented. For quark-antiquark jet systems a method to obtain explicit conservation of energy, momentum and flavour is introduced. Combined with the gluon jet model, the scheme is extended to quark-antiquark-gluon events. The matrix element for $e^+e^- \to \gamma \to q\bar{q}$ or $q\bar{q}g$ is implemented, using a set of physical cuts to distinguish between $q\bar{q}g$ and $q\bar{q}$ events. The three-gluon and gluon-gluon-photon decays of heavy "onia" resonances are also studied. The model for the decays of the unstable particles, in particular the weak decays of heavy mesons, is outlined. The program is presented and all program components are listed in FORTRAN 77.

1. Introduction

The last year has seen a rapid growth of the energies available in e^+e^- annihilation events. With this has come not only the clear observation of two-jet events but also of events with a three-jet structure [1,2], where the third jet is believed to be due to the emission of a hard gluon. The general features of these event classes are in agreement with what is expected from QCD, the candidate theory of strong interactions. Perturbative QCD may be used reliably for large spacelike Q^2, where the coupling constant is small. In the timelike region, like for e^+e^- annihilation, a corresponding description has been given with W^2 taking the place of Q^2. In the hadronization process we then recognize two time scales, one short scale for "hard" processes, such as the emission of gluons, where the perturbative QCD description may be used, and one longer for the "soft" fragmentation into hadrons, where perturbative methods are not applicable. The distinction is to some extent arbitrary, since there should be a continuous transition between the two descriptions, but for practical purposes it is a very useful one. The hard processes, the soft fragmentation and the subsequent decays of primary mesons into stable particles are stochastic processes in our model; it is therefore natural to give a description in terms of a Monte Carlo program simulating the complete breakup process. The purpose of this paper is to present such a program, with main emphasis on $q\bar{q}$, $q\bar{q}g$, ggg, and $gg\gamma$ events. Studies partly of a similar kind have previously been presented by Hoyer et al. [3] and by Ali et al. [4].

The natural starting point is a model for quark (q) jets, both for the light u,d,s quarks and the heavy c,b,t ones (the t quark has not yet been discovered, but is expected in most flavour schemes). Models for light quark jets have been suggested e.g. by Field and Feynman (FF) [5] and by Andersson, Gustafson, Peterson and others in the Lund group (LU) [6,7]. These models are implemented in ref. [8], while a possible extension to heavy quark jets is studied in ref. [9]. We will recapitulate the main points here; in particular we will present the three-dimensional Lund model [10]. Also needed is a model for gluon (g) jet fragmentation, and for this we will use the ideas of the Lund model [7,10].

A jet never appears alone, however. This causes special problems with energy, momentum and flavour conservation. For instance, consider a $q\bar{q}$ event in the CM frame, where a quark and an antiquark go out in opposite directions, initially with half the energy each. Then, during the hadronization process, energy (and flavour) will flow along the colour force field between the quark and the antiquark, so that the total energy of the final state particles on the two sides (the q and the $\bar{q}$ ones) will not be the same. This variation is reproduced by the single jet models, but there is no simple way to find "matching" q and $\bar{q}$ jets that give the correct total energy. Instead we have developed a scheme in which the fragmentation of a $q\bar{q}$ system is considered as a whole, and where energy, momentum and flavour can be conserved exactly.

This approach becomes even more important in the case of $q\bar{q}g$ events. In our model we assume a string (a colour flux tube) which is stretched between the quark and the antiquark via the gluon. Hence, we do not have three jets, q , $\bar{q}$ and g , fragmenting independently of each other, but the final particles are instead distributed around two hyperbolas, giving a structure which can be experimentally tested in e^+e^- annihilation [11] or in leptoproduction [12] (in the latter case, for baryon targets, the rôle of the antiquark is taken by a diquark, which in QCD language also is an antitriplet in colour).

With models for $q\bar{q}$ and $q\bar{q}g$ fragmentation at hand, we turn to a study of the matrix element for $e^+e^- \to \gamma \to q\bar{q}$ or $q\bar{q}g$. In particular we wish to obtain a smooth transition between two-jet and three-jet events, and will for that purpose use two physically motivated cuts on the $q\bar{q}g$ matrix element. Combining this with the QED cross section for the different quark flavours we obtain an event generator.

For new heavy flavour $q\bar{q}$ resonances, e.g. a "toponium" ($t\bar{t}\,1^{--}$) state, we expect ggg and ggγ decays to dominate. A model for such decays is outlined.

Many particles produced in the fragmentation process are unstable and subsequently decay. In particular, heavy mesons (D , F , B , ...) decay weakly into a wealth of different channels. The treatment of these decays [9] is reviewed.

Finally we give a description of all program components and parameters. The program itself is found in Appendix 1, and a summary of the particle data used in Table 1.

2. Single quark and gluon jets

2a. Field-Feynman-like quark jets

In an iterative quark jet model [13], it is assumed that a primary quark q, carrying the quantity $W_{+o} = E_o + p_{zo}$ (with the jet axis chosen to lie in the $+z$ direction), generates a quark-antiquark pair $q_1\bar{q}_1$ in its colour field. The quark q and antiquark $\bar{q}_1$ form a primary meson $q\bar{q}_1$ with $E + p_z$ fraction $z_{+1} = (E + p_z)_{q\bar{q}_1}/W_{+o}$ leaving $W_{+1} = (1 - z_{+1})W_{+o}$ to a remaining quark jet q_1. The procedure is iterated and a chain of primary mesons is produced.

In the Field-Feynman model [5] the quark-antiquark pairs created in the field are taken to be $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ in the ratio 2:2:1 and the mesons formed pseudoscalars or vectors in the ration 1:1. Furthermore, a scaling function describing the probability distribution in z_+

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

with $a = 0.77$ is used.

For heavier quark flavours we expect the scaling function to become successively shifted towards higher z_+ values [14], represented e.g. by a smaller $a \geq 0$ in eq.(1) or a rising function

$$f(z_+)\,dz_+ = (1+b)\,z_+^b\,dz_+ \qquad (2)$$

with $b \geq 0$. At present we will however use a flat scaling function for charm, bottom and top.

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

$$f_q(\bar{p}_\perp)\, d^2p_\perp = \frac{1}{\pi\sigma^2}\, e^{-(p_\perp^2/\sigma^2)}\, d^2p_\perp \qquad (3)$$

with $\sigma = 0.35$ GeV and the constraint that the total $\bar{p}_\perp$ of each $q\bar{q}$ pair created be zero [5,10]. The transverse momenta of the quarks are then added vectorially to give the $\bar{p}_\perp$ of the mesons formed from them.

A point not entirely clear is the question whether the original quark should have a $\bar{p}_\perp$ with respect to the jet axis or not. In the FF quark jet model, this quark is given a random $\bar{p}_\perp$ in accordance with eq.(3). This might be seen as representing a "primordial" $\bar{k}_\perp$ in hadronic reactions, although such a $\bar{k}_\perp$ could perhaps better be simulated by allowing the direction of of the jet axis itself to vary. In $q\bar{q}$ and $q\bar{q}g$ events it could also be argued that the different jet axes are defined by the outgoing partons. Therefore the FF single quark jet model is the only place where we give the original quark a $\bar{p}_\perp$.

2b. The Lund model for quark jets

The Lund model is based on the dynamics of the massless relativistic string with not excited transverse degrees of freedom, and provides a causal and relativistically invariant description of the fragmentation process [6,7,10]. The one-dimensional model is similar to the FF model, but with

$$f(z_+)\, dz_+ = 1\ dz_+ \qquad (4)$$

This choice is motivated by the assumptions that the density of states as a function of the mass squared M^2 of a highly excited $q\bar{q}$ system is dn/dM^2 = constant , and that all kinematically allowed states are equally populated in the "decay" of a $q\bar{q}$ system into a meson and a remainder-system.

In ref. [10] an extension to three dimensions is made. If the $q\bar{q}$ pairs formed in the field have nonzero transverse masses, they can not classically be formed in one point. From the quantum mechanical production vertex they have to tunnel out a distance corresponding to the field energy that goes into the formation of their transverse masses. This gives rise to an extra matrix element suppression factor $|g(\kappa\tau_i/m_{\perp q_i})|^2$ where κ is the string force constant, τ_i the invariant distance from the starting point of the original $q\bar{q}$ pair to the production vertex of the $q_i\bar{q}_i$ pair and $m_{\perp q_i}$ is the transverse mass of the q_i (and $\bar{q}_i$) $m_{\perp q} = \sqrt{m_q^2 + \bar{p}_{\perp q}^{\,2}}$. The exact behaviour of $|g|^2$ varies with the assumptions made, but independently of the details of the model $|g(\alpha)|^2$ is small for small α , rapidly approaches 1 when $\alpha >> 1$ and is smoothly varying in between. Fortunately, different functions $|g|^2$ with these properties give very similar results. We will in this paper use

$$|g|^2 = \frac{(\kappa\tau)^2}{(\kappa\tau)^2 + m_{\perp q}^2} = \frac{\Gamma}{\Gamma + m_{\perp q}^2} \qquad (5)$$

The factor Γ_i may be calculated recursively

$$\Gamma_0 = 0 \qquad (6a)$$

$$\Gamma_i = (1 - z_{+,i})\left(\Gamma_{(i-1)} + \frac{m_{\perp i}^2}{z_{+i}}\right) \qquad (6b)$$

where $m_{\perp i}$ is the transverse mass of the meson $q_{(i-1)}\bar{q}_i$.

In this model the relative probability to create $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ pairs in the field is in principle fixed by the appearance of an extra factor $e^{-m_q^2/\sigma^2}$ in eq.(3) (i.e. $p_{\perp q}$ is replaced by $m_{\perp q}$ [15]) giving the suppression of the different quark flavours. Due to uncertainties in the definition of quark masses and $\sigma = \sqrt{\kappa/\pi}$ we will however continue to consider the relative probability for $s\bar{s}$ pair production as a free parameter.

2c. The gluon jet model

Again considering the massless relativistic string, we note that it is possible for a small pointlike part of the string to carry a finite amount of energy and momentum [7,11]. Such a "kink" mode is acted upon by the string by twice the force upon an endpoint quark. This gives features very similar to those of a gluon in QCD, where the corresponding force ratio is expected to be $2/(1 - 1/n_c^2)$ with n_c the number of colours.

A gluon jet may then be pictured as two parallel string "legs" connected via the endpoint kink. To obtain a model for gluon fragmentation we make two assumptions, firstly that the two legs will contain an equal amount of energy (in the string model, the

kink loses energy equally rapidly to each leg) and secondly that the two sides will fragment independently of each other. Further, the kink can not break as long as it still carries energy, so the first rank meson [5] of the gluon jet must be formed around the kink.

As in the case of quark jets, the actual fragmentation is of an "inside-out" character [6] where the slowest meson in a given frame of reference is the first to be formed in that frame, but also as for quark jets it is advantageous to formulate it as a recursive scheme starting with the first rank meson. This meson $q_1\bar{q}_2$ is formed by the creation of a $q_1\bar{q}_1$ pair in one string and a $q_2\bar{q}_2$ pair in the other. For each of these a $\bar{p}_\perp$ is defined as in eq.(3), which add vectorially to give the $\bar{p}_\perp$ of the meson.

The meson will also take a fraction $z_+^{(i)}$ of the $W_+^{(i)} = (E + p_z)^{(i)}$ on the two sides $i=1,2$, i.e.

$$(E+p_z)_{meson} = z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)} \approx$$
$$= (z_+^{(1)} + z_+^{(2)}) \frac{W_{+g}}{2} \qquad (7)$$

using our assumption $W_+^{(1)} = W_+^{(2)} = W_{+g}/2$. The $z_+^{(i)}$ are distributed independently of each other between 0 and 1 , and may be chosen either according to the LU or the FF scaling functions $f(z_+)$.

Within the Lund scheme there will also be a matrix element factor coming from the production of the $q_1\bar{q}_1$ and $q_2\bar{q}_2$ pairs like in eq.(5)

$$\left| g\left(\frac{K\tau_1}{m_{\perp q_1}}\right)\right|^2 \left| g\left(\frac{K\tau_2}{m_{\perp q_2}}\right)\right|^2 = \frac{\Gamma^{(1)}}{\Gamma^{(1)} + m_{\perp q_1}^2} \cdot \frac{\Gamma^{(2)}}{\Gamma^{(2)} + m_{\perp q_2}^2} \qquad (8)$$

Introducing $W_-^{(i)} = (E - p_z)^{(i)}$ and corresponding fractions $z_-^{(i)}$, the transverse mass $m_\perp$ of the first rank meson is given by

$$(z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)})(z_-^{(1)} W_-^{(1)} + z_-^{(2)} W_-^{(2)}) = m_\perp^2 \qquad (9)$$

which means that

$$0 \le z_-^{(i)} W_-^{(i)} \le \frac{m_\perp^2}{z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)}} \qquad i = 1,2 \qquad (10)$$

We will assume that $z_-^{(1)}\ W_-^{(1)}$ is uniformly distributed in the allowed region. Then we may find the $\Gamma^{(i)}$, which are given by

$$\Gamma^{(i)} = (1 - z_+^{(i)})\, W_+^{(i)} z_-^{(i)} W_-^{(i)} \qquad i = 1,2 \qquad (11)$$

What remains after the formation of the first meson is an antiquark jet $\bar{q}_1$ with known $\bar{p}_{\perp q_1}$, $E + p_z = (1 - z_+^{(1)}) W_+^{(1)}$ and $\Gamma^{(1)}$, and a correspondingly known quark jet q_2. The continued fragmentation of these jets will then proceed as in two ordinary, independent quark jets.

This scheme means that a gluon jet will be softer than a quark jet with the same energy but harder than just two quark jets with half the energy each. Also, the flavour and spin of the

first rank meson in the gluon jet is distributed as for any meson formed in the string, since the kinks in our model do not carry any flavour properties. (If future findings show e.g. that the gluon spin is transferred to the meson in a particular fashion or that the gluon gives the meson special flavour properties (cf ref. [16])this could be included in the program, but it is not in the spirit of the model presented.)

2d. Finite jets and jet systems

The schemes above have to be complemented with a prescription for when to stop the jet generation. One could e.g. choose either to keep all stable final particles with $p_z > 0$ or to keep all stable particles coming from a primary meson with $p_z > 0$ [9].

It would with such cuts on momentum parallel to the respective jets axis be possible to generate systems of quark and gluon jets to simulate e.g. $q\bar{q}$, $q\bar{q}g$, or ggg events. Such a model would not conserve energy, momentum or flavour except as properties on the mean. At high enough energies one would expect the errors to be small when interest lies mainly in the rather fast particles so that the joining of the jets in the center does not enter. In the following sections we will however choose another approach to the question of generating jet systems.

3. Quark-antiquark jet systems

The simplest jet system is the $q\bar{q}$ event. Seen in the CM frame we have a quark q going out in the $+z$ direction and an

antiquark $\bar{q}$ in the -z direction, with $W_{+o} = W_{-o} = E_{cm}$, the center of mass energy.

Neither the FF nor the LU fragmentation scheme is completely symmetric, in the sense that the final result is different if a jet system is generated from right to left or from left to right [5]. To overcome partly this limitation, we will at each step of the generation scheme allow a particle to be formed with equal probability on either side of the then remaining system. We will refer to these as right (+z) and left (-z) side mesons, keeping in mind that this flavour and coordinate space ordering may look entirely different in momentum space.

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

$$\frac{m_\perp^2}{W_+ W_-} < z < 1 - \frac{m_\perp'^2}{W_+ W_-} \qquad (12)$$

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

$$W_{+i} = (1 - z_{+i})\, W_{+(i-1)} \qquad (13a)$$

$$W_{-i} = W_{-(i-1)} - \frac{m_{\perp i}^2}{z_{+i}\, W_{+(i-1)}} \qquad (13b)$$

In the Lund model, a matrix element factor $|g|^2$ according to eq.(5) will appear for each $q\bar{q}$ pair created. Hence we have to keep track of a Γ_+ on the right side and a Γ_- on the left side. These may be obtained recursively as in eq.(6), but with the difference that whereas a left side meson will take a part of the total W_+, it will not influence the value of Γ_+. Hence we need to keep track of a variable $\tilde{W}_+$ which only depends on how much $E + p_z$ right side mesons carry away, so that in the formation of such a particle

$$\tilde{W}_{+i} = \tilde{W}_{+(i-1)} - z_{+i} W_{+(i-1)} = (1 - \tilde{z}_{+i}) \tilde{W}_{+(i-1)} \qquad (14)$$

where it is the thus defined $\tilde{z}_{+i}$ that enters in eq.(6).

The separation off of mesons may go on so long as the energy of the remaining $q_i\bar{q}_j$ system is sufficiently large

$$W_+ W_- \geq (m_{q_i} + m_{q_j} + W_{min})^2 \qquad (15)$$

When this no longer is satisfied, the then remaining system is assumed to give the two final mesons $q_i\bar{q}_n$ and $q_n\bar{q}_j$. The value of W_{min} is fixed (for high energy initial $q\bar{q}$ systems) by the demand of a flat rapidity plateau in the center, $W_{min} \approx 2.2$ GeV for FF and ≈ 1.4 GeV for LU fragmentation.

For the two final mesons the respective masses and transverse momenta and the total W_+ and W_- are known (flavour and $\bar{p}_\perp$ properties of the final $q_n\bar{q}_n$ pair are as for the other $q\bar{q}$ pairs created in the field). If W_+W_- is too small, no kinematically allowed solution will exist, in which case we reject all previous steps and start all over again. Otherwise two

possible solutions exist, one in which the right side meson moves to the right in the CM frame of the two mesons, and one in which it moves to the left. The probability for the latter is ≈ 0.39 in the FF and ≈ 0.27 in the LU scheme for two adjacent mesons elsewhere in the chain, hence the same numbers are put in by hand for the final two.

The recipe given above will conserve energy, momentum and flavour at each step of the generation process. The result will agree with the single quark jet recipe for the fast particles on either side while we obtain a smooth joining of the two jets in the center. It is however important to remember that no scheme of this kind can be made entirely consistent. In particular, the invariant mass distribution of the final two mesons will be somewhat different from that of any two adjacent mesons elsewhere. Due to the cut in eq.(15) there is no tail up to very high masses; there are also fewer events close to the lower limit, where the two mesons are formed at rest with respect to each other. Even the mean invariant mass of the final two comes out slightly wrong, too high in the FF scheme and too low in the LU one.

The lower stopping point (given by W_{min}) in the LU case means that the final two mesons usually are pseudoscalars. We obtain a flat rapidity plateau for pseudoscalars and vectors separately, the surplus of pseudoscalars showing up as a somewhat longer plateau for them. In the FF case the final mesons almost as often are vectors, so due to their higher mass there

will be a slight top in the center for vectors and a corresponding dip there for pseudoscalars.

The general behaviour of the model has above been studied in the high energy limit, but the model can obviously be used also for lower energies. The minimum number of primary mesons that must be generated with this scheme is three; for CM energies below $2m_q + W_{min}$ we by hand put in a probability for the production of two mesons only. The model may not be particularly relevant for a $q\bar{q}$ system below 3 GeV, say, since at such energies resonance production plays an important rôle not covered in this program. The general formalism will however be useful even at such low energies, to describe parts of larger systems.

4. Quark-antiquark-gluon jet systems

4a. The generation scheme

In e^+e^- annihilation into $q\bar{q}g$ the emission of the hard gluon according to perturbative QCD takes place on a shorter timescale than the longtime soft hadronization, so the partons can be pictured as coming out from a common origin. In our model this origin is a point in space-time, and it should be noted that the relativistically invariant fragmentation scheme outlined below in no way relies on a fixed point in space. (This can be contrasted with other models [3,4] in which it is assumed that the three jets really are connected in the center during the fragmentation process.) As the partons move apart, a string is

stretched out between the quark and the antiquark via the gluon. This string will break up and give particles distributed along two hyperbolas in momentum space, with mesons from the qg and the $\bar{q}g$ string pieces, respectively (Fig. 1a). A broadening of the hyperbolic shape is due to differences in particle mass and $\bar{p}_\perp$. Typically the distance from the origin to the hyperbolas is ~ 0.3 GeV/c for primary mesons, i.e. of the same order of magnitude as the average $p_\perp$. If the gluon is soft, the hyperbolas will come closer to the origin (Fig. 1b), and if the gluon is almost collinear with e.g. the q, the qg hyperbola will be further out while the $\bar{q}g$ one again comes closer (Fig. 1c).

The mesons created may be divided into three groups: the first rank meson formed around the gluon and the mesons formed elsewhere along either of the two strings. As in the single gluon jet case, the natural starting point of the generation scheme is the first rank meson of the gluon jet. The new element here is that the strings no longer are parallel, so the kinematics will become more complicated.

To study the kinematical situation, we assume known q, $\bar{q}$ and g energies and momenta in the CM frame, and choose the xz plane as event plane, with the gluon in the $+z$ direction and the quark having $p_x > 0$. Since the gluon energy again should be divided equally between the two sides, we define one subsystem (no. 1) containing the quark and half the gluon energy and another (no. 2) with the antiquark and the remaining gluon

energy. For these, opening angles $\alpha_1 > 0$ and $\alpha_2 < 0$ are given at the gluon corner (Fig. 2). This also defines Lorentz boosts $\bar{\beta}_1$ and $\bar{\beta}_2$, which correspond to the transverse velocities of the two string pieces, and hence go between the CM frame and a rest frame of the respective string piece. In these rest frames the W_+ and W_- of the subsystems, counting the $+z$ axis to lie in the gluon direction, are

$$W_+^{(1)} = (E_q + p_{zq} + E_g)\cos\alpha_1 - p_{xq}\sin\alpha_1 \qquad (16a)$$

$$W_-^{(1)} = (E_q - p_{zq})\cos\alpha_1 + p_{xq}\sin\alpha_1 \qquad (16b)$$

and correspondingly for the other subsystem.

The first rank meson $q_1\bar{q}_2$ of the gluon jet is formed from a $q_1\bar{q}_1$ pair in the qg leg and a $q_2\bar{q}_2$ pair in the $\bar{q}g$ leg, to which are associated $\bar{p}_\perp^{(i)}$, $i = 1,2$, defined in a rest frame of the respective string, according to eq.(3) and $z_+^{(i)}$, the fractions of the $W_+^{(i)}$ taken by the leading meson, according to eq.(1) or (4). This is however not sufficient to define the momentum of the meson $q_1\bar{q}_2$ uniquely. Introducing $z_-^{(1)}$ and $z_-^{(2)}$ for $q_1\bar{q}_2$ we find that the mass condition in eq.(9), which corresponds to $\alpha_1 = \alpha_2 = 0$, is generalized to

$$A\, z_-^{(1)} + B\, z_-^{(2)} + C\, z_-^{(1)} z_-^{(2)} = D \qquad (17)$$

where

$$A = \left\{ z_+^{(1)} W_+^{(1)} + z_+^{(2)} W_+^{(2)} \frac{\cos\alpha_1}{\cos\alpha_2} + 2\, p_x^{(2)} \cos\alpha_1 (\tan\alpha_2 - \tan\alpha_1) \right\} W_-^{(1)} \qquad (17a)$$

$$B = \left\{ z_+^{(2)} W_+^{(2)} + z_+^{(1)} W_+^{(1)} \frac{\cos\alpha_2}{\cos\alpha_1} + 2 p_x^{(1)} \cos\alpha_2 (\tan\alpha_1 - \tan\alpha_2) \right\} W_-^{(2)} \qquad (17b)$$

$$C = \cos\alpha_1 \cos\alpha_2 (\tan\alpha_1 - \tan\alpha_2)^2 W_-^{(1)} W_-^{(2)} \qquad (17c)$$

$$D = m^2 + (p_x^{(1)} + p_x^{(2)})^2 + (p_y^{(1)} + p_y^{(2)})^2 \qquad (17d)$$

Here m is the mass of the $q_1\bar{q}_2$, but it should be noted that D is not the transverse mass squared of the meson, since $p_x^{(1)}$ and $p_x^{(2)}$ are defined with respect to different axes.

Equation (17) describes a hyperbola in the $z_-^{(1)}$ - $z_-^{(2)}$ plane corresponding to the $q_1\bar{q}_2$ meson having the correct physical mass. The allowed region is $0 \leq z_-^{(i)} \leq 1$, $i=1,2$. Also, to ensure that the leading meson is not unreasonably soft, we reject sets of $z_+^{(i)}$ and $p_\perp^{(i)}$ such that $z_-^{(1)} + z_-^{(2)} > 1$ is possible. We will assume that the physical states are distributed uniformly along the hyperbola and select z_- pairs accordingly. For the LU model this choice will also define the $r^{(i)}$ according to eq.(11) and the matrix element suppression factor in eq.(8).

The momentum of the $q_1\bar{q}_2$ meson in the CM frame may now be found

$$p_x = p_x^{(1)} + z_-^{(1)} W_-^{(1)} \sin\alpha_1 + p_x^{(2)} + z_-^{(2)} W_-^{(2)} \sin\alpha_2 \qquad (18a)$$

$$p_y = p_y^{(1)} + p_y^{(2)} \qquad (18b)$$

$$E - p_z = z_-^{(1)} W_-^{(1)} \cos\alpha_1 + z_-^{(2)} W_-^{(2)} \cos\alpha_2 \qquad (18c)$$

$$E + p_z = \frac{1}{\cos\alpha_1} \left\{ z_+^{(1)} W_+^{(1)} + z_-^{(1)} W_-^{(1)} \sin^2\alpha_1 + 2 p_x^{(1)} \sin\alpha_1 \right\} + \frac{1}{\cos\alpha_2} \left\{ z_+^{(2)} W_+^{(2)} + z_-^{(2)} W_-^{(2)} \sin^2\alpha_2 + 2 p_x^{(2)} \sin\alpha_2 \right\} \qquad (18d)$$

After the formation of the first rank meson, two jet systems $q\bar{q}_1$ and $q_2\bar{q}$ remain. Our knowledge of α_i , $\bar{\beta}_i$, $W_{\pm}^{(i)}$, $z_{\pm}^{(i)}$, and $\bar{p}_{\perp}^{(i)}$ completely specifies the kinematical situation. The fragmentation of each of these systems will proceed as outlined in chapter 3 if seen in a rest frame of the respective string. As will be explained further below, we will demand that the systems have a minimum energy so that at least two particles may be formed from each of them, or else we will reject the choice of the first rank meson.

4b. The matrix element and physical cuts.

We will now study the matrix element for production of $q\bar{q}g$ events in e^+e^- annihilation, and for that purpose introduce scaled energy variables in the CM frame $x_1 = 2E_q/E_{cm}$, $x_2 = 2E_{\bar{q}}/E_{cm}$ and $x_3 = 2E_g/E_{cm}$. For the special case of $m_q = 0$ the differential cross section in first order QCD is [17]

$$\frac{d\sigma_{q\bar{q}g}}{dx_1\,dx_2} = \sigma_0 \frac{\alpha_s}{\pi} \frac{2}{3} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \qquad (19)$$

where σ_0 is the lowest order QED cross section (we will in this paper consider neither radiative corrections in QED nor terms coming from the exchange of a Z^0 boson). This cross section diverges for x_1 or $x_2 \to 1$, but also including the first order vertex and propagator corrections, a corresponding singularity with opposite sign appears in the $q\bar{q}$ cross section, so that

$$\sigma_{q\bar{q}} + \sigma_{q\bar{q}g} = \left(1 + \frac{\alpha_s}{\pi}\right) \sigma_0 \qquad (20)$$

Physically, this cancellation corresponds to a difficulty to distinguish a single quark from a quark accompanied by a weak or collinear gluon. Before implementing the matrix element we will thus have to introduce cuts giving a separation into $q\bar{q}$ and $q\bar{q}g$ events, cuts which qualitatively are physically motivated, but quantitatively somewhat arbitrary.

In our scheme, the $q\bar{q}g$ system consists of a quark-gluon leg and an antiquark-gluon one. The invariant mass squared $M^2_{q_{\frac{1}{2}}g} = (p_q + \frac{1}{2} p_g)^2$ is thus to go into the formation of the particles on the quark-gluon side, including "half" the first rank meson of the gluon jet. If this system is so small that no break ($q_1\bar{q}_1$ pair creation) will take place in it, i.e. that the first rank meson will be built up directly by the q quark, we are effectively in a $q\bar{q}$ situation. If one break would take place, we expect the resulting change of event shape still to be unnoticeable. Therefore we choose to demand two or more breaks in each leg for a bona fide $q\bar{q}g$ event. Taking $m_a \sim 0.7$ GeV to be an "average" meson mass and $m_q + \frac{1}{2} m_a$ (with m_q the constituent quark mass, see section 6a) to be the mass of the meson built up from the endpoint q quark, an estimate including an average relative motion of the mesons gives

$$M_{q_{\frac{1}{2}}g} \gtrsim m_q + \frac{5}{2} m_a \qquad (21)$$

as a suitable cut. Since

$$M^2_{q\frac{1}{2}g} = m_q^2 + \frac{1}{2} E_{cm}^2 (1-x_2) \qquad (22)$$

we obtain the cut

$$x_2 < 1 - \frac{5m_q (5m_q + 4m_q)}{2 E_{cm}^2} \qquad (23)$$

and a corresponding cut on x_1 .

To find a suitable expression for the weak gluon cut, we regard the event in a frame where the q and $\bar{q}$ go out in opposite directions and the g goes out perpendicularly to them. If the gluon is weak in that frame, it will rapidly lose its energy and only remain as a transverse excitation on the $q\bar{q}$ string by the time the soft fragmentation sets in, giving a slightly increased average $p_\perp$ but otherwise no significant effects. From our knowledge of $\Gamma(\sim\tau^2)$ in $q\bar{q}$ systems and remembering that the gluon loses energy twice as fast as a quark, we may choose the cut

$$E_3'^2 \gtrsim 4\ GeV^2 \approx 8m_q^2 \qquad (24)$$

using the prime to denote energies in this frame. To obtain the form of the cut in the CM frame, we note that for $m_q = 0$

$$E_3'^2 = \frac{(2E_1'E_3')(2E_2'E_3')}{(4E_1'E_2')} =$$

$$= \frac{M^2_{qg} M^2_{\bar{q}g}}{M^2_{q\bar{q}}} = \frac{(1-x_2)(1-x_1)}{(1-x_3)} E_{cm}^2 \qquad (25)$$

For $m_q \neq 0$ the exact expression will become more complicated without adding anything significantly new, so we will use the cut

$$\frac{(1-x_1)(1-x_2)}{(1-x_3)} > \frac{8m_q^2}{E_{cm}^2} \qquad (26)$$

for all m_q .

With these two cuts a relative $q\bar{q}g$ event rate is obtained which is higher than the one in refs. [3,4]. The difference is however not very important for practical purposes, since the $q\bar{q}g$ events included by us but not in refs. [3,4] in general are almost two-jet like.

With these two cuts we obtain a separation between $q\bar{q}$ and $q\bar{q}g$ events. For $m_q \approx 0$ we may express the allowed region within the cuts A_γ using the single parameter γ

$$\gamma = \frac{8m_q^2}{E_{cm}^2} \approx \left(\frac{2\,GeV}{E_{cm}}\right)^2 \qquad (27)$$

$$A_\gamma \begin{cases} 2\gamma \leq x_i \leq 1-2\gamma \qquad i = 1,2 & (28a) \\ (1-x_1)(1-x_2) > \gamma(1-x_3) = \gamma(x_1+x_2-1) & (28b) \end{cases}$$

Using e.g. Monte Carlo methods we may now for different γ calculate

$$I(\gamma) = \frac{2}{3} \int_{A_\gamma} \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}\, dx_1\, dx_2 \qquad (29)$$

which to a good approximation can be parametrized by an expression

$$I(\gamma) = a + b \cdot (-\ln \gamma)^c \qquad (30)$$

According to eqs. (19) and (20) the probability for a $q\bar{q}g$ event within the given cuts is

$$P_{q\bar{q}g} = \frac{\alpha_s/\pi}{1 + \alpha_s/\pi} \cdot I(\gamma) \qquad (31)$$

where α_s is the running coupling constant

$$\frac{\alpha_s}{\pi}(E_{cm}) = \frac{12}{(33 - 2n_f) \ln (E_{cm}^2/\Lambda^2)} \qquad (32)$$

e.g. with the number of flavours $n_f = 5$ and $\Lambda = 0.5$ GeV [4]. As it stands, $P_{q\bar{q}g}$ is increasing with the energy and will eventually become larger than 1. This is of course due to the neglect of terms of higher order in α_s [18]. Recognizing this basic limitation to our approach, we will adopt an algorithm (without any deeper physical meaning) which gives the correct differential cross section, also for $m_q \neq 0$, but where the region A is chosen so that $P_{q\bar{q}g}$ never becomes greater than 1. To do this for a given E_{cm}, we choose a set of cuts characterized by a γ' such that $P_{q\bar{q}g} = 1$ within the area $A_{\gamma'}$. Then a point $(x_1, x_2) \in A_{\gamma'}$ is found according to eq. (19). If this point lies outside the area given by eqs. (23) and (26) or outside the kinematically allowed region for massive quarks

$$\frac{(1-x_1)(1-x_2)(1-x_3)}{x_3^2} \geq \frac{m_q^2}{E_{cm}^2} \qquad (33)$$

we will consider the event to be a $q\bar{q}$ one. Also, for massive quarks the correct cross section is [19,20].

$$\frac{d\sigma_{q\bar{q}g}}{dx_1 dx_2} = \sigma_0 \frac{\alpha_s}{\pi} \frac{2}{3} \left\{ \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)} \right.$$

$$- \frac{4m_q^2}{E_{cm}^2}\left(\frac{1}{1-x_1} + \frac{1}{1-x_2}\right) - \frac{2m_q^2}{E_{cm}^2}\left(\frac{1}{(1-x_1)^2} + \frac{1}{(1-x_2)^2}\right)$$

$$\left. - \frac{4m_q^4}{E_{cm}^4}\left(\frac{1}{1-x_1} + \frac{1}{1-x_2}\right)^2 \right\} =$$

$$= \left(\frac{d\sigma_{q\bar{q}g}}{dx_1 dx_2}\right)_{m_q=0} \cdot f_{q\bar{q}g}\left(x_1, x_2, \frac{4m_q^2}{E_{cm}^2}\right) \qquad (34)$$

where $f_{q\bar{q}g} \leq 1$. Hence the introduction of the correct matrix element may be considered as a simple weighting, with probability $1 - f_{q\bar{q}g}$ giving a $q\bar{q}$ event. The points (x_1, x_2) not rejected above we consider to characterize genuine $q\bar{q}g$ events.

4c. An event generator

In (off-resonance) e^+e^- annihilation the different quark flavours are, according to QED, produced with relative probabilities [20]

$$P_{q\bar{q}} + P_{q\bar{q}g} \propto e_q^2 \left(1 + \frac{2m_q^2}{E_{cm}^2}\right) \sqrt{1 - \frac{4m_q^2}{E_{cm}^2}} \qquad (35)$$

where e_q is the quark charge. Immediately above a quark

threshold, higher order QCD effects will introduce major corrections, giving a higher probability for the production of the new quark than indicated above, but with large fluctuations.

For each flavour the procedure outlined in the previous section will give the probability for a $q\bar{q}$ or a $q\bar{q}g$ event, in the latter case characterized by x_1 and x_2, according to the QCD matrix element. In sections 3 and 4a the theory for the soft fragmentation in the different cases is described. Only the orientation of the event remains to be discussed.

Take the e^+ and e^- to be coming in along the $\pm z$ axis, with transverse polarizations in the x direction P^+ and P^-, respectively. A $q\bar{q}$ event then is characterized e.g. by the polar (θ) and azimuthal (φ) angles of the outgoing quark. A $q\bar{q}g$ event may be specified by these two angles for one of the partons, which we will take to be the q or the $\bar{q}$, whichever is the fastest, and an angle χ between the $-z$ axis and the (slow) $\bar{q}(q)$ around the axis defined by the (fast) $q(\bar{q})$ seen from the direction of the $q(\bar{q})$. In terms of these three angles and $P = P^+P^-$ we may write [21,22]

$$
\begin{aligned}
(2\pi)^2 \frac{d^3\sigma}{d(\cos\theta)\,d\varphi\,d\chi} = \frac{3}{8}\left(1+\cos^2\theta + P\sin^2\theta\cos 2\varphi\right)\sigma_U \\
+ \frac{3}{4}\left(1 - P\cos 2\varphi\right)\sin^2\theta\ \sigma_L \\
+ \frac{3}{4}\left\{\left(\sin^2\theta + P\cos 2\varphi\,(1+\cos^2\theta)\right)\cos 2\chi \right. \\
\left. - 2P\sin 2\varphi\cos\theta\sin 2\chi\right\}\sigma_T \\
- \frac{3}{\sqrt{2}}\left\{\left(1 - P\cos 2\varphi\right)\cos\theta\cos\chi \right. \\
\left. + P\sin 2\varphi\sin\chi\right\}\sin\theta\ \sigma_I \qquad (36)
\end{aligned}
$$

For $q\bar{q}g$ events the σ's should be thought of as differential cross sections $d\sigma/dx_1\,dx_2$. The expressions are rather tedious [20] so we won't write them out here, but with known x_1 and x_2 the σ's are easily calculated. The θ, φ and χ angles may then be found in accordance with eq.(36).

5. Three-gluon jet systems

For heavy $J^{PC} = 1^{--}$ resonances the dominant decay modes are expected to be three-gluon and gluon-gluon-photon decays. Decays via a virtual photon into e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, $q\bar{q}g$ etc. are also important, but since these decays are of the same character as seen off-resonance, no new model is necessary in this case. Deviations from phase space models and hints at a three jet structure have been observed in Υ decays [23], but the Υ mass is on the low side for comparisons with three-gluon jet models really to be meaningful. With the discovery of a "toponium" $(t\bar{t})$ resonance, however, a visible three-jet structure would be expected.

In ggg decays we expect the string pieces between the gluons to form an expanding triangle with the gluons at the corners [7]. Using the experience gained in the $q\bar{q}g$ case, the model for ggg fragmentation is easily formulated. For a given geometry characterized by energy fractions $x_i = 2E_{gi}/E_{cm}$, $i=1,2,3$, the energies $W_{\pm}^{(i)}$ and angles α_i of the three systems, each containing half the energy of two gluons, are easily calculated. A first rank meson is formed at each corner,

precisely as outlined for the gluon corner in $q\bar{q}g$ fragmentation, and the remaining energy goes into three $q\bar{q}$ systems which then fragment further, independently of each other.

The matrix element for $q\bar{q} \to ggg$ is (in lowest order) [24]

$$\frac{1}{\sigma}\,\frac{d\sigma}{dx_1\,dx_2} = \frac{1}{\pi^2 - 9}\left\{\left(\frac{1-x_1}{x_2\,x_3}\right)^2 + \left(\frac{1-x_2}{x_1\,x_3}\right)^2 + \left(\frac{1-x_3}{x_1\,x_2}\right)^2\right\} \qquad (37)$$

This is a well-defined expression, without the kind of singularities encountered in the $q\bar{q}g$ matrix element. From a practical point of view we will however still have problems when two gluons lie very close to each other. Hence, for each subsystem consisting of two half gluons, we require it to have an invariant mass so large that, after subtracting the energy that is to go into the mesons at the two adjacent corners, enough energy is left to give at least a further two mesons. This corresponds to

$$M^2_{\frac{1}{2}g\frac{1}{2}g} \gtrsim 3.5\, m_2 \approx 2.5\ GeV \qquad (38)$$

which may be rewritten as

$$x_i < 1 - \left(\frac{7\,m_2}{E_{cm}}\right)^2 \qquad i = 1, 2, 3 \qquad (39)$$

In case this condition is not fulfilled, there still is a definite three-gluon colour structure, but two gluons lie so close that they effectively give a single, somewhat broader, jet. Hence we can allow the ggg system to fragment as were it

a two-gluon jet system (i.e. into two first rank mesons and two remaining $q\bar{q}$ systems).

Another process is $q\bar{q} \to gg\gamma$, obtained by replacing a gluon in $q\bar{q} \to ggg$ by a photon, which has the same normalized differential cross section as in eq.(37) above if e.g. x_3 is taken to refer to the photon. The relative rate is [24]

$$\frac{\sigma_{gg\gamma}}{\sigma_{ggg}} = \frac{36}{5} e_q^2 \frac{\alpha_{em}}{\alpha_s} \qquad (40)$$

where the electromagnetic coupling constant $\alpha_{em} \approx 1/137$.

The fragmentation of the two-gluon system is best studied in the CM frame of the two gluons. For invariant masses $M_{gg} > 7m_a \approx 5$ GeV the two-gluon jet model may be used, while between 1 and 5 GeV we use a phase space model (see section 6d). Below 1 GeV we do not attempt at a description, but even up to 3 GeV, say, the behaviour could well be modified by the existence of glueballs [25], a problem which is not considered here.

As in the case of $q\bar{q}$ and $q\bar{q}g$ events, the orientation of ggg and $gg\gamma$ events may be described in the form of eq. (36), given the relevant differential cross sections [24].

6. Particle decays

6a. Quarks and particles

In this work we include six quarks, u , d , s , c , b , and t , the latter still not discovered. The masses of these quarks are not well defined, but fortunately the choice of quark masses is

not critical for most applications in our program. For the calculation of heavy meson masses and for quark masses appearing in cuts or in matrix elements we introduce "constituent" quark masses

$$m_u = m_d = 0.3 \text{ GeV}, \quad m_s = 0.5 \text{ GeV},$$
$$m_c = 1.6 \text{ GeV}, \quad m_b = 5.0 \text{ GeV}, \quad m_t = 20.0 \text{ GeV}$$

In the matrix element weighting of eqs. (5) and (8) in the LU model we feel that "current algebra" quark masses should be used instead; since again the exact values are not critical, we simply subtract 0.275 GeV from the masses above in this case. The gluon is always taken to be massless.

The pseudoscalar and vector multiplets in the six quark model are used, including the not yet seen pseudoscalars [26]

$$B_u^- = b\bar{u}, \quad B_d^0 = b\bar{d}, \quad B_s^0 = b\bar{s}, \quad B_c^- = b\bar{c},$$
$$T_u^0 = t\bar{u}, \quad T_d^+ = t\bar{d}, \quad T_s^+ = t\bar{s}, \quad T_c^0 = t\bar{c}, \quad T_b^+ = t\bar{b},$$
$$\eta_b = b\bar{b}, \quad \eta_t = t\bar{t}$$

and vectors

$$B_u^{*-}, \ldots, T_u^{*0}, \ldots, \phi_t = t\bar{t}.$$

The masses of the B and T mesons have been constructed from the constituent quark masses above, adding a fixed spin term to give a small ($< m_\pi$) mass splitting between the pseudoscalars and the vectors. The $t\bar{t}$ particle masses have been chosen to obtain the expected distance between the toponium resonance and the threshold for free top production [27].

The leptons of the e , μ and τ families are included in the list of possible decay products, as is the photon. We will also consider K_S^0 and K_L^0 as separate particles, coming from the "decay" of K^0 and $\bar{K}^0$.

6b. Strong and electromagnetic decays

The decays of mesons containing the "ordinary" u , d and s quarks into two or three particles are known and branching ratios may be found in ref. [28]. We assume that the momentum distributions are given by phase space [9,29], except for ω and φ decaying into $\pi^+\pi^-\pi^0$. Here a matrix element of the form

$$|M|^2 \propto |\bar{p}_{\pi+} \times \bar{p}_{\pi-}|^2 \qquad (41)$$

is used, where $\bar{p}_{\pi^\pm}$ are the momenta in the rest frame of the ω and φ , respectively [8].

The B^* and T^* mesons are assumed to decay electromagnetically only. These decays, $B^* \to B\gamma$ and $T^* \to T\gamma$, and also $D^* \to D\pi$, $D^* \to D\gamma$ and $F^* \to F\gamma$ [2], are treated in the same way as other two-particle decays.

6c. Weak decays of heavy mesons.

The weak decay of a meson $Q\bar{q}$ containing the heavy quark Q may (neglecting QCD corrections) go either as a "free" quark decay

$$Q\bar{q} \to q_1\bar{q}_2 q_3\bar{q} \quad \text{or} \quad l\nu_l q\bar{q} \qquad (42)$$

or via quark annihilation

$$Q\bar{q} \rightarrow q_1\bar{q}_2 \quad \text{or} \quad l\nu_l \tag{43}$$

The structure of the weak mixing between the families as described in the Kobayashi-Maskawa model [30] motivates a simplification so that only the decay chain $t \rightarrow b \rightarrow c \rightarrow s$ need be considered in free quark decays. For B and T mesons the relative probabilities for the different processes is calculated by Ali et al. [26], and we use their results here. The semi-leptonic branching ratios for D mesons are experimentally known [31], while the picture is not fully clear for F and hadronic D decays, so that "educated guesses" have to be made.

The quarks produced in the primary decay interact in the final state so that only hadrons come out. The momenta of the leptons in semileptonic decays are determined by the primary decay matrix element, but this is not so for the hadrons. We expect that the quarks stretch out colour force fields between them in a way similar to quark jets in e^+e^- events. Quark-antiquark pairs can be produced in these fields and combine into hadrons.

We know that the particle distributions in e^+e^- events below a total energy $\sim$6 GeV are fairly well reproduced by a phase space model. For this reason we do not expect jet-like events in c and b quark weak decays, in particular in view of the fact that in most cases more than one quark-antiquark pair share the available energy. Depending on the actual mass of

the top quark, multijet structures may be visible in t decays, but if the t quark is to be found in the PETRA and PEP energy range ($m_t \lesssim 20$ GeV) the deviations from phase space will probably not be large, keeping in mind that a large fraction of the available energy is taken by the B meson. At higher energies it would be possible to simulate the final state jets with one or two $q\bar{q}$ jet systems, each decaying as described in chapter 3, using suitable frames of reference.

For nonleptonic decays we expect the average multiplicity to grow logarithmically with the available energy, with somewhat more particles in free quark decays (eq. (42)). Hence we will assume

$$< n > = \frac{n_o}{2} + c_1 \ln\left(\frac{m}{c_2}\right) = \frac{n_o}{2} + c \qquad (44)$$

where m is the mass of the decaying meson and n_o is the number of $q\bar{q}$ pairs in the primary decay, i.e. 1 or 2 . The constants c_1 and c_2 should be determined experimentally. While waiting for more data we use $c_1 = 1.8$ and $c_2 = 0.9$ GeV , which is consistent with observed charged multiplicities for D^0 and D^+ decays [31]. For convenience we use a Gaussian multiplicity distribution of the form

$$f_n(n)\, dn \propto e^{-\left(n - \frac{n_o}{2} - c\right)^2 / 2c}\, dn \qquad (45)$$

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

Once the multiplicity n of a decay has been determined, our model gives the flavour of the mesons in a way very similar to the $q\bar{q}$ jet system model of chapter 3. Consider e.g. a weak decay giving four primary quarks q_1, $\bar{q}_2$, q_3, and $\bar{q}$. A pair $q_4\bar{q}_4$ is now created, with equal probability in either of the four colour fields, one associated with each quark. The pair is pulled aparat to give a meson, either $q_1\bar{q}_4$, $q_4\bar{q}_2$, $q_3\bar{q}_4$ or $q_4\bar{q}$, leaving behind a new state with four quarks. This procedure is iterated $n-2$ times, the final two mesons being obtained by a random combination of the quarks then left. The mesons formed according to this quark jet picture are then, following the arguments above, given momenta according to phase space only.

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

$$H \to h l \nu_l \qquad l = e, \mu, \tau \tag{46}$$

Here H is the decaying heavy meson and h is the product, a pseudoscalar or vector meson. Phase space only would not suffice here, since the $e^{\pm}$ and $\mu^{\pm}$ will give rise to energy spectra reflecting the primary decay, little disturbed by final state interactions and secondary decays, contrary to the case for hadrons. Instead the momentum distribution is determined by a matrix element [32]

$$|M|^2 \propto (p_H p_{l+})(p_{\nu_l} p_h) \qquad (47a)$$

if H contains a heavy quark Q with charge + 2/3 and

$$|M|^2 \propto (p_H p_{\bar{\nu}_l})(p_{l-} p_h) \qquad (47b)$$

if Q has charge - 1/3 .

6d. τ and light "onia" decays

The hadronic decays of the heavy τ lepton are treated as the hadronic decays of heavy mesons, except that the ν_τ is included in n_o and n . No particular care is thus taken with the ν_τ energy spectrum. For the leptonic decays, we use the relevant matrix element

$$|M|^2 \propto (p_{\tau^-} p_{\bar{\nu}_l})(p_{l-} p_{\nu_\tau}) \qquad l = e, \mu \qquad (48)$$

The ψ and η_c (and also T and η_b) decay predominantly via gluons, but the energies are so low that the model outlined in section 5 is not relevant. We will instead use a simple phase space model, with the same particle generation scheme as outlined for heavy meson hadronic decays. The original $q\bar{q}$ pair needed in that formalism is taken to be $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ in the usual proportions (2:2:1), so that particle flavours are distributed in the same way as in the ggg and gg event models. The average multiplicity is not necessarily the same as in eq. (44), in fact we choose (n_o=1)

$$c = c_1 \ln\left(\frac{m}{c_2}\right) + c_3 \qquad (49)$$

with c_1 and c_2 as above and $c_3 = 2$ to obtain a smooth joining to the gg model. For the vector mesons the leptonic $\ell^+\ell^-$, $\ell = e,\mu,\tau$, channels are also included [2].

7. The program components

Below we describe the different elements available in our program, the "physics" subroutines that contain our jet generation recipes and matrix element treatment, and the "service" procedures handling particle decays and other tasks common to the different jet models. The information stored in the commonblocks, in particular the parameters of the models, is also outlined. We close by giving some advice on the use of the program.

The program, which is listed in Appendix 1, is written in FORTRAN 77. The only nonstandard feature is our use of a random number generator RANF giving numbers R with uniform probability distribution in the interval $0 < R < 1$. If a random generator is available under another name, a function RANF calling this generator should be created. For LIST we assume a standard output file with logical file number 6 as well.

The "physics" subroutines can be divided into two hierarchies, dismissing the simple DECGEN subroutine. In one group, QJET and GJET may be used to generate single quark and gluon jets, respectively, while MULJET (via calls to QJET and GJET) is meant to generate systems of independently fragmenting jets, without any demands on exact conservation of energy, momentum or flavour. In the bottom of the second hierarchy, where these

properties are conserved exactly, the QQJET is used to generate $q\bar{q}$ systems, and is also heavily used in internal calls to generate $q\bar{q}$ subsystems. QQGJET and GGGJET may be used to generate $q\bar{q}g$ and ggg (or gg) systems, respectively, for given parton momenta. The matrix elements for $e^+e^- \to q\bar{q}g$ or $q\bar{q}$ and $1^{--} \to ggg$ or $gg\gamma$ are implemented in QQGGEN and GGGGEN, respectively, which use the relevant subroutines above to generate the corresponding event. In these subroutines the events have a standard orientation in the xz plane; the correct angular dependence may be obtained by an ANGGEN call after the event has been generated. Finally, in EVTGEN, a call to QQJET, QQGGEN or GGGGEN is combined with an ANGGEN call, to give the most versatile subroutine.

An often recurring argument in the subroutines is IFL, the quark flavour, with code 1=u, 2=d, 3=s, 4=c, 5=b, 6=t, -1=$\bar{u}$, -2=$\bar{d}$, -3=$\bar{s}$, -4=$\bar{c}$, -5=$\bar{b}$ and -6=$\bar{t}$. Sometimes we will also use 0=g and 7 and 8 for different quark mixtures, but these are not valid arguments except when explicitly stated. We will often refer to IFL as the "quark" flavour and -IFL as the "antiquark" one. This terminology is used only to indicate relative flavour ordering (u is the antiquark to $\bar{u}$ etc.) except in the definition of K(I,1), where an absolute distinction is made (quarks are those with IFL > 0).

Other usual arguments are EBEG, the initial energy of a single quark or gluon jet, around which the energy of the physical jet generated will be distributed, and ECM, the energy of a jet

system in the center of mass, which will be exactly conserved. All energies, momenta and masses are given in GeV (c=1).

7a. The "physics" subroutines

SUBROUTINE DECGEN (KI2)

Purpose: To generate the decay chain of a given particle.

Argument: KI2 is the particle code according to Table 1.

Remark: The decaying particle is taken to be at rest.

SUBROUTINE QJET(IFL,EBEG)

Purpose: To generate a single quark jet.

Arguments: IFL is the flavour of the quark,

EBEG is its initial energy.

Remark: The quark is taken to be going out in the +z direction.

SUBROUTINE GJET(EBEG)

Purpose: To generate a single gluon jet.

Argument: EBEG is the initial energy of the gluon.

Remark: The gluon is taken to be going out in the +z direction.

SUBROUTINE MULJET(IPZCUT)

Purpose: To generate a system of quark and gluon jets with a series of QJET and GJET calls, i.e. with the jets taken to be independently fragmenting entities.

Argument: IPZCUT is the cut type used in EDIT to obtain finite jets (IPZCUT = 1 or 2).

Remark: The number of partons NC and the flavour KC(IC) (IFL code for quarks, 0 for gluons) and momentum PC(IC,J), J=1,2,3, for each of the partons must be given explicitly in the commonblock JET before the call can be made.

SUBROUTINE QQJET(IFL,ECM)

Purpose: To generate a quark-antiquark jet system.

Arguments: IFL is the flavour of the quark,

ECM is the energy of the system.

Remark: The event is studied in the CM frame, with the quark going out in the +z direction.

SUBROUTINE QQGJET(IFL,ECM,X1,X2)

Purpose: To generate a quark-antiquark-gluon jet system.

Arguments: IFL is the flavour of the quark,

ECM is the energy of the system,

X1 is twice the energy fraction taken by the quark,

X2 is ditto for the antiquark.

Remark: The event is studied in the CM frame, with the xz plane as event plane, the quark going out in the +z direction and the antiquark having $p_x > 0$.

SUBROUTINE QQGGEN(IFL,ECM)

Purpose: To generate a quark-antiquark or quark-antiquark-gluon jet system according to the matrix element given by QCD for e^+e^- annihilation.

Arguments: IFL is the flavour of the quark,

ECM is the energy of the system.

Remarks: The event is oriented as described for QQJET and QQGJET, respectively. For $q\bar{q}g$ events it is assumed that IFL gives the flavour of the fastest quark (i.e. $x_1 > x_2$), so that arguments IFL and -IFL are not equivalent.

SUBROUTINE GGGJET(ECM,X1,X2)

Purpose: To generate a three-gluon or two-gluon jet system.

Arguments: ECM is the energy of the system,

X1 is twice the energy fraction taken by gluon no.1,

X2 is ditto for gluon no. 2,

in particular X1 = X2 = 1 for a two-gluon system.

Remark: The event is studied in the CM frame, with the xz plane as event plane, gluon no. 1 going out in the +z direction and gluon no. 2 having $p_x \geq 0$.

SUBROUTINE GGGGEN(ECM,ICH)

Purpose: To generate a three-gluon or gluon-gluon-photon jet system according to the matrix element given by QCD for 1^{--} "onium" resonance decays.

Arguments: ECM is the energy of the system,

ICH is the charge of the quark giving the resonance, with ICH = 1,2 corresponding to $e_q = \pm \frac{1}{3}, \pm \frac{2}{3}$, respectively (this determines the probability for ggγ events, by choosing ICH = 0 it is possible to generate ggg events only).

Remark: The event is oriented as described for GGGJET; in a ggγ event the photon will replace gluon no. 3.

SUBROUTINE ANGGEN(ECM,POL)

Purpose: To generate the angular orientation of $q\bar{q}$, $q\bar{q}g$, ggg and ggγ (the latter two from 1^{--} resonance decays) e^+e^- annihilation events according to QCD (and QED).

Arguments: ECM is the energy of the system,

POL describes the polarization of the incoming e^+ and e^- , either POL = P^+P^- where $P^\pm$ are the transverse polarizations of $e^\pm$, respectively [21], or POL = $-P_\perp^2/(1 - P_{||}^2)$ where it is assumed that the spin $\bar{s}(e^+) = -\bar{s}(e^-)$ and $P_\perp$ and $P_{||}$ are the transverse and longitudinal polarizations, respectively [22].

Remarks: The event is studied in the CM frame, with the $e^{\pm}$ taken to be coming in along the $\pm$ z axis, respectively, and with transverse polarizations (if any) in the x direction. It is assumed that no ROTBST calls are made by the user between the generation of the jet system and the ANGGEN call.

SUBROUTINE EVTGEN(IFL,ECM,IMODE)

Purpose: To present a coherent hadronic e^+e^- annihilation event generator using the subroutines above for $e^+e^- \to \gamma \to q\bar{q}$ or $q\bar{q}g$, optionally with a mixing q=u,d,s,c,b, or t according to QED, and for $e^+e^- \to 1^{--} \to ggg$ or $gg\gamma$.

Arguments: IFL is the flavour, 0 denotes a 1^{--} resonance, 1-6 the separate quark flavours, 7 a QED mixture of u,d,s,c,b, and 8 ditto with t as well,

ECM is the energy of the system,

IMODE is for ggg and ggγ events the charge of the quark giving the resonance, 1 for $e_q = \pm \frac{1}{3}$ and 2 for $e_q = \pm \frac{2}{3}$ (cf. ICH for GGGGEN) while otherwise it is used to indicate whether one wants to generate $q\bar{q}$ events only, IMODE = 0, or a mixture of $q\bar{q}$ and $q\bar{q}g$ events according to the first order QCD matrix element, IMODE = 1.

Remark: The event is oriented as described for ANGGEN, with unpolarized incoming $e^{\pm}$ (this may be changed with the parameter PAR(2) in the commonblock DATA1).

7b. The "service" procedures

SUBROUTINE EDIT(ITHROW,IPZCUT,PZMIN,PMIN)

Purpose: To exclude unstable or undetectable particles or apply cuts on p_z or p.

Arguments: ITHROW tells which particle types are to be thrown away, if 0 all are kept (except for cuts on p_z or p), if 1 unstable particles are thrown away,

if 2 neutrinos are also thrown away, if 3 K_L^0 and γ are thrown away as well, leaving only charged stable particles (assuming default values for the IDB vector),

IPZCUT gives the type of cut on p_z to be used, if 0 no cut is made, if 1 all particles with $p_z <$ PZMIN are thrown away, if 2 primary mesons with $p_z <$ PZMIN are thrown away together with their decay products, irrespectively of the p_z of these products,

PZMIN is minimum particle p_z as used above,

PMIN indicates that all particles with momentum $p <$ PMIN should be thrown away (note that if PMIN = 0. no cut is made).

SUBROUTINE ROTBST(THETA,PHI,BETAX,BETAY,BETAZ)

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

Arguments: THETA, PHI are standard polar coordinates θ, φ giving the direction of a particle initially along the +z axis,

BETAX,BETAY,BETAZ gives the direction and size $\tilde{\beta}$ of a Lorentz boost, such that a particle initially at rest will have $\tilde{p}/E = \tilde{\beta}$ afterwards.

SUBROUTINE LIST

Purpose: To give a list of all particles generated, including their origin, momentum, energy, and mass. Also, where applicable, to give a list of the original partons.

Arguments: None.

Remarks: The outgoing partons are listed before the particles. For ggg events three or two jets may be listed, the latter if the condition in eq. (39) is not fulfilled. For ggγ events two or none jets may be listed, the latter if $M_{gg} < 5$ GeV, in which case a "particle" GPS (K(I,2) = 5) is used to represent the initial state of the gluon phase space model. For jets, origins U,D,...,UB,DB,...,GLU represent u,d,...,$\bar{u}$,$\bar{d}$,...,g jets, respectively. For particles, UD represents a particle coming from a $u\bar{d}$ quark pair in the string, etc., PRIM denotes a primary particle of unspecified flavour (the γ in ggγ events, the particle in DEGGEN calls, etc.) and numbers represent decay products coming from the decay of the particle with that I number (after an EDIT call, when 0, a decay product of unknown origin). (Cf. the example in Appendix 2.)

SUBROUTINE TMASS(TM)

Purpose: To change the top quark mass and the top meson masses.

Argument: TM is the top quark mass.

FUNCTION KPART(KI1,ISPIN)

Purpose: Given a quark-antiquark flavour and the spin, a particle is constructed, with due allowance for $u\bar{u}$-$d\bar{d}$-$s\bar{s}$ flavour mixing.

SUBROUTINE PTDIST(PX,PY,SIGMA)

Purpose: To give p_x and p_y for a quark pair according to two independent Gaussian distributions, each with mean 0 and standard deviation SIGMA/$\sqrt{2}$.

FUNCTION ZDIST(IFL,ZMIN,ZMAX)

Purpose: To generate a z between given limits according to the different scaling functions.

SUBROUTINE DECAYS

Purpose: To administrate the decay chains of all primary mesons.

SUBROUTINE DECAY(IPD,I)

Purpose: To allow the particle in position IPD to decay.

BLOCK DATA

Purpose: To give default values for all particle data and model parameters.

7c. The commonblocks

COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)

Purpose: To give the relevant data about a generated event.

Notation: N is the number of particles generated and stored in the N first rows of the K and P matrices.

K(I,1) describes the origin of the I:th particle; if between 1 and 36 it denotes a primary meson with K(I,1) = 6 · IFL(quark) - IFL(antiquark) - 6, if 38 it denotes a primary particle of unspecified flavour, if negative it represents a product coming from the decay of the particle stored in position -K(I,1), if 0 it is again a decay product, but with unknown origin.

K(I,2) gives the particle code according to Table 1.

P(I,1),P(I,2),P(I,3) give the particle momentum (p_x, p_y, p_z).

P(I,4) gives the particle energy E.

P(I,5) gives the particle mass m.

NC is the number of primary partons (quarks and gluons) generated.

KC(IC) gives the flavour of the IC:th parton (1-6 for quarks, (-1)-(-6) for antiquarks, 0 for gluons).

PC(IC,1),PC(IC,2),PC(IC,3) give the parton momentum.

PC(IC,4) gives the parton energy.

COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)

Purpose: To make available the most frequently used parameters and data.

Notation: IST (by default 0) is used mostly in internal calls, and should normally not be touched, except that the value -1 may be used to generate the partons only in QQGGEN, GGGGEN and EVTGEN calls.

IFR (by default 2) is used to choose fragmentation scheme, for 1 it gives an "extended Field-Feynman" and for 2 it gives the "Lund model".

PUD (by default 0.4) is the fraction of $u\bar{u}$ quark-antiquark pairs created in the field, taken to be the same for $d\bar{d}$ pairs, with 1-2 PUD the probability for $s\bar{s}$ pairs.

PS1 (by default 0.5) is the fraction of primary mesons that have spin 1, 1-PS1 is the fraction with spin 0.

SIGMA (by default 0.35 GeV) is the standard deviation of the transverse momentum (p_x and p_y components) of primary mesons formed in the field.

QMAS (by default 0.3,0.3,0.5,1.6,20.0,0.275) is for components 1-6 the constituent quark masses assumed for u,d,s,c,b, and t, while the current algebra masses are represented by subtracting the seventh component from the above.

PMAS gives particle masses (see Table 1).

PAR(1) (by default 0.1 GeV) gives the remaining W_+, below which the generation scheme in QJET is stopped.

PAR(2) (by default 0) is used to represent polarized $e^{\pm}$ beams in EVTGEN calls and corresponds to the argument POL in ANGGEN calls.

PAR(3),PAR(4) (by default 1.,0. GeV) give optional maximum quark thrust and minimum gluon energy cuts, respectively, for the $q\bar{q}g$ matrix element.

PAR(5) (by default 0.0073) gives $\alpha_{em} \approx 1/137$.

PAR(6),PAR(7) (by default 5., 0.5 GeV) give the strong coupling constant

$$\alpha_s/\pi = 6/((33 - 2 \cdot PAR(6)) \cdot \ell n(E_{cm}/PAR(7))) .$$

PAR(8) (by default 0.005 GeV) gives minimum total kinetic energy allowed in decays.

PAR(9) (by default 0.7 GeV) represents an average (transverse) meson mass used in various matrix element cuts.

PAR(10) (by default 0.9) represents the maximum cuts allowed for the z range in QQJET.

PAR(11),PAR(12) (by default 2.2 GeV, 1.4 GeV) are used to define the stopping point in the $q\bar{q}$ generation scheme for IFR=1 and 2, respectively.

PAR(13),PAR(14) (by default 0.39,0.27) give the probability for "reverse" relative rapidity ordering of the final two mesons for IFR=1 and 2, respectively.

PAR(15),PAR(16),PAR(17) (by default -0.8839, 0.2250, 2.355) give a parametrization of the $q\bar{q}g$ matrix element integral $I(\gamma)$

$$I(\gamma) = PAR(15) + PAR(16) \cdot (-\ell n\gamma)^{PAR(17)} .$$

PAR(18)-PAR(25) are unused.

COMMON /DATA2/ CZF(6), MESO(36),CMIX(6,2),CHA1(17),CHA2(96)

Purpose: To make available further parameters and data of more specialized occurrence.

Notation: CZF gives the shape of the scaling function in the FF scheme (IFR=1) for the different quark flavours IFL so that, with $c = CZF(IFL)$, $f(z) = 1-c+3c(1-z)^2$ if $0 \leq c \leq 1$ and $f(z) = (1 + |c|)z^{|c|}$ if $c < 0$.

MESO provides a renumbering of the meson flavours.

CMIX gives a parametrization of the $u\bar{u}$-$d\bar{d}$-$s\bar{s}$ flavour mixing for pseudoscalar and vector mesons.

CHA1 contains assorted character strings.

CHA2 contains particle names (see Table 1).

COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)

Purpose: To give all particle decay data and parameters.

Notation: IDB gives the entry point into the particle decay table (see Table 1), in particular if IDB(KI2) = 0 the particle with code KI2 is taken to be stable.

CBR gives cumulative branching ratios for the different decay channels (cf. Table 1).

KDP gives the decay products in the different channels, 0 corresponds to no particle, positive numbers to particle codes and negative ones to quark-antiquark flavours (as explained for K(I,1), but with a - sign, with -37 corresponding to the usual mixture of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$).

CND gives the primary multiplicity distribution in particle decays according to eqs. (44),(45),(49)

$$\langle n \rangle = \text{const} + \text{CND(1)} \cdot \ln(m/\text{CND(2)})(+ \text{CND(3)}) \ .$$

WTCOR gives corrective factors to the weight calculations for multiparticle decays.

7d. General information

After a call to either of the "physics" subroutines, the JET commonblock will contain information about all particle generated in the event, including resonances which subsequently have decayed and, for QJET and GJET, a number of particles with negative p_z. To study some questions this is advantageous,

but often one is only interested in e.g. the charged particles, and in that case an EDIT call may often be used to throw away the unwanted particles.

It is recommended to use LIST to write out a few events in the beginning of a run, in particular if parameters have been given new and unusual values, to get a first check that everything is working as planned.

The generation of the primary partons according to the different matrix elements without the subsequent jet fragmentation can be obtained by putting IST = -1. The soft fragmentation can instead be performed with the help of MULJET, to test the difference between our model and a model with an independent fragmentation of jets. It is also easy to replace gluons with quarks before the MULJET call to test the hypothesis that gluons fragment like quarks.

In all the jets models we recognize two different fragmentation schemes, the Field-Feynman and the Lund ones. The LU scheme is obtained by default, IFR = 2 , while the FF scheme can be obtained by choosing IFR = 1 . Within the FF model we have further parameters, CZF, determining the shape of the scaling functions for the different quarks. By and large the two models give rather similar results, although differences may be found. Notably, the FF scheme with its softer scaling function gives a somewhat higher average multiplicity.

A number of other possibilities to vary basic parameters are provided, but the user is cautioned that some of the parameters are interrelated (the stopping point in the $q\bar{q}$ generation scheme depends slightly on the mean $p_\perp$ for quarks, just to give one example) so that drastic changes should be made only after some thought. Also, if a parameter or an argument is given an erroneous value, the result is often unpredictable.

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Figure captions

Fig. 1 The momentum distribution of mesons in $q\bar{q}g$ events. In Fig. 1a the typical distribution along two hyperbolas is shown, where the hatched areas indicate the broadening coming from differences in mass and $p_\perp$, while in Figs. 1b and 1c the corresponding structures are shown for a weak and a collinear gluon, respectively. Note that for small M_{qg} in the latter case, the leading meson may take a large fraction both of the quark and of the gluon momentum, so that the kinematically allowed region extends beyond the separate parton momenta.

Fig. 2 The kinematics of a $q\bar{q}g$ system, in particular for the formation of the first rank meson $q_1\bar{q}_2$ of the gluon jet. The vectors $\bar{\beta}_q$, $\bar{\beta}_{\bar{q}}$ and $\bar{\beta}_g$ give the velocities $(\bar{p}/E)$ of the outgoing partons and are used to find the α_i and $\bar{\beta}_i$, $i=1,2$. In the same figure we also indicate the conventions adopted for $W_+^{(i)}$, $W_-^{(i)}$ and $p_x^{(i)}$. The $q_1\bar{q}_1$ and $q_2\bar{q}_2$ pairs, which normally are created very close to the gluon corner, are here shown further away to make the figure more legible.

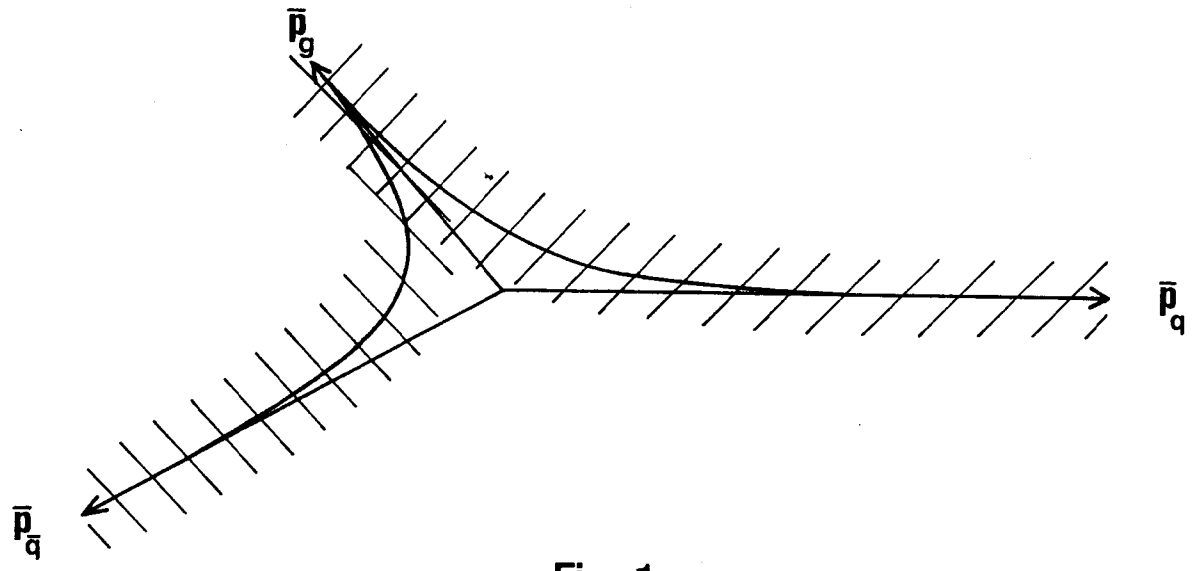

Fig. 1a

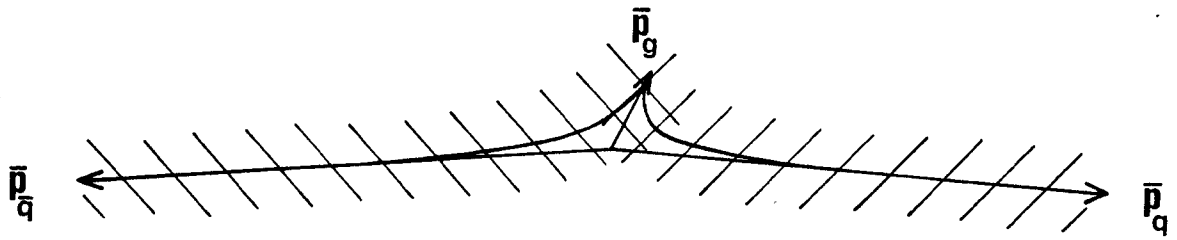

Fig. 1b

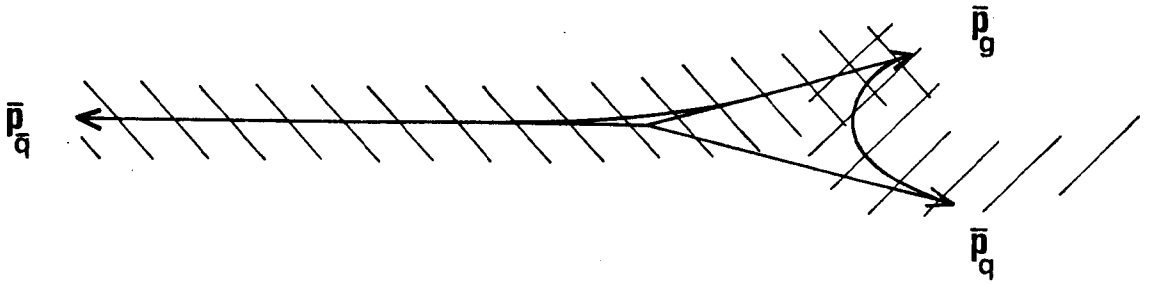

Fig. 1c

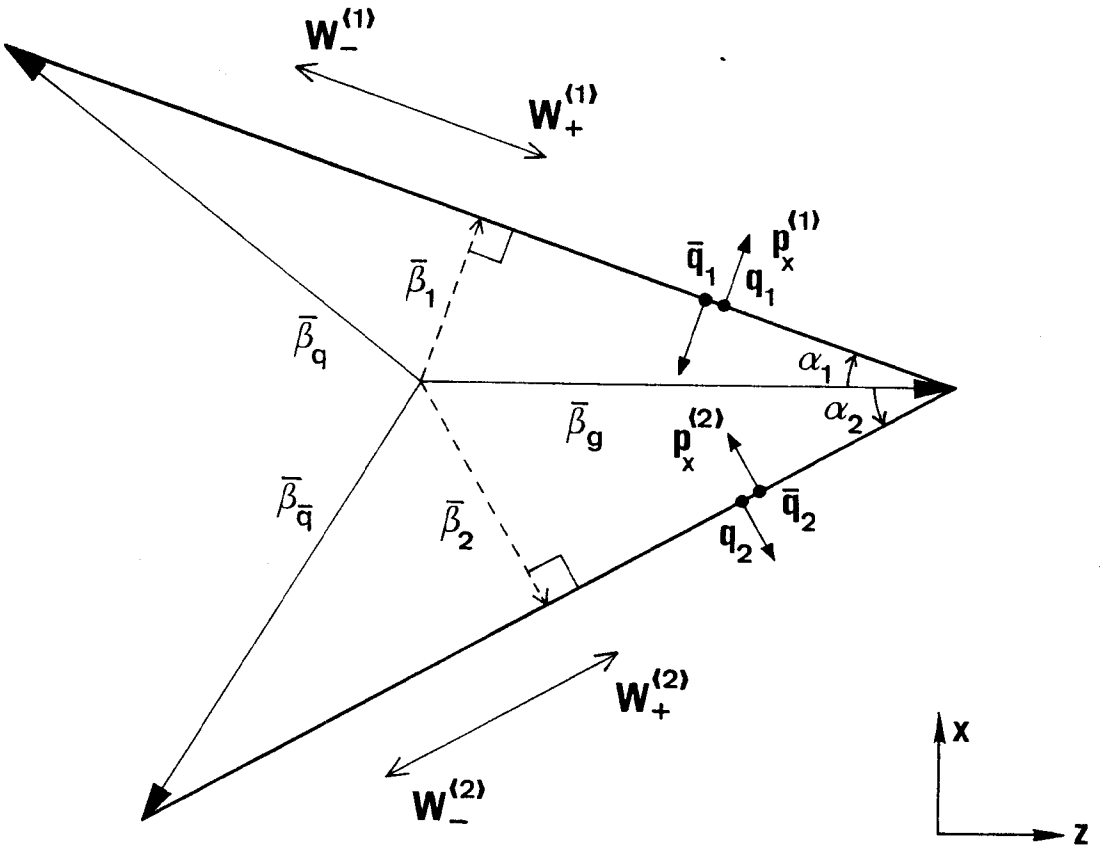
$W_-^{(1)}$
$W_+^{(1)}$
$\bar{\beta}_1$
$\bar{\beta}_q$
$\bar{q}_1$
$p_x^{(1)}$
q_1
α_1
α_2
$\bar{\beta}_g$
$p_x^{(2)}$
$\bar{\beta}_{\bar{q}}$
$\bar{\beta}_2$
$\bar{q}_2$
q_2
$W_+^{(2)}$
$W_-^{(2)}$
X
Z

Fig. 2

Table 1

PARTICLE DATA USED IN THE PROGRAM

K(I,2)		PART	MASS	DECAY PRODUCTS			B.R.	IDC
1	γ	GAMM	.000					
2								
3								
4								
5	(see below)	GPS	.000	*QQ*			100.0	1
6								
7	e^-	E-	.001					
8		E+	.001					
9	ν_e	NUE	.000					
10		NUEB	.000					
11	μ^-	MU-	.106					
12		MU+	.106					
13	ν_μ	NUM	.000					
14		NUMB	.000					
15	τ^-	TAU-	1.782	NUEB	E-	NUT	17.0	2
16		TAU+	1.782	NUMB	MU-	NUT	17.0	3
				NUT	*DU*		66.0	4
17	ν_τ	NUT	.000					
18		NUTB	.000					
19								
20								
21	π^+	PI+	.140					
22		PI-	.140					
23	K^+	K+	.494					
24		K-	.494					
25	K°	KC	.498	KOS			50.0	5
26		KB	.498	KOL			50.0	6
27	D°	DC	1.863	E+	NUE	*SU*	5.0	7
28		DB	1.863	MU+	NUM	*SU*	5.0	8
				UD	*SU*		50.0	9
				SD			40.0	10
29	D^+	D+	1.868	E+	NUE	*SD*	16.0	11
30		D-	1.868	MU+	NUM	*SD*	16.0	12
				UD	*SD*		68.0	13
31	F^+	F+	2.040	E+	NUE	*SS*	10.0	14
32		F-	2.040	MU+	NUM	*SS*	10.0	15
				UD	*SS*		50.0	16
				UD			30.0	17
33	B_u^-	BU-	5.270	NUEB	E-	*CU*	17.0	18
34		BU+	5.270	NUMB	MU-	*CU*	17.0	19
				NUTB	TAU-	*CU*	5.0	20
				DU	*CU*		51.0	21
				SC	*CU*		10.0	22
35	B_d°	BDC	5.270	NUEB	E-	*CD*	17.0	23
36		BDB	5.270	NUMB	MU-	*CD*	17.0	24
				NUTB	TAU-	*CD*	5.0	25
				DU	*CD*		51.0	26
				SC	*CD*		10.0	27
37	B_s°	BSC	5.470	NUEB	E-	*CS*	16.0	28
38		BSB	5.470	NUMB	MU-	*CS*	16.0	29
				NUTB	TAU-	*CS*	5.0	30
				DU	*CS*		48.0	31
				SC	*CS*		10.0	32
				CC			5.0	33
39	B_c^-	BC-	6.570	TAU-	NUTB		7.0	34
40		BC+	6.570	NUEB	E-	*CC*	11.0	35
				NUMB	MU-	*CC*	11.0	36
				NUTB	TAU-	*CC*	3.0	37
				DU	*CC*		34.0	38
				SC	*CC*		7.0	39
				SC			27.0	40

41	T_u^0	TUO	20.270	E+	NUE	*BU*	9.0	41
42		TUB	20.270	MU+	NUM	*BU*	9.0	42
				TAU+	NUT	*BU*	8.0	43
				UD	*BU*		29.0	44
				CS	*BU*		22.0	45
				BD			23.0	46
43	T_d^+	TD+	20.270	E+	NUE	*BD*	12.0	47
44		TD-	20.270	MU+	NUM	*BD*	12.0	48
				TAU+	NUT	*BD*	10.0	49
				UD	*BD*		37.0	50
				CS	*BD*		29.0	51
45	T_s^+	TS+	20.470	E+	NUE	*BS*	12.0	52
46		TS-	20.470	MU+	NUM	*BS*	12.0	53
				TAU+	NUT	*BS*	10.0	54
				UD	*BS*		37.0	55
				CS	*BS*		29.0	56
47	T_c^0	TCO	21.570	E+	NUE	*BC*	9.0	57
48		TCB	21.570	MU+	NUM	*BC*	9.0	58
				TAU+	NUT	*BC*	8.0	59
				UD	*BC*		29.0	60
				CS	*BC*		22.0	61
				BS			23.0	62
49	T_b^+	TB+	24.970	E+	NUE	*BB*	9.0	63
50		TB-	24.970	MU+	NUM	*BB*	9.0	64
				TAU+	NUT	*BB*	8.0	65
				UD	*BB*		29.0	66
				CS	*BB*		22.0	67
				CS			23.0	68
51	π^0	PIO	.135	GAMM	GAMM		98.8	69
				GAMM	E+	E-	1.2	70
52	η	ETA	.549	GAMM	GAMM		38.1	71
				PIO	PIO	PIO	30.0	72
				PI-	PI+	PIO	23.7	73
				GAMM	PI-	PI+	5.1	74
				GAMM	GAMM	PIO	3.1	75
53	η'	ETAP	.958	PI+	PI-	ETA	42.6	76
				PIO	PIO	ETA	23.6	77
				GAMM	RHOO		29.7	78
				GAMM	OMEG		2.1	79
				GAMM	GAMM		2.0	80
54	η_c	ETAC	2.970	*QQ*			100.0	81
55	η_b	ETAB	9.400	*QQ*			100.0	82
56	η_t	ETAT	38.970	*QQ*			100.0	83
57	K_S^0	KOS	.498	PI+	PI-		68.6	84
				PIO	PIO		31.4	85
58	K_L^0	KOL	.498					
59								
60								
61	ρ^+	RHO+	.766	PI+	PIO		100.0	86
62		RHO-	.766					
63	K^{*+}	K*+	.892	KO	PI+		66.7	87
64		K*-	.892	K+	PIO		33.3	88
65	K^{*0}	K*O	.896	K+	PI-		66.7	89
66		K*B	.896	KO	PIO		33.3	90
67	D^{*0}	D*O	2.006	DO	PIO		55.0	91
68		D*B	2.006	DO	GAMM		45.0	92
69	D^{*+}	D*+	2.009	DO	PI+		65.0	93
70		D*-	2.009	D+	PIO		29.0	94
				D+	GAMM		6.0	95
71	F^{*+}	F*+	2.140	F+	GAMM		100.0	96
72		F*-	2.140					
73	B_u^{*-}	BU*-	5.310	BU-	GAMM		100.0	97
74		BU*+	5.310					

75	B_d^{*0}	BD*0	5.310	BD0	GAMM		100.0	98
76		BD*B	5.310					
77	B_s^{*0}	BS*0	5.510	BS0	GAMM		100.0	99
78		BS*B	5.510					
79	B_c^{*-}	BC*-	6.610	BC-	GAMM		100.0	100
80		BC*+	6.610					
81	T_u^{*0}	TU*0	20.310	TU0	GAMM		100.0	101
82		TU*B	20.310					
83	T_d^{*+}	TD*+	20.310	TD+	GAMM		100.0	102
84		TD*-	20.310					
85	T_s^{*+}	TS*+	20.510	TS+	GAMM		100.0	103
86		TS*-	20.510					
87	T_c^{*0}	TC*0	21.610	TC0	GAMM		100.0	104
88		TC*B	21.610					
89	T_b^{*+}	TB*+	25.010	TB+	GAMM		100.0	105
90		TB*-	25.010					
91	ρ^0	RH00	.770	PI+	PI-		100.0	106
92	ω	OMEG	.783	PI-	PI+	PI0	89.9	107
				GAMM	PI0		8.8	108
				PI-	PI+		1.3	109
93	ϕ	PHI	1.020	K+	K-		48.6	110
				K0	KB		35.1	111
				PI+	PI-	PI0	14.7	112
				GAMM	ETA		1.6	113
94	ψ	PSI	3.097	E+	E-		7.0	114
				MU+	MU-		7.0	115
				QQ			86.0	116
95	$\overline{\upsilon}$	UPSI	9.460	E+	E-		3.0	117
				MU+	MU-		3.0	118
				TAU+	TAU-		3.0	119
				QQ			91.0	120
96	ϕ_t	PHIT	39.010	E+	E-		8.0	121
				MU+	MU-		8.0	122
				TAU+	TAU-		8.0	123
				QQ			76.0	124

Comments: The first column gives the particle code, as stored in K(I,2). Names (used e.g. in LIST) and masses (in GeV) are given for all particles. Where applicable, the entries are ordered in particle-antiparticle pairs, so that the customary names (hand-written) and decay data need only be given for the particle. For decay products, the notation *UD* is used to designate a $u\bar{d}$ quark pair which subsequently is hadronized (section 6c), etc., while *QQ* gives a mixture of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ which is used for the gluon phase space model (section 6d). The "particle" no. 5 is used to represent such initial $q\bar{q}$ states in e.g. $gg\gamma$ decays. Finally, branching ratios (in %) and decay channel numbers are also given.

Appendix 1

A listing of the program components.

```
      SUBROUTINE DECGEN(KI2)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
C  ALLOW A PARTICLE AT REST TO DECAY
      NC=0
      K(1,1)=38
      K(1,2)=KI2
      P(1,1)=0.
      P(1,2)=0.
      P(1,3)=0.
      P(1,4)=PMAS(KI2)
      P(1,5)=PMAS(KI2)
      N=1
      CALL DECAYS
      RETURN
      END

      SUBROUTINE QJET(IFL,EBEG)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
C  INITIAL VALUES, USER AND INTERNAL CALLS, RESPECTIVELY
      IF(IST.EQ.0) THEN
      NC=1
      KC(1)=IFL
      PC(1,1)=0.
      PC(1,2)=0.
      PC(1,3)=SQRT(EBEG**2-QMAS(IABS(IFL))**2)
      PC(1,4)=EBEG
      I=0
      IFL1=IFL
      CALL PTDIST(PX1,PY1,(2-IFR)*SIGMA)
      W=PC(1,4)+PC(1,3)
      GAMM=0.
      ELSE
      I=N
      IFL1=K(250,1)
      PX1=P(250,1)
      PY1=P(250,2)
      W=P(250,3)
      GAMM=P(250,5)
      ENDIF
C  GENERATE A QUARK-ANTIQUARK PAIR. FORM A MESON
  100 I=I+1
      IFL2=ISIGN(1+INT(RANF(0)/PUD),-IFL1)
      K(I,1)=6*MAX(IFL1,IFL2)-MIN(IFL1,IFL2)-6
      K(I,2)=KPART(K(I,1),INT(PS1+RANF(0)))
      P(I,5)=PMAS(K(I,2))
C  GENERATE PT AND Z. WEIGHTING IN GAMMA FOR IFR=2
  110 CALL PTDIST(PX2,PY2,SIGMA)
      Z=ZDIST(IFL1,0.,1.)
      PMTS=P(I,5)**2+(PX1+PX2)**2+(PY1+PY2)**2
      IF(IFR.EQ.2) THEN
      QMTS=(QMAS(IABS(IFL2))-QMAS(7))**2+PX2**2+PY2**2
      GAMP=(1.-Z)*(GAMM+PMTS/Z)
      IF(GAMP/(QMTS+GAMP).LT.RANF(0)) GOTO 110
      GAMM=GAMP
      ENDIF
C  FOUR-MOMENTUM FOR MESON. REMAINING FLAVOUR AND MOMENTUM
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      P(I,3)=0.5*(Z*W-PMTS/(Z*W))
      P(I,4)=0.5*(Z*W+PMTS/(Z*W))
      IFL1=-IFL2
      PX1=-PX2
      PY1=-PY2
      W=(1.-Z)*W
C  IF ENOUGH ENERGY LEFT, CONTINUE GENERATION
      IF(W.GT.PAR(1)) GOTO 100
      N=I
      IF(IST.EQ.0) CALL DECAYS
      RETURN
      END

      SUBROUTINE GJET(EBEG)
```

```
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      DIMENSION IFL(2),PX(2),PY(2),Z(2),QMTS(2),GAMM(2)
C   INITIAL VALUES, USER AND INTERNAL CALLS, RESPECTIVELY
      IF(IST.EQ.0) THEN
      NC=1
      KC(1)=0
      PC(1,1)=0.
      PC(1,2)=0.
      PC(1,3)=EBEG
      PC(1,4)=EBEG
      I=1
      W=2.*EBEG
      ELSE
      I=N+1
      W=P(250,3)
      ENDIF
C   GENERATE TWO QUARK-ANTIQUARK PAIRS. FORM LEADING MESON
      IFL(1)=1+INT(RANF(0)/PUD)
      IFL(2)=-(1+INT(RANF(0)/PUD))
      K(I,1)=6*MAX(IFL(1),IFL(2))-MIN(IFL(1),IFL(2))-6
      K(I,2)=KPART(K(I,1),INT(PS1+RANF(0)))
      P(I,5)=PMAS(K(I,2))
C   GENERATE PT AND Z FOR EACH LEG. WEIGHTING IN GAMMA FOR IFR=2
  100 DO 110 JT=1,2
      CALL PTDIST(PX(JT),PY(JT),SIGMA)
  110 Z(JT)=ZDIST(IFL(JT),0.,1.)
      PMTS=P(I,5)**2+(PX(1)+PX(2))**2+(PY(1)+PY(2))**2
      IF(IFR.EQ.2) THEN
      HSUM=PMTS/(Z(1)+Z(2))
      HDIF=(2.*RANF(0)-1.)*HSUM
      DO 120 JT=1,2
      QMTS(JT)=(QMAS(IABS(IFL(JT)))-QMAS(7))**2+PX(JT)**2+PY(JT)**2
  120 GAMM(JT)=(1.-Z(JT))*0.5*(HSUM+HDIF*(-1.)**JT)
      IF(GAMM(1)/(QMTS(1)+GAMM(1))*GAMM(2)/(QMTS(2)+GAMM(2)).LT.
     &RANF(0)) GOTO 100
      ENDIF
C   FOUR-MOMENTUM FOR LEADING MESON
      P(I,1)=PX(1)+PX(2)
      P(I,2)=PY(1)+PY(2)
      P(I,3)=0.5*(0.5*(Z(1)+Z(2))*W-PMTS/(0.5*(Z(1)+Z(2))*W))
      P(I,4)=0.5*(0.5*(Z(1)+Z(2))*W+PMTS/(0.5*(Z(1)+Z(2))*W))
      N=I
C   GENERATE TWO QUARK JETS WITH REMAINING FLAVOUR AND MOMENTUM
      IST=IST+1
      DO 130 JT=1,2
      K(250,1)=-IFL(JT)
      P(250,1)=-PX(JT)
      P(250,2)=-PY(JT)
      P(250,3)=0.5*(1.-Z(JT))*W
      P(250,5)=GAMM(JT)
  130 CALL GJET(0,0.)
      IST=IST-1
      IF(IST.EQ.0) CALL DECAYS
      RETURN
      END


      SUBROUTINE MULJET(IPZCUT)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
C   GENERATE QUARK AND GLUON JETS ACCORDING TO SPECIFICATIONS IN /JET/
      IF(IST.GE.-1) N=0
      IF(IST.EQ.-2) IST=-1
      IST=IST+2
      DO 100 IC=1,NC
      K(250,2)=N
      PAS=PC(IC,1)**2+PC(IC,2)**2+PC(IC,3)**2
      IF(KC(IC).NE.0) PC(IC,4)=SQRT(QMAS(IABS(KC(IC)))**2+PAS)
      IF(KC(IC).EQ.0) PC(IC,4)=SQRT(PAS)
      K(250,1)=KC(IC)
      P(250,1)=0.
      P(250,2)=0.
      P(250,3)=PC(IC,4)+SQRT(PAS)
      P(250,5)=0.
      IF(KC(IC).NE.0) CALL QJET(0,0.)
      IF(KC(IC).EQ.0) CALL GJET(0.)
      CALL EDIT(0,IPZCUT,0.,0.)
      THETA=ACOS(PC(IC,3)/SQRT(PAS))
      PHI=SIGN(ACOS(PC(IC,1)/SQRT(PC(IC,1)**2+PC(IC,2)**2)),PC(IC,2))
  100 CALL ROTBST(THETA,PHI,0.,0.,0.)
      IST=IST-2
      CALL DECAYS
      RETURN
```

```
      END


      SUBROUTINE QQJET(IFL,ECM)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      DIMENSION IFL1(2),PX1(2),PY1(2),PMTS(2),W(2),WG(2),GAMM(2)
C  INITIAL VALUES, USER AND INTERNAL CALLS, RESPECTIVELY
  100 IF(IST.LE.0) THEN
      NC=2
      I=0
      DO 110 JT=1,2
      KC(JT)=IFL*(-1)**(JT+1)
      PC(JT,1)=0.
      PC(JT,2)=0.
      PC(JT,3)=SQRT((0.5*ECM)**2-QMAS(IABS(IFL))**2)*(-1.)**(JT+1)
      PC(JT,4)=0.5*ECM
      IFL1(JT)=IFL*(-1)**(JT+1)
      PX1(JT)=0.
      PY1(JT)=0.
      W(JT)=ECM
      WG(JT)=ECM
  110 GAMM(JT)=0.
      IF(IST.LT.0) RETURN
      ELSE
      I=N
      DO 120 JT=1,2
      IFL1(JT)=K(248+JT,1)
      PX1(JT)=P(248+JT,1)
      PY1(JT)=P(248+JT,2)
      W(JT)=P(248+JT,3)
      WG(JT)=P(248+JT,4)
  120 GAMM(JT)=P(248+JT,5)
      ENDIF
C  IF THE CM ENERGY IS LOW, GENERATE ONLY TWO PRIMARY MESONS
      WMAX=QMAS(IABS(IFL1(1)))+QMAS(IABS(IFL1(2)))+PAR(IFR+10)
      IF(W(1)*W(2).LE.(WMAX-(PAR(IFR+10)-PAR(9))*RANF(0))**2) GOTO 150
C  CHOOSE SIDE. GENERATE A QUARK-ANTIQUARK PAIR. FORM A MESON
  130 I=I+1
      JT=1.+2.*RANF(0)
      IFL2=ISIGN(1+INT(RANF(0)/PUD),-IFL1(JT))
      K(I,1)=6*MAX(IFL1(JT),IFL2)-MIN(IFL1(JT),IFL2)-6
      K(I,2)=KPART(K(I,1),INT(PS1+RANF(0)))
      P(I,5)=PMAS(K(I,2))
C  GENERATE PT AND Z (NOTE CONSTRAINTS). WEIGHTING IN GAMMA FOR IFR=2
      PMTS(3-JT)=(QMAS(IABS(IFL1(3-JT)))+QMAS(IABS(IFL2)))**2
  140 CALL PTDIST(PX2,PY2,SIGMA)
      PMTS(JT)=P(I,5)**2+(PX1(JT)+PX2)**2+(PY1(JT)+PY2)**2
      IF(PMTS(1)+PMTS(2).GE.PAR(10)*W(1)*W(2)) GOTO 100
      Z=ZDIST(IFL1(JT),PMTS(JT)/(W(1)*W(2)),1.-PMTS(3-JT)/(W(1)*W(2)))
      IF(IFR.EQ.2) THEN
      QMTS=(QMAS(IABS(IFL2))-QMAS(7))**2+PX2**2+PY2**2
      GAMP=(1.-Z*W(JT)/WG(JT))*(GAMM(JT)+PMTS(JT)*WG(JT)/(Z*W(JT)))
      IF(GAMP/(QMTS+GAMP).LT.RANF(0)) GOTO 140
      GAMM(JT)=GAMP
      WG(JT)=WG(JT)-Z*W(JT)
      ENDIF
C  FOUR-MOMENTUM FOR MESON. REMAINING FLAVOUR AND MOMENTUM
      P(I,1)=PX1(JT)+PX2
      P(I,2)=PY1(JT)+PY2
      P(I,3)=0.5*(Z*W(JT)-PMTS(JT)/(Z*W(JT)))*(-1.)**(JT+1)
      P(I,4)=0.5*(Z*W(JT)+PMTS(JT)/(Z*W(JT)))
      IFL1(JT)=-IFL2
      PX1(JT)=-PX2
      PY1(JT)=-PY2
      W(1)=W(1)-P(I,4)-P(I,3)
      W(2)=W(2)-P(I,4)+P(I,3)
C  IF ENOUGH ENERGY LEFT, CONTINUE GENERATION
      WMAX=QMAS(IABS(IFL1(1)))+QMAS(IABS(IFL1(2)))+PAR(IFR+10)
      IF(W(1)*W(2).GE.WMAX**2) GOTO 130
C  GENERATE FINAL QUARK-ANTIQUARK PAIR. GIVES FINAL TWO MESONS
  150 I=I+2
      IFL2=ISIGN(1+INT(RANF(0)/PUD),-IFL1(1))
      K(I-1,1)=6*MAX(IFL1(1),IFL2)-MIN(IFL1(1),IFL2)-6
      K(I,1)=6*MAX(IFL1(2),-IFL2)-MIN(IFL1(2),-IFL2)-6
      CALL PTDIST(PX2,PY2,SIGMA)
      DO 160 JT=1,2
      K(I-2+JT,2)=KPART(K(I-2+JT,1),INT(PS1+RANF(0)))
      P(I-2+JT,5)=PMAS(K(I-2+JT,2))
      P(I-2+JT,1)=PX1(JT)+PX2*(-1.)**(JT+1)
      P(I-2+JT,2)=PY1(JT)+PY2*(-1.)**(JT+1)
  160 PMTS(JT)=P(I-2+JT,5)**2+P(I-2+JT,1)**2+P(I-2+JT,2)**2
C  IF TOO LOW ENERGY, START ALL OVER. ELSE CHOOSE ONE OF TWO SOLUTIONS
      IF(SQRT(W(1)*W(2)).LE.SQRT(PMTS(1))+SQRT(PMTS(2))) GOTO 100
```

```
      PSA=W(1)*W(2)+PMTS(1)-PMTS(2)
      PSB=SIGN(SQRT(PSA**2-4.*W(1)*W(2)*PMTS(1)),RANF(0)-PAR(IFR+12))
      P(I-1,3)=0.25*((PSA+PSB)/W(2)-(PSA-PSB)/W(1))
      P(I-1,4)=0.25*((PSA+PSB)/W(2)+(PSA-PSB)/W(1))
      P(I,3)=0.5*(W(1)-W(2))-P(I-1,3)
      P(I,4)=0.5*(W(1)+W(2))-P(I-1,4)
      N=I
      IF(IST.EQ.0) CALL DECAYS
      RETURN
      END


      SUBROUTINE QQGJET(IFL,ECM,X1,X2)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      DIMENSION SA(2),CA(2),W(2,2),IFLQ(2),PX(2),PY(2),Z(2,2),QMTS(2),
     &GAMM(2)
C   INITIAL VALUES (GLUON ALONG Z AXIS, FASTEST QUARK PX>0)
      NC=3
      KC(1)=IFL
      KC(2)=-IFL
      KC(3)=0
      PC(1,4)=0.5*X1*ECM
      PC(2,4)=0.5*X2*ECM
      PC(3,4)=0.5*(2.-X1-X2)*ECM
      PC(1,2)=0.
      PC(2,2)=0.
      PC(3,2)=0.
      PC(3,3)=PC(3,4)
      PC(3,1)=0.
      PC(1,3)=(PC(2,4)**2-PC(1,4)**2-PC(3,4)**2)/(2.*PC(3,4))
      PC(1,1)=SQRT(PC(1,4)**2-PC(1,3)**2-QMAS(IABS(IFL))**2)
      PC(2,3)=-PC(1,3)-PC(3,3)
      PC(2,1)=-PC(1,1)-PC(3,1)
      IF(IST.LT.0) GOTO 170
C   TOP ANGLE, W+ AND W- FOR TWO JET SYSTEMS. ALSO QUARK-ANTIQUARK PAIRS
      DO 100 JS=1,2
      SA(JS)=PC(JS,1)/SQRT((PC(JS,4)-PC(JS,3))**2+PC(JS,1)**2)
      CA(JS)=SQRT(1.-SA(JS)**2)
      W(JS,1)=(PC(JS,4)+PC(JS,3)+PC(3,4))*CA(JS)-PC(JS,1)*SA(JS)
      W(JS,2)=(PC(JS,4)-PC(JS,3))*CA(JS)+PC(JS,1)*SA(JS)
  100 IFLQ(JS)=ISIGN(1+INT(RANF(0)/PUD),IFL*(-1)**(JS+1))
C   FORM LEADING (GLUON) MESON. GENERATE PT1, PT2, Z1+ AND Z2+
      K(1,1)=6*MAX(IFLQ(1),IFLQ(2))-MIN(IFLQ(1),IFLQ(2))-6
      K(1,2)=KPART(K(1,1),INT(PS1+RANF(0)))
      P(1,5)=PMAS(K(1,2))
  110 DO 120 JS=1,2
      CALL PTDIST(PX(JS),PY(JS),SIGMA)
  120 Z(JS,1)=ZDIST(IFLQ(JS),0.,1.)
C   CHOOSE Z1- AND Z2- ALONG HYPERBOLA
      HA=(Z(1,1)*W(1,1)+Z(2,1)*W(2,1)*CA(1)/CA(2)+2.*PX(2)*CA(1)*
     &(SA(2)/CA(2)-SA(1)/CA(1)))*W(1,2)
      HB=(Z(2,1)*W(2,1)+Z(1,1)*W(1,1)*CA(2)/CA(1)+2.*PX(1)*CA(2)*
     &(SA(1)/CA(1)-SA(2)/CA(2)))*W(2,2)
      HC=CA(1)*CA(2)*(SA(1)/CA(1)-SA(2)/CA(2))**2*W(1,2)*W(2,2)
      HD=P(1,5)**2+(PX(1)+PX(2))**2+(PY(1)+PY(2))**2
      IF(HA.LE.HD.OR.HB.LE.HD) GOTO 110
      HE=(HA*HB+HC*HD)**2
  130 Z(1,2)=RANF(0)*HD/HA
      Z(2,2)=(HD-HA*Z(1,2))/(HB+HC*Z(1,2))
      IF(1.+HE/(HB+HC*Z(1,2))**4.LT.(1.+HE/HB**4)*RANF(0)**2) GOTO 130
C   WEIGHTING IN GAMMA FOR IFR=2. REJECT IF REMAINING SYSTEMS TOO SMALL
      IF(IFR.EQ.2) THEN
      DO 140 JS=1,2
      QMTS(JS)=(QMAS(IABS(IFLQ(JS)))-QMAS(7))**2+PX(JS)**2+PY(JS)**2
  140 GAMM(JS)=(1.-Z(JS,1))*Z(JS,2)*W(JS,1)*W(JS,2)
      IF(GAMM(1)/(QMTS(1)+GAMM(1))*GAMM(2)/(QMTS(2)+GAMM(2)).LT.
     &RANF(0)) GOTO 110
      ENDIF
      DO 150 JS=1,2
  150 IF((1.-Z(JS,1))*(1.-Z(JS,2))*W(JS,1)*W(JS,2)-PX(JS)**2-PY(JS)**2.
     &LT.(QMAS(IABS(IFL))+QMAS(IABS(IFLQ(JS)))+PAR(9))**2) GOTO 110
C   FOUR-MOMENTUM FOR LEADING (GLUON) MESON
      P(1,1)=PX(1)+Z(1,2)*W(1,2)*SA(1)+PX(2)+Z(2,2)*W(2,2)*SA(2)
      P(1,2)=PY(1)+PY(2)
      P(1,4)=(0.5*Z(1,1)*W(1,1)+0.5*Z(1,2)*W(1,2)+PX(1)*SA(1))/CA(1)+
     &(0.5*Z(2,1)*W(2,1)+0.5*Z(2,2)*W(2,2)+PX(2)*SA(2))/CA(2)
      P(1,3)=P(1,4)-Z(1,2)*W(1,2)*CA(1)-Z(2,2)*W(2,2)*CA(2)
      N=1
C   CALL QQJET FOR TREATMENT OF REMAINING SYSTEMS
      IST=IST+1
      DO 160 JS=1,2
      K(250,2)=N
      K(249,1)=-IFLQ(JS)
```

```
      P(249,1)=-PX(JS)
      P(249,2)=-PY(JS)
      P(249,3)=(1.-Z(JS,1))*W(JS,1)
      P(249,4)=(1.-Z(JS,1))*W(JS,1)
      P(249,5)=GAMM(JS)
      K(250,1)=IFL*(-1)**(JS+1)
      P(250,1)=0.
      P(250,2)=0.
      P(250,3)=(1.-Z(JS,2))*W(JS,2)
      P(250,4)=W(JS,2)
      P(250,5)=0.
      CALL QQJET(0,0.)
      CALL ROTBST(0.,0.,SA(JS),0.,0.,0.)
  160 CALL ROTBST(-ASIN(SA(JS)),0.,0.,0.,0.)
      IST=IST-1
C  ROTATE SO FASTEST QUARK IS ALONG Z AXIS, GLUON PX<0
  170 THEQ=ACOS(PC(1,3)/SQRT(PC(1,1)**2+PC(1,3)**2))
      CALL ROTBST(-THEQ,0.,0.,0.,0.)
      IF(IST.EQ.0) CALL DECAYS
      RETURN
      END


      SUBROUTINE QQGGEN(IFL,ECM)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
C  CHOOSE X1 AND X2 WITHIN AREA WITH TOTAL PROBABILITY=1
      ALS=6./((33.-2.*PAR(6))*ALOG(ECM/PAR(7)))
      CR=EXP(-((1.+1./ALS-PAR(15))/PAR(16))**(1./PAR(17)))
      CRA=-ALOG(2.*CR)
  100 V1=CRA*RANF(0)
      V2=CRA*RANF(0)
      X1=1.-EXP(-MAX(V1,V2))
      X2=1.-EXP(-MIN(V1,V2))
      X3=2.-X1-X2
      IF((1.-X1)*(1.-X2).LE.CR*(1.-X3)) GOTO 100
      IF(X1**2+X2**2.LE.2.*RANF(0)) GOTO 100
C  CORRECTIONS (GIVING QQ SYSTEMS) DUE TO QUARK MASSES AND CUTS
      QME=(2.*QMAS(IABS(IFL))/ECM)**2
      IF(4.*(1.-X1)*(1.-X2)*(1.-X3)/X3**2.LE.QME) GOTO 110
      IF(QME*X3+0.5*QME**2+(0.5*QME+0.25*QME**2)*((1.-X2)/(1.-X1)+
     &(1.-X1)/(1.-X2)).GT.(X1**2+X2**2)*RANF(0)) GOTO 110
      IF(X1.GT.1.-2.5*PAR(9)*(5.*PAR(9)+4.*QMAS(IABS(IFL)))/ECM**2
     &.OR.(1.-X1)*(1.-X2)/(1.-X3).LT.8.*(PAR(9)/ECM)**2) GOTO 110
      IF(X1.GT.PAR(3).OR.0.5*X3*ECM.LT.PAR(4)) GOTO 110
C  CALL EITHER QQJET OR QQGJET
      CALL QQGJET(IFL,ECM,X1,X2)
      RETURN
  110 CALL QQJET(IFL,ECM)
      RETURN
      END


      SUBROUTINE GGGJET(ECM,X1,X2)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      DIMENSION THEG(3),SA(3),CA(3),W(3,2),IFLQ(6),PX(6),PY(6),Z(6,2),
     &QMTS(6),GAMM(6)
C  INITIAL VALUES, TWO-GLUON AND THREE-GLUON EVENTS
      DO 100 IC=1,3
      KC(IC)=0
      PC(IC,1)=0.
  100 PC(IC,2)=0.
      IF(MAX(X1,X2,2.-X1-X2).GE.1.-(7.*PAR(9)/ECM)**2) THEN
      NC=2
      DO 110 IC=1,2
      PC(IC,3)=0.5*ECM*(-1.)**(IC+1)
  110 PC(IC,4)=0.5*ECM
      ELSE
      NC=3
      PC(1,4)=0.5*X1*ECM
      PC(2,4)=0.5*X2*ECM
      PC(3,4)=0.5*(2.-X1-X2)*ECM
      PC(1,3)=PC(1,4)
      PC(2,3)=(PC(3,4)**2-PC(2,4)**2-PC(1,4)**2)/(2.*PC(1,4))
      PC(2,1)=SQRT(PC(2,4)**2-PC(2,3)**2)
      PC(3,3)=-PC(1,3)-PC(2,3)
      PC(3,1)=-PC(1,1)-PC(2,1)
      ENDIF
C  SMALL SYSTEMS GENERATED WITH PHASE SPACE ONLY
      IF(IST.LT.0) RETURN
      IF(ECM.LT.7.*PAR(9)) THEN
      PMAS(5)=ECM
      CALL DECGEN(5)
      RETURN
```

```
      ENDIF
C  ANGLES AND ENERGIES FOR JET SYSTEMS
      DO 120 JS=1,NC
      JR=JS+1-NC*(JS/NC)
      THEG(JS)=SIGN(ACOS(PC(JS,3)/PC(JS,4)),PC(JS,1))
      CA(JS)=SQRT(0.5*(1.-(PC(JS,1)*PC(JR,1)+PC(JS,3)*PC(JR,3))/
     &(PC(JS,4)*PC(JR,4))))
      SA(JS)=SQRT(1.-CA(JS)**2)
      W(JS,1)=PC(JS,4)*CA(JS)
  120 W(JS,2)=PC(JR,4)*CA(JS)
C  FORM MESONS AT GLUON CORNERS. GENERATE PT AND Z+
  130 DO 160 JS=1,NC
      JR=JS-1+NC*((NC+1-JS)/NC)
      J1=2*JR
      J2=2*JS-1
      IFLQ(J1)=1+INT(RANF(0)/PUD)
      IFLQ(J2)=-(1+INT(RANF(0)/PUD))
      K(JS,1)=6*MAX(IFLQ(J1),IFLQ(J2))-MIN(IFLQ(J1),IFLQ(J2))-6
      K(JS,2)=KPART(K(JS,1),INT(PS1+RANF(0)))
      P(JS,5)=PMAS(K(JS,2))
  140 CALL PTDIST(PX(J1),PY(J1),SIGMA)
      CALL PTDIST(PX(J2),PY(J2),SIGMA)
      Z(J1,2)=ZDIST(IFLQ(J1),0.,1.)
      Z(J2,1)=ZDIST(IFLQ(J2),0.,1.)
C  CHOOSE Z- COMPONENTS ALONG HYPERBOLA
      HA=(Z(J1,2)*W(JR,2)+Z(J2,1)*W(JS,1)*CA(JR)/CA(JS)+2.*PX(J2)*
     &CA(JR)*(SA(JR)/CA(JR)+SA(JS)/CA(JS)))*W(JR,1)
      HB=(Z(J2,1)*W(JS,1)+Z(J1,2)*W(JR,2)*CA(JS)/CA(JR)+2.*PX(J1)*
     &CA(JS)*(SA(JR)/CA(JR)+SA(JS)/CA(JS)))*W(JS,2)
      HC=CA(JR)*CA(JS)*(SA(JR)/CA(JR)+SA(JS)/CA(JS))**2*W(JR,1)*W(JS,2)
      HD=P(JS,5)**2+(PX(J1)-PX(J2))**2+(PY(J1)+PY(J2))**2
      IF(HA.LE.HD.OR.HB.LE.HD) GOTO 140
      HE=(HA*HB+HC*HD)**2
  150 Z(J1,1)=RANF(0)*HD/HA
      Z(J2,2)=(HD-HA*Z(J1,1))/(HB+HC*Z(J1,1))
      IF(1.+HE/(HB+HC*Z(J1,1))**4.LT.(1.+HE/HB**4)*RANF(0)**2) GOTO 150
C  WEIGHTING IN GAMMA FOR IFR=2. REJECT IF REMAINING SYSTEMS TOO SMALL
      IF(IFR.EQ.2) THEN
      QMTS(J1)=(QMAS(IABS(IFLQ(J1)))-QMAS(7))**2+PX(J1)**2+PY(J1)**2
      GAMM(J1)=(1.-Z(J1,2))*Z(J1,1)*W(JR,1)*W(JR,2)
      QMTS(J2)=(QMAS(IABS(IFLQ(J2)))-QMAS(7))**2+PX(J2)**2+PY(J2)**2
      GAMM(J2)=(1.-Z(J2,1))*Z(J2,2)*W(JS,1)*W(JS,2)
      IF(GAMM(J1)/(QMTS(J1)+GAMM(J1))*GAMM(J2)/(QMTS(J2)+GAMM(J2)).LT.
     &RANF(0)) GOTO 140
      ENDIF
  160 CONTINUE
      DO 170 JS=1,NC
      WR1=(1.-Z(2*JS-1,1)-Z(2*JS,1))*W(JS,1)
      WR2=(1.-Z(2*JS-1,2)-Z(2*JS,2))*W(JS,2)
      WRS=WR1*WR2-(PX(2*JS-1)+PX(2*JS))**2-(PY(2*JS-1)+PY(2*JS))**2
      WMIN=QMAS(IABS(IFLQ(2*JS-1)))+QMAS(IABS(IFLQ(2*JS)))+PAR(9)
  170 IF(WR1.LE.0..OR.WRS.LE.WMIN**2) GOTO 130
C  FOUR-MOMENTUM FOR MESONS AT CORNERS
      DO 180 JS=1,NC
      JR=JS-1+NC*((NC+1-JS)/NC)
      J1=2*JR
      J2=2*JS-1
      P(JS,2)=PY(J1)+PY(J2)
      P(JS,4)=(0.5*Z(J1,2)*W(JR,2)+0.5*Z(J1,1)*W(JR,1)+PX(J1)*SA(JR))/
     &CA(JR)+(0.5*Z(J2,1)*W(JS,1)+0.5*Z(J2,2)*W(JS,2)+PX(J2)*SA(JS))/
     &CA(JS)
      PTP=PX(J2)+Z(J2,2)*W(JS,2)*SA(JS)-PX(J1)-Z(J1,1)*W(JR,1)*SA(JR)
      PLP=P(JS,4)-Z(J1,1)*W(JR,1)*CA(JR)-Z(J2,2)*W(JS,2)*CA(JS)
      P(JS,1)=COS(THEG(JS))*PTP+SIN(THEG(JS))*PLP
  180 P(JS,3)=COS(THEG(JS))*PLP-SIN(THEG(JS))*PTP
      N=NC
C  CALL QQJET FOR TREATMENT OF REMAINING SYSTEMS
      IST=IST+1
      DO 200 JS=1,NC
      K(250,2)=N
      DO 190 JT=1,2
      K(248+JT,1)=-IFLQ(2*JS-2+JT)
      P(248+JT,1)=-PX(2*JS-2+JT)
      P(248+JT,2)=-PY(2*JS-2+JT)
      P(248+JT,3)=(1.-Z(2*JS-1,JT)-Z(2*JS,JT))*W(JS,JT)
      P(248+JT,4)=(1.-Z(2*JS-2+JT,JT))*W(JS,JT)
  190 P(248+JT,5)=GAMM(2*JS-2+JT)
      CALL QQJET(0,0.)
      CALL ROTBST(0.,0.,SA(JS),0.,0.)
  200 CALL ROTBST(THEG(JS)-ASIN(SA(JS)),0.,0.,0.,0.)
      IST=IST-1
      IF(IST.EQ.0) CALL DECAYS
      RETURN
      END
```

```
      SUBROUTINE GGGGEN(ECM,ICH)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)
C  CHOICE OF X1 AND X2 ACCORDING TO MATRIX ELEMENT
  100 X1=RANF(0)
      X2=RANF(0)
      X3=2.-X1-X2
      IF(X3.GE.1..OR.((1.-X1)/(X2*X3))**2+((1.-X2)/(X1*X3))**2+
     &((1.-X3)/(X1*X2))**2.LE.2.*RANF(0)) GOTO 100
      P(248,1)=X1
      P(248,2)=X2
C  THREE-GLUON OR GLUON-GLUON-PHOTON EVENT
      PGAM=0.382*(ICH/3.)**2*PAR(5)*(33.-2.*PAR(6))*ALOG(ECM/PAR(7))
      IF(RANF(0).GT.PGAM/(1.+PGAM)) THEN
      CALL GGGJET(ECM,X1,X2)
      ELSE
      ECMR=SQRT(1.-X3)*ECM
      IF(ECMR.LE.1.) GOTO 100
      CALL GGGJET(ECMR,1.,1.)
      CALL ROTBST(ACOS((X2-X1)/X3),0.,0.,0.,-X3/(X1+X2))
      N=N+1
      IF(IST.EQ.-1) N=1
      IF(IST.EQ.-1) IST=-2
      K(N,1)=38
      K(N,2)=1
      P(N,1)=0.
      P(N,2)=0.
      P(N,3)=0.5*X3*ECM
      P(N,4)=P(N,3)
      P(N,5)=0.
      CALL ROTBST(-ACOS(PC(1,3)/PC(1,4)),0.,0.,0.,0.)
      ENDIF
      RETURN
      END


      SUBROUTINE ANGGEN(ECM,POL)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      IF(KC(1).NE.0) QME=(2.*QMAS(IABS(KC(1)))/ECM)**2
      IF(NC.EQ.2.AND.KC(1).NE.0) THEN
C  DIFFERENTIAL CROSS SECTIONS FOR QQ EVENTS
      SIGU=1.
      SIGL=QME
      SIGT=0.
      SIGI=0.
      ELSEIF(NC.EQ.3.AND.KC(1).NE.0) THEN
C  DIFFERENTIAL CROSS SECTIONS FOR QQG EVENTS
      X1=2.*PC(1,4)/ECM
      X2=2.*PC(2,4)/ECM
      X3=2.-X1-X2
      XQ=(1.-X1)/(1.-X2)
      CT12=(X1*X2-2.*X1-2.*X2+2.+QME)/SQRT((X1**2-QME)*(X2**2-QME))
      ST12=SQRT(1.-CT12**2)
      SIGU=2.*X1**2+X2**2*(1.+CT12**2)-QME*(3.+CT12**2-X1-X2)-
     &QME*X1/XQ+0.5*QME*((X2**2-QME)*ST12**2-2.*X2)*XQ
      SIGL=2.*(X2*ST12)**2-2.*QME*(3.-CT12**2-2.5*(X1+X2)+X1*X2+QME)+
     &QME*(X1**2-X1-QME)/XQ+QME*((X2**2-QME)*CT12**2-X2)*XQ
      SIGT=(X1**2-QME-0.5*QME*(X2**2-QME)/XQ)*ST12**2
      SIGI=(4.-2.*QME*XQ)*(X2**2-QME)*ST12*CT12+4.*QME*(1.-X1-X2+
     &0.5*X1*X2+0.5*QME)*ST12/CT12
      ELSE
C  DIFFERENTIAL CROSS SECTIONS FOR GGG EVENTS
      X1=P(248,1)
      X2=P(248,2)
      X3=2.-X1-X2
      CT12=(X1*X2-2.*X1-2.*X2+2.)/(X1*X2)
      ST12=SQRT(1.-CT12**2)
      SIGL=X2**2*((1.-X2)**2+(1.-X3)**2)*ST12**2
      SIGU=(X1*(1.-X1))**2+(X2*(1.-X2))**2+(X3*(1.-X3))**2-0.5*SIGL
      SIGT=0.5*SIGL
      SIGI=SIGL*CT12/ST12+2.*X1*X2*(1.-X3)**2*ST12
      ENDIF
C  GENERATION OF ANGULAR ORIENTATION
      SIGM=(2.+DIM(ABS(POL),1.))*ABS(SIGU)+(1.+ABS(POL))*ABS(SIGL)+
     &1.42*(1.+ABS(POL)+DIM(ABS(POL),1.))*(ABS(SIGT)+0.5*ABS(SIGI))
  100 CHI=6.2832*RANF(0)
      CTHE=2.*RANF(0)-1.
      THE=ACOS(CTHE)
      PHI=6.2832*RANF(0)
      SIG=(1.+(CTHE**2)*SIGU+(1.-CTHE**2)*(SIGL+COS(2.*CHI)*SIGT)+CTHE*
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     &SIN(THE)*COS(CHI)*SIGI+POL*((1.-CTHE**2)*COS(2.*PHI)*(SIGU-SIGL)+
     &((1.+CTHE**2)*COS(2.*PHI)*COS(2.*CHI)-2.*CTHE*SIN(2.*PHI)*
     &SIN(2.*CHI))*SIGT+(CTHE*COS(2.*PHI)*COS(CHI)-SIN(2.*PHI)*
     &SIN(CHI))*SIGI)
      IF(SIG.LT.SIGM*RANF(0)) GOTO 100
      CALL ROTBST(0.,CHI,0.,0.,0.)
      CALL ROTBST(THE,PHI,0.,0.,0.)
      RETURN
      END


      SUBROUTINE EVTGEN(IFL,ECM,IMODE)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
C   CHOOSE FLAVOUR (FOR IFL>6) ACCORDING TO QED
      IFLC=IFL
      IF(IFL.GE.7) THEN
  100 IFLC=MAX(1,INT(6.*RANF(0)-2.))
      IF(ECM.GT.2.*QMAS(4)+PAR(9).AND.4..GT.10.*RANF(0)) IFLC=4
      IF(ECM.GT.2.*QMAS(5)+PAR(9).AND.1..GT.11.*RANF(0)) IFLC=5
      IF(ECM.GT.2.*QMAS(6)+PAR(9).AND.4..GT.15.*RANF(0)) IFLC=6
      IF(IFL.EQ.7.AND.IFLC.EQ.6) GOTO 100
      QME=(2.*QMAS(IFLC)/ECM)**2
      IF((1.+0.5*QME)*SQRT(1.-QME).LT.RANF(0)) GOTO 100
      ENDIF
      IFLC=IFLC*(-1)**INT(RANF(0)+0.5)
C   GENERATE EVENT AND ANGULAR ORIENTATION
      IF(IFL.NE.0.AND.IMODE.LE.0) CALL QQJET(IFLC,ECM)
      IF(IFL.NE.0.AND.IMODE.GE.1) CALL QQGGEN(IFLC,ECM)
      IF(IFL.EQ.0) CALL GGGGEN(ECM,IMODE)
      CALL ANGGEN(ECM,PAR(2))
      RETURN
      END


      SUBROUTINE EDIT(ITHROW,IPZCUT,PZMIN,PMIN)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)
      DIMENSION PZ(250)
C   FIND LOWER I LIMIT. FIND RELEVANT PZ FOR LATER CUT
      IO=1
      IF(IST.GE.1) IO=1+K(250,2)
      DO 110 I=IO,N
      PZ(I)=PZMIN+1.
      IF(IPZCUT.GE.1) PZ(I)=P(I,3)
      IF(IPZCUT.EQ.2.AND.K(I,1).LT.0) THEN
      IP=I
  100 IP=-K(IP,1)
      IF(K(IP,1).LT.0) GOTO 100
      PZ(I)=P(IP,3)
      ENDIF
  110 CONTINUE
C   THROW AWAY UNSTABLE OR NEUTRALS OR WITH TOO LOW PZ OR P
      I1=IO-1
      DO 130 I=IO,N
      IF(ITHROW.GE.1.AND.IDB(K(I,2)).GT.0) GOTO 130
      IF(ITHROW.GE.2.AND.(K(I,2).EQ.9.OR.K(I,2).EQ.10.OR.K(I,2).EQ.13.
     &OR.K(I,2).EQ.14.OR.K(I,2).EQ.17.OR.K(I,2).EQ.18)) GOTO 130
      IF(ITHROW.GE.3.AND.(K(I,2).EQ.1.OR.K(I,2).EQ.58)) GOTO 130
      IF(PZ(I).LT.PZMIN.OR.P(I,4)**2-P(I,5)**2.LT.PMIN**2) GOTO 130
      I1=I1+1
      K(I1,1)=IDIM(K(I,1),0)
      K(I1,2)=K(I,2)
      DO 120 J=1,5
  120 P(I1,J)=P(I,J)
  130 CONTINUE
      N=I1
      RETURN
      END


      SUBROUTINE ROTBST(THETA,PHI,BETAX,BETAY,BETAZ)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      DIMENSION ROT(3,3), PR(3)
C   FIND LOWER I LIMIT. STORE JETS AFTER PARTICLES
      IC=1
      IF(IST.GE.1) IC=1+K(250,2)
      DO 100 IC=1,NC
      DO 100 J=1,4
  100 P(N+IC,J)=PC(IC,J)
C   ROTATE JET (TYPICALLY FROM Z AXIS TO DIRECTION THETA, PHI)
      IF(THETA**2+PHI**2.LT.1E-8) GOTO 130
      ROT(1,1)=COS(THETA)*COS(PHI)
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      ROT(1,2)=-SIN(PHI)
      ROT(1,3)=SIN(THETA)*COS(PHI)
      ROT(2,1)=COS(THETA)*SIN(PHI)
      ROT(2,2)=COS(PHI)
      ROT(2,3)=SIN(THETA)*SIN(PHI)
      ROT(3,1)=-SIN(THETA)
      ROT(3,2)=0.
      ROT(3,3)=COS(THETA)
      DO 120 I=IO,N+NC
      DO 110 J=1,3
  110 PR(J)=P(I,J)
      DO 120 J=1,3
  120 P(I,J)=ROT(J,1)*PR(1)+ROT(J,2)*PR(2)+ROT(J,3)*PR(3)
C  LORENTZ BOOST JET (TYPICALLY FROM REST TO MOMENTUM/ENERGY=BETA)
  130 IF(BETAX**2+BETAY**2+BETAZ**2.LT.1E-8) GOTO 150
      GA=1./SQRT(1.-BETAX**2-BETAY**2-BETAZ**2)
      DO 140 I=IO,N+NC
      BEP=BETAX*P(I,1)+BETAY*P(I,2)+BETAZ*P(I,3)
      GABEP=GA*(GA*BEP/(1.+GA)+P(I,4))
      P(I,1)=P(I,1)+GABEP*BETAX
      P(I,2)=P(I,2)+GABEP*BETAY
      P(I,3)=P(I,3)+GABEP*BETAZ
  140 P(I,4)=GA*(P(I,4)+BEP)
C  JETS ARE TRANSFORMED (IN MOST CASES)
  150 IF(NC.EQ.0.OR.IST.GT.0) RETURN
      DO 160 IC=1,NC
      DO 160 J=1,4
  160 PC(IC,J)=P(N+IC,J)
      RETURN
      END


      SUBROUTINE LIST
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA2/ CZF(6),MESO(36),CMIX(6,2),CHA1(17),CHA2(96)
      COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)
      WRITE(6,130)
C  GIVE DATA FOR JETS
      IF(NC.EQ.0) GOTO 110
      DO 100 IC=1,NC
  100 WRITE(6,140) IC, CHA1(KC(IC)+7), (PC(IC,J), J=1,4)
      WRITE(6,150)
C  GIVE DATA FOR ALL PARTICLES
  110 DO 120 I=1,N
      C2=CHA2(K(I,2))
      C3=CHA1(14)
      IF(IDB(K(I,2)).EQ.0) C3=CHA1(15)
      IF(K(I,1).LE.0) THEN
      WRITE(6,160) I, -K(I,1), C2, C3, (P(I,J), J=1,5)
      ELSEIF(K(I,1).GE.1.AND.K(I,1).LE.36) THEN
      IFL1=(K(I,1)+5)/6
      IFL2=6*IFL1-6-K(I,1)
      WRITE(6,170) I, CHA1(7+IFL1), CHA1(7-IFL2), C2,C3, (P(I,J), J=1,5)
      ELSE
      WRITE(6,180) I, CHA1(K(I,1)-21), C2, C3, (P(I,J), J=1,5)
      ENDIF
  120 CONTINUE
      RETURN
  130 FORMAT(////T12,'I',T18,'ORIG',T26,'PART',T34,'STAB',
     &T46,'PX',T58,'PY',T70,'PZ',T82,'E',T94,'M'/)
  140 FORMAT(10X,I3,4X,A4,4X,'JET',9X,4(4X,F8.3))
  150 FORMAT(10X)
  160 FORMAT(10X,I3,4X,I4,2(4X,A4),5(4X,F8.3))
  170 FORMAT(10X,I3,4X,2A1,2X,2(4X,A4),5(4X,F8.3))
  180 FORMAT(10X,I3,4X,A4,2(4X,A4),5(4X,F8.3))
      END


      SUBROUTINE TMASS(TM)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
C  CHANGE TOP QUARK MASS TO TM (GEV) WITH RESULTING MESON MASS CHANGES
      QMAS(6)=TM
      DO 100 J=1,5
      PMAS(39+2*J)=TM+QMAS(J)-0.03
      PMAS(40+2*J)=TM+QMAS(J)-0.03
      PMAS(79+2*J)=TM+QMAS(J)+0.01
  100 PMAS(80+2*J)=TM+QMAS(J)+0.01
      PMAS(56)=2.*TM-1.03
      PMAS(96)=2.*TM-0.99
      RETURN
      END


      FUNCTION KPART(KI1,ISPIN)
```

```
      COMMON /DATA2/ CZF(6),MESO(36),CMIX(6,2),CHA1(17),CHA2(96)
C  RENUMBER MESON FLAVOURS, ADD SPIN AND MIX DIAGONAL MESON FLAVOURS
      KI1M=MESO(KI1)
      KPART=20+40*ISPIN+KI1M
      IF(KI1M.LE.30.OR.KI1M.GE.34) RETURN
      TMIX=RANF(0)
      KM=KI1M-30+3*ISPIN
      KPART=51+40*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
      RETURN
      END


      SUBROUTINE PTDIST(PX,PY,SIGMA)
C  GIVE PX AND PY ACCORDING TO INDEPENDENT GAUSSIAN DISTRIBUTIONS
      PT=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI=6.2832*RANF(0)
      PX=PT*COS(PHI)
      PY=PT*SIN(PHI)
      RETURN
      END


      FUNCTION ZDIST(IFL,ZMIN,ZMAX)
C  GENERATE Z ACCORDING TO DIFFERENT FRAGMENTATION FUNCTIONS
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      COMMON /DATA2/ CZF(6),MESO(36),CMIX(6,2),CHA1(17),CHA2(96)
      IFLA=IABS(IFL)
  100 ZDIST=RANF(0)
      IF(IFR.EQ.2) GOTO 110
      IF(CZF(IFLA).GT.RANF(0)) ZDIST=1.-ZDIST**(1./3.)
      IF(CZF(IFLA).LT.0.) ZDIST=ZDIST**(1./(1.-CZF(IFLA)))
  110 IF(ZDIST.LT.ZMIN.OR.ZDIST.GT.ZMAX) GOTO 100
      RETURN
      END


      SUBROUTINE DECAYS
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)
C  ADMINISTRATE THE DECAY CHAINS OF ALL PRIMARY MESONS
      I=N
      IPD=0
  100 IPD=IPD+1
      IF(IDB(K(IPD,2)).GT.0) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.235) GOTO 100
      N=I
      RETURN
      END


      SUBROUTINE DECAY(IPD,I)
      COMMON /JET/ N,K(250,2),P(250,5),NC,KC(10),PC(10,4)
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)
      DIMENSION IFLQ(4), IFL1(4), PM(12,5), RND(12), U(3), BE(3)
      PAWT(A,B,C)=SQRT((A**2-(B+C)**2)*(A**2-(B-C)**2))/(2.*A)
      FOUR(I,J)=P(I,4)*P(J,4)-P(I,1)*P(J,1)-P(I,2)*P(J,2)-P(I,3)*P(J,3)
C  CHOOSE DECAY CHANNEL, GIVES DECAY PRODUCTS (PARTICLES AND QUARK JETS)
      TBR=RANF(0)
      IDC=IDB(K(IPD,2))-1
  100 IDC=IDC+1
      IF(TBR.GT.CBR(IDC)) GOTO 100
      NP=0
      NQ=0
      PSUMP=0.
      DO 110 I1=I+1,I+3
      K(I1,2)=KDP(IDC,I1-I)
      IF(K(I1,2).GT.0) THEN
      NP=NP+1
      K(I1,1)=-IPD
      P(I1,5)=PMAS(K(I1,2))
      PSUMP=PSUMP+P(I1,5)
      ELSEIF(K(I1,2).LT.0.AND.K(I1,2).GE.-36) THEN
      NQ=NQ+1
      IFLQ(2*NQ-1)=(5-K(I1,2))/6
      IFLQ(2*NQ)=K(I1,2)+6*(IFLQ(2*NQ-1)-1)
      ELSEIF(K(I1,2).EQ.-37) THEN
      NQ=NQ+1
      IFLQ(2*NQ-1)=1+INT(RANF(0)/PUD)
      IFLQ(2*NQ)=-IFLQ(2*NQ-1)
      ENDIF
  110 CONTINUE
C  CHOOSE DECAY MULTIPLICITY ACCORDING TO GAUSSIAN
      ND=NP+NQ
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```
      PSUM=PSUMP
      IF(NQ.EQ.0) GOTO 170
      CNDE=CND(1)*ALOG(P(IPD,5)/CND(2))
      IF(KDP(IDC,1).EQ.-37) CNDE=CNDE+CND(3)
  120 GAUSS=SQRT(-2.*CNDE*ALOG(RANF(0)))*SIN(6.2832*RANF(0))
      ND=0.5+0.5*(NP+NQ)+CNDE+GAUSS
      IF(ND.LT.NP+NQ.OR.ND.LT.2.OR.ND.GT.10) GOTO 120
      IF(NP+NQ.EQ.3.AND.K(I+2,2).GE.7.AND.K(I+2,2).LE.18) ND=3
C  GENERATE AND PAIR OFF QUARK-ANTIQUARK PAIRS
      DO 130 JT=1,4
  130 IFL1(JT)=IFLQ(JT)
      IF(ND.EQ.NP+NQ) GOTO 150
      DO 140 I1=I+NP+1,I+ND-NQ
      JT=1+2*NQ*RANF(0)
      IFL2=ISIGN(1+INT(RANF(0)/PUD),-IFL1(JT))
      K(I1,1)=6*MAX(IFL1(JT),IFL2)-MIN(IFL1(JT),IFL2)-6
  140 IFL1(JT)=-IFL2
  150 JT=2+2*INT(NQ*RANF(0))
      K(I+ND-NQ+1,1)=6*IFL1(1)-IFL1(JT)-6
      IF(NQ.EQ.2) K(I+ND,1)=6*IFL1(3)-IFL1(6-JT)-6
C  FORM MESONS. IF TOTAL MASS TOO LARGE TRY AGAIN
      PSUM=PSUMP
      DO 160 I1=I+NP+1,I+ND
      K(I1,2)=KPART(K(I1,1),INT(PS1+RANF(0)))
      K(I1,1)=-IPD
      P(I1,5)=PMAS(K(I1,2))
  160 PSUM=PSUM+P(I1,5)
      IF(PSUM+PAR(8).GT.P(IPD,5)) GOTO 120
C  PRODUCT CHARGE CONJUGATION FOR DECAYING ANTIPARTICLE
  170 IF(2*(K(IPD,2)/2).EQ.K(IPD,2)) THEN
      DO 180 I1=I+1,I+ND
      KCOR=K(I1,2)-(-1)**(K(I1,2)-2*(K(I1,2)/2))
      IF(K(I1,2).GE.7.AND.K(I1,2).LE.50) K(I1,2)=KCOR
  180 IF(K(I1,2).GE.61.AND.K(I1,2).LE.90) K(I1,2)=KCOR
      ENDIF
C  ONE-PARTICLE DECAY. START ND-PARTICLE DECAY
      IF(ND.EQ.1) THEN
      DO 190 J=1,4
  190 P(I+1,J)=P(IPD,J)
      GOTO 330
      ENDIF
      DO 200 J=1,5
  200 PM(1,J)=P(IPD,J)
      PM(ND,5)=P(I+ND,5)
      IF(ND.EQ.2) GOTO 260
C  CALCULATE MAXIMUM WEIGHT
      WTMAX=1./WTCOR(ND)
      PMAX=PM(1,5)-PSUM+P(I+ND,5)
      PMIN=0.
      DO 210 IL=ND-1,1,-1
      PMAX=PMAX+P(I+IL,5)
      PMIN=PMIN+P(I+IL+1,5)
  210 WTMAX=WTMAX*PAWT(PMAX,PMIN,P(I+IL,5))
C  M-GENERATOR GIVES WEIGHT, IF REJECTED TRY AGAIN
  220 RND(1)=1.
      DO 240 IL1=2,ND-1
      RAN=RANF(0)
      DO 230 IL2=IL1-1,1,-1
      IF(RAN.LE.RND(IL2)) GOTO 240
  230 RND(IL2+1)=RND(IL2)
  240 RND(IL2+1)=RAN
      RND(ND)=0.
      WT=1.
      DO 250 IL=ND-1,1,-1
      PM(IL,5)=PM(IL+1,5)+P(I+IL,5)+(RND(IL)-RND(IL+1))*(P(IPD,5)-PSUM)
  250 WT=WT*PAWT(PM(IL,5),PM(IL+1,5),P(I+IL,5))
      IF(WT.LT.RANF(0)*WTMAX) GOTO 220
C  PERFORM TWO-PARTICLE DECAYS IN CM FRAME
  260 DO 280 IL=1,ND-1
      PA=PAWT(PM(IL,5),PM(IL+1,5),P(I+IL,5))
      U(3)=2.*RANF(0)-1.
      PHI=6.2832*RANF(0)
      U(1)=SQRT(1.-U(3)**2)*COS(PHI)
      U(2)=SQRT(1.-U(3)**2)*SIN(PHI)
      DO 270 J=1,3
      P(I+IL,J)=PA*U(J)
  270 PM(IL+1,J)=-PA*U(J)
      P(I+IL,4)=SQRT(PA**2+P(I+IL,5)**2)
  280 PM(IL+1,4)=SQRT(PA**2+PM(IL+1,5)**2)
C  LORENTZ TRANSFORM DECAY PRODUCTS TO LAB FRAME
      DO 290 J=1,4
  290 P(I+ND,J)=PM(ND,J)
      DO 320 IL=ND-1,1,-1
      DO 300 J=1,3
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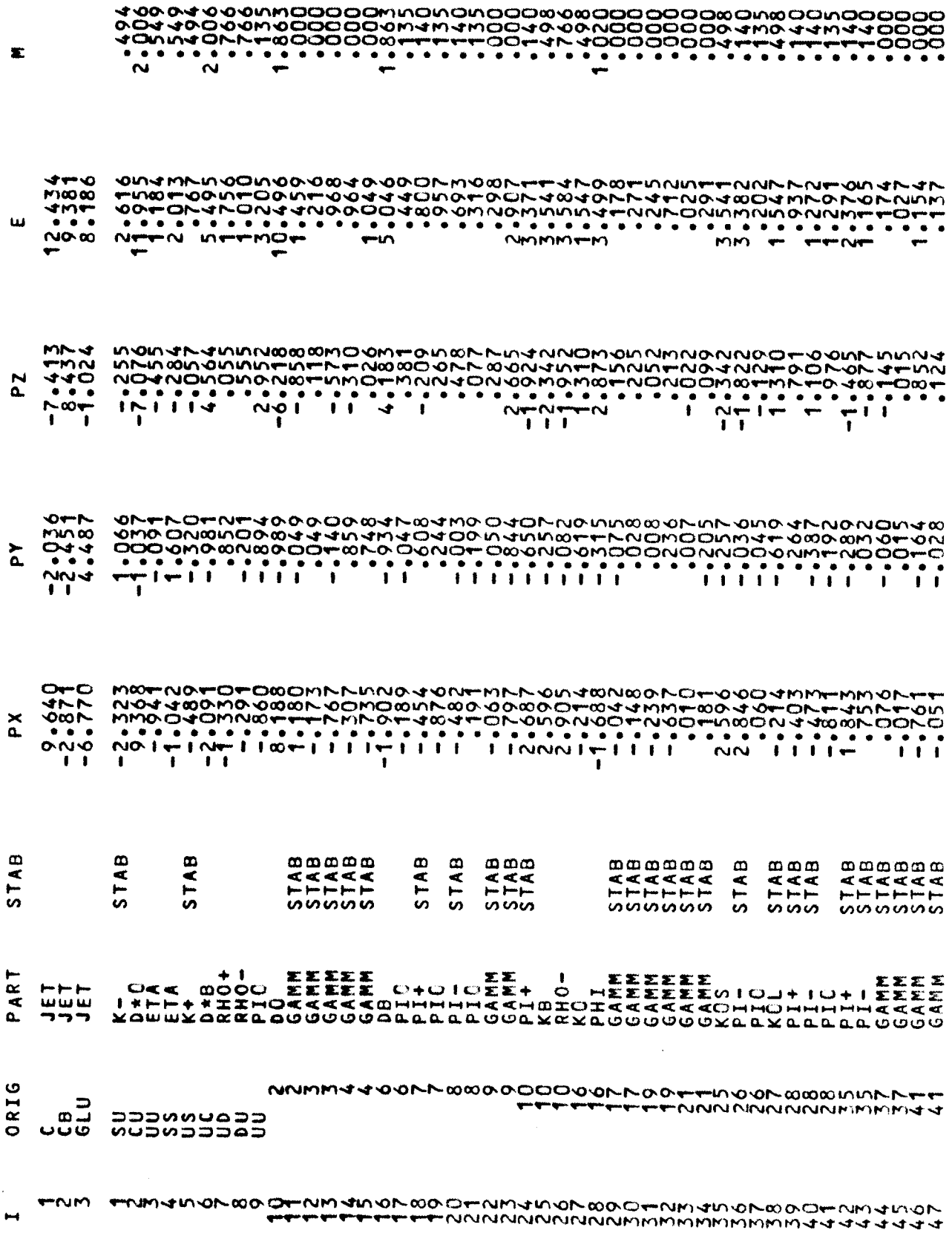
```
  300 BE(J)=PM(IL,J)/PM(IL,4)
      GA=PM(IL,4)/PM(IL,5)
      DO 320 I1=I+IL,I+ND
      BEP=BE(1)*P(I1,1)+BE(2)*P(I1,2)+BE(3)*P(I1,3)
      DO 310 J=1,3
  310 P(I1,J)=P(I1,J)+GA*(GA*BEP/(1.+GA)+P(I1,4))*BE(J)
  320 P(I1,4)=GA*(P(I1,4)+BEP)
C  MATRIX ELEMENTS FOR SEMILEPTONIC AND OMEG AND PHI DECAYS
      IF(ND.EQ.3.AND.K(I+2,2).GE.7.AND.K(I+2,2).LE.18) THEN
      WT=FOUR(IPD,I+1)*FOUR(I+2,I+3)
      IF(WT.LT.RANF(0)*P(IPD,5)**4/WTCOR(1)) GOTO 220
      ELSEIF(ND.EQ.3.AND.(K(IPD,2).EQ.92.OR.K(IPD,2).EQ.93)) THEN
      WT=(P(I+1,5)*P(I+2,5)*P(I+3,5))**2-(P(I+1,5)*FOUR(I+2,I+3))**2
     &-(P(I+2,5)*FOUR(I+1,I+3))**2-(P(I+3,5)*FOUR(I+1,I+2))**2
     &+2.*FOUR(I+1,I+2)*FOUR(I+1,I+3)*FOUR(I+2,I+3)
      IF(WT.LT.RANF(0)*P(IPD,5)**6/WTCOR(2)) GOTO 220
      ENDIF
  330 I=I+ND
      RETURN
      END


      BLOCK DATA
      COMMON /DATA1/ IST,IFR,PUD,PS1,SIGMA,QMAS(7),PMAS(96),PAR(25)
      COMMON /DATA2/ CZF(6),MESO(36),CMIX(6,2),CHA1(17),CHA2(96)
      COMMON /DATA3/ IDB(96),CBR(135),KDP(135,3),CND(3),WTCOR(10)
C  DATA1, CONTAINING MOST PARAMETERS, AND PARTICLE MASSES
      DATA IST/0/, IFR/2/, PUD/0.4/, PS1/0.5/, SIGMA/0.35/
      DATA QMAS/0.3,0.3,0.5,1.6,5.0,20.0,0.275/
      DATA PMAS/6*0.,2*0.0005,2*0.,2*0.1057,2*0.,2*1.782,4*0.,
     &2*0.1396,2*0.4937,2*0.4977,2*1.8633,2*1.8683,2*2.04,4*5.27,2*5.47,
     &2*6.57,4*20.27,2*20.47,2*21.57,2*24.97,0.135,0.5488,0.9576,2.97,
     &9.4,38.97,2*0.4977,2*0.,2*0.7659,2*0.8922,2*0.8963,2*2.006,
     &2*2.0086,2*2.14,4*5.31,2*5.51,2*6.61,4*20.31,2*20.51,2*21.61,
     &2*25.01,0.7702,0.7826,1.0196,3.097,9.46,39.01/
      DATA PAR/0.1,0.,1.,0.,0.0073,5.,0.5,0.005,0.7,0.9,2.2,1.4,
     &0.39,0.27,-0.8839,0.2250,2.355,8*0./
C  DATA2, WITH FRAGMENTATION, FLAVOUR TREATMENT AND CHARACTER DATA
      DATA CZF/2*0.77,0.77,0.,0.,0./
      DATA MESO/31,1,3,8,14,22,2,32,5,10,16,24,4,6,33,12,18,26,7,9,11,
     &34,20,28,13,15,17,19,35,30,21,23,25,27,29,36/
      DATA CMIX/2*0.5,1.,2*0.5,1.,2*0.25,0.5,2*0.,1./
      DATA CHA1/'TB','BB','CB','SB','DB','UB','GLU','U','D','S','C',
     &'B','T',' ','STAB','QQ',' ','PRIM'/
      DATA CHA2/'GAMM',' ',' ',' ','GPS',' ',' ','E-','E+','NUE','NUEB',
     &'MU-','MU+','NUM',' ','NUMB',' ','TAU-','TAU+','NUT','NUTB',' ',' ',
     &'PI+','PI-','K+','K-','K0','KB','D0','DB','D+','D-','F+','F-',
     &'BU-','BU+','BD0','BDB','BS0','BSB','BC-','BC+','TUC','TUB','TD+',
     &'TD-','TS+','TS-','TC0','TCB','TB+','TB-','PIO','ETA','ETAP',
     &'ETAC','ETAB','ETAT','K0S','K0L',' ',' ','RHO+','RHO-','K*+',
     &'K*-','K*0','K*B','D*0','D*B','D*+','D*-','F*+','F*-','BU*-',
     &'BU*+','BD*0','BD*B','BS*0','BS*B','BC*-','BC*+','TU*0','TU*B',
     &'TD*+','TD*-','TS*+','TS*-','TC*0','TC*B','TB*+','TB*-',
     &'RHO0','OMEG','PHI','PSI','UPSI','PHIT'/
C  DATA3, DEVOTED TO PARTICLE DECAY DATA AND PARAMETERS
      DATA IDB/4*0,1,9*0,2*2,8*0,2*5,2*7,2*11,2*14,2*18,2*23,2*28,
     &2*34,2*41,2*47,2*52,2*57,2*63,69,71,76,81,82,83,84,3*0,2*86,
     &2*87,2*89,2*91,2*93,2*96,2*97,2*98,2*99,2*100,2*101,2*102,2*103,
     &2*104,2*105,106,107,110,114,117,121/
      DATA CBR/1.,.17,.34,1.,.50,1.,.05,.10,.60,1.,.16,.32,1.,.10,
     &.20,.70,1.,.17,.34,.39,.90,1.,.17,.34,.39,.90,1.,.16,.32,.37,
     &.95,.95,1.,.07,.18,.29,.32,.66,.73,1.,.09,.18,.26,.55,.77,1.,
     &.12,.24,.34,.71,1.,.12,.24,.34,.71,1.,.09,.18,.26,.55,.77,1.,
     &.09,.18,.26,.55,.77,1.,.988,1.,.381,.681,.918,.969,1.,.426,.662,
     &.959,.98,4*1.,.686,2*1.,.667,1.,.667,1.,.55,1.,.65,.94,12*1.,
     &.899,.987,1.,.486,.837,.984,1.,.07,.14,1.,.03,.06,.09,1.,.08,
     &.16,.24,1.,.11*.0/
      DATA KDP/-37,10,14,17,57,58,8,12,-2,-14,8,12,-2,8,12,2*-2,10,
     &14,18,-7,-16,10,14,18,-7,-16,10,14,18,-7,-16,-22,15,10,14,18,
     &-7,2*-16,8,12,16,-2,-21,-26,8,12,16,-2,-21,8,12,16,-2,-21,8,
     &12,16,-2,-21,-27,8,12,16,-2,2*-21,3*1,51,22,2*1,21,51,3*1,3*-37,
     &21,51,21,25,2*23,25,3*27,2*29,31,33,35,37,39,41,43,45,47,49,
     &21,22,1,22,23,25,21,1,8,12,-37,8,12,16,-37,8,12,16,-37,12*0,
     &7,11,-7,2*0,9,13,-13,0,9,13,-14,9,13,-15,0,7,11,15,2*-19,7,11,
     &15,2*-20,7,11,15,2*-21,0,18,7,11,15,2*-22,0,9,13,17,2*-25,0,
     &9,13,17,2*-26,9,13,17,2*-27,9,13,17,2*-28,0,9,13,17,2*-29,0,
     &1,8,1,51,21,22,1,22,51,91,92,1,3*0,22,2*51,21,51,22,2*51,1,21,
     &51,11*1,22,21,51,21,24,26,22,52,7,11,0,7,11,15,0,7,11,15,13*0,
     &2*17,3*0,2*-13,2*0,2*-14,0,2*-15,2*0,3*-19,2*0,3*-20,2*0,3*-21,
     &4*0,3*-22,3*0,3*-25,3*0,3*-26,2*0,3*-27,2*0,3*-28,3*0,3*-29,
     &4*0,7,0,2*51,21,51,2*52,29*0,51,4*0,51,23*0/
      DATA CND/1.8,0.9,2./
      DATA WTCOR/16.,150.,2.,5.,15.,60.,250.,1500.,1.2E4,1.2E5/
      END
```

Appendix 2

Example of a $q\bar{q}g$ event generated with EVTGEN and printed with LIST.