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The Lund Monte Carlo for Jet Fragmentation and e^+e^- Physics - JETSET version 6.3 - an Update

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Abstract:

Version 6.2 of JETSET has been presented in a previous publication. This program contains models for jet fragmentation (string and independent) and particle decays, generators for e^+e^- annihilation events, and some event analysis routines. Here we describe improvements and changes in the new version of the program. Most affected is the simulation of timelike parton showers, as presented in detail. The program may be run essentially like version 6.2. Where new options have been added or default values changed, these are enumerated.

1. Introduction

Jet physics is not a closed subject, but in a state of steady development. This comes from an interplay between theory and experiment. The Lund Monte Carlo for jet fragmentation and e^+e^- physics occupies a middle ground, in which impulses from both directions are incorporated into a detailed phenomenological model for multiparticle production. Several versions have appeared in the past [1]; JETSET version 6.2 is roughly a year old by now [2]. Since then, we have carried out a detailed study of timelike parton showers in e^+e^- physics [3], which has lead to the development of a new LUSHOW routine.

There is accumulating evidence that second order matrix elements (plus jet fragmentation) is not enough to provide a fully satisfactory description of present PETRA/PEP data [4], and even larger discrepancies can be expected at TRISTAN/SLC/LEP. It is therefore natural to put more emphasis on parton showers and less on matrix elements. Indeed, this shift is the main reason for presenting a new version already now.

Apart from the parton showers, there are only minor changes: particle data have been brought up to date, a few new options introduced for event analysis (in LUCELL), some (noncritical) bugs found and corrected, and a few lines of code added to cover new cases encountered in the development of the Lund Monte Carlo for Hadronic Processes, PYTHIA version 4.7 [5]. Roughly 90% of the code is unchanged, and the JETSET version 6.2 manual is more than 90% relevant.

Under these circumstances, a supplement to the original manual [2] was deemed the most appropriate format. The original numbering of sections has been kept, for greater ease of usage, although this leads to some large gaps where no changes have been made. Further, terminology introduced in [2] or references given there are not repeated here.

3. Jet Fragmentation

The borderline between the perturbative QCD treatment, in terms of matrix elements or parton showers, and the realm of nonperturbative fragmentation effects is not well defined. Rather, the cutoff scale Q_0 could be chosen over

a wide range. It now seems that, with parton showers, a small value $Q_0 \approx 1$ GeV is preferred [3], rather than the $Q_0 \approx 5$ GeV used with matrix elements. The amount of gluon emission is therefore increased. This leads to a softening of the particle momentum spectrum, which has to be compensated by a hardening of the "nonperturbative" fragmentation function. In the formula

$$f(z) = z^{-1} (1-z)^a \exp(-bm_T^2/z) \qquad (1)$$

the default values have thus been changed from a = 1, b = 0.7 GeV^{-2} to a = 0.5, b = 0.9 GeV^{-2}. This may seem like a large change, but in terms of average charged multiplicity it corresponds to a shift of about 10% (for one and the same perturbative treatment). The infrared safe properties of string fragmentation contributes to keeping necessary changes modest, whereas much larger shifts are necessary if independent fragmentation is used. A further consequence of the increased gluon emission is that the σ parameter, related to average transverse momentum of primary hadrons ($\langle p_T^2 \rangle = 2\sigma^2$), may be decreased from 0.40 to 0.35 GeV. Finally, the requirement of a flat rapidity plateau necessitates a retuning of W_{min0}. The old value was 1.1 GeV, the new one 0.8 GeV.

In the generation of heavy flavours (c and above), an error has been found in the calculation of the point where the next breakup is assumed to give the final two hadrons rather than a hadron and a remainder-system. It only affects the non-standard (Field-Feynman, Peterson et al., etc.) fragmentation functions. A new procedure has therefore been implemented, as follows. Assume a remainder-system $q_i\bar{q}_j$ of transverse mass W_{rem}, with q_i and/or $\bar{q}_j$ a heavy flavour. In addition to the ordinary test (performed for light flavours), the following execise is then carried out. By the production of a $q_n\bar{q}_n$ pair a hadron $q_i\bar{q}_n$ is formed, leaving a remainder $q_n\bar{q}_j$. The range of allowed z values, i.e. the fraction of remaining $E+p_z$ that may be taken by the $q_i\bar{q}_n$ hadron, is constrained away from 0 and 1 by the $q_i\bar{q}_n$ and $q_n\bar{q}_j$ masses. The limits of the physical z range is obtained when the $q_n\bar{q}_j$ system only consists of one single particle. From the z value obtained with the infinite-energy fragmentation function formulae, a rescaled z' value between these limits is given by

$$z' = \frac{W_{rem}^2 + m_{Tin}^2 - m_{Tnj}^2 + \left\{(W_{rem}^2 - m_{Tin}^2 - m_{Tnj}^2)^2 - 4m_{Tin}^2 m_{Tnj}^2\right\}^{1/2}(2z-1)}{2W_{rem}^2} \qquad (2)$$

From the z' value, the actual transverse mass $m'_{Tnj} \geq m_{Tnj}$ of the $q_n\bar{q}_j$ system may be calculated. For more than one particle to be produced out of this system, the requirement

$$m'^2_{Tnj} = (1 - z')\left(W^2_{rem} - \frac{m^2_{Tin}}{z'}\right) > (m_{qj} + W_{min0})^2 + p^2_T \qquad (3)$$

has to be fulfilled. If not, the $q_n\bar{q}_j$ system is assumed to collapse to one single particle.

The consequence of the procedure above is that, the more the infinite energy fragmentation function f(z) is peaked close to z=1, the more likely it is that only two particles are produced. In particular, for $t\bar{t}$ systems, where very large <z> values are predicted, the expectation is that two particle final states will dominate far above the threshold region. The procedure above has been constructed so that the two particle fraction can be calculated directly from the shape of f(z) and the (approximate) mass spectrum, but it is not unique. For the symmetric Lund fragmentation function (eq. (1)), a number of alternatives tried all give essentially the same result, whereas other fragmentation functions may be more sensitive to details.

Once an allowed setup of two final hadrons has been produced, two orderings are possible. The probability for the reverse one, i.e. where the rapidity and the flavour orderings disagree, is parametrized by

$$P_{reverse} = \frac{1}{2}\left\{\frac{m_{T1} + m_{T2}}{W_{rem}}\right\}^d \qquad (4)$$

In the program, d has been assumed constant. Actually, for symmetric fragmentation, the ordering is expected to be increasingly strict when the particles involved are more massive. A better approximation (but still far from perfect), with $d \to d_0 \cdot (m^2_{T1}+m^2_{T2})^2$ is now used.

4. Particles and their Decays

Particle masses and branching ratios have been updated in accordance with the Particle Data Group 1986 edition [6]. The major changes are in the D^0 and D^+ branching ratios. Still, a number of decay modes remain to be found and measured, so the known ones are complemented with "educated guesses", as before.

Particle names have not yet been modified to agree with the new conventions [6]. In particular, our B meson is still the one that contains a b quark, rather than a $\bar{b}$ one, and similarly for mesons containing the hypothetical

fourth generation down quark 1. Further, the D_s^+ is still called F^+.

Three new particles have been introduced for usage within PYTHIA 4.7 [5], a horizontal gauge boson R^0, $\bar{R}^0$ [7], a charged Higgs $H^\pm$ and an additional "extended electroweak" gauge boson Z'^0. Default masses are chosen as 5000 GeV, 300 GeV and 900 GeV, respectively.

5. Description of the Jet Fragmentation Routines

5.1. The Event Record

K(I,2) : three new particle codes have been introduced

91	R^0	-91	$\bar{R}^0$	(horizontal gauge boson)
92	H^+	-92	H^-	(charged Higgs)
93	Z'^0			(second neutral electroweak gauge boson)

These codes were previously at the disposal of the user, and can so still be used, except when the production of one of these particles is studied in PYTHIA.

5.2. Definition of Initial Configuration

SUBROUTINE LU2JET(IP,IFL1,IFL2,ECM)
SUBROUTINE LU3JET(IP,IFL1,IFL3,ECM,X1,X3)
SUBROUTINE LU4JET(IP,IFL1,IFL2,IFL3,IFL4,ECM,X1,X2,X4,X12,X14)

IP : all three routines now accept the option IP<0 to signify that jets should be stored in every second line, starting with line -IP. A second line for each jet will then contain extra colour connection information, so that a parton shower can be generated by a LUSHOW call (with up to three showering partons), followed by a LUEXEC call, if so desired.

5.5. The General Switches and Parameters

COMMON/LUDAT1/MST(40),PAR(80)
Status codes and parameters with new options or changed default values are the following.

MST(7) : (D=2) particle decays.

= 0 : all particle decays are inhibited.

= 1 : particles declared unstable in the IDB vector are allowed to decay. A particle may decay into jets, which then may fragment further as dictated by MST(5).

= 2 : as =1, except that a $q\bar{q}$ jet system produced in a decay (e.g. of a B meson) is always allowed to fragment according to string fragmentation rather than according to the MST(5) value (this means that energy, momentum and charge are always conserved in the decay).

PAR(12) : (D=0.35) corresponds to the width in the Gaussian p_x and p_y transverse momentum distributions for primary hadrons.

PAR(23), PAR(25): (D=0.8 GeV, 0.8 GeV) are, together with quark masses, used to define the remaining energy below which the fragmentation of a jet system is stopped and two final hadrons formed. The two alternatives refer to MST(4)=1 or 3.

PAR(28), PAR(30): (D=2.5, 2.5) gives the d parameter (eq. (4)) for reverse rapidity ordering of the final two hadrons, in the form d = PAR(..)$\cdot(m_{T1}^2+m_{T2}^2)^2$. The two alternatives refer to MST(4)=1 or 3.

PAR(31), PAR(32) : (D=0.5, 0.9 GeV^{-2}) give the a and b parameters of the symmetric Lund fragmentation function for MST(4)=1 (and MST(4)=3 for ordinary hadrons) $f(z) = z^{-1} (1-z)^a \exp(-bm_T^2/z)$, where m_T is the transverse mass of the hadron.

PAR(33), PAR(34) : (D=0.5, 0.9 GeV^{-2}) give the a and b parameters as above for the special case of a gluon jet generated with MST(5)=4 or 6.

PAR(35), PAR(36) : (D=0.5, 0.9 GeV^{-2}) give the a and b parameters as above for the special case of a hadron or diquark jet before the J- and/or I-quarks have been used up.

6. e^+e^- Physics

6.1. Annihilation Events in the Continuum

Recent data have tended to shift the value for the electroweak mixing angle upwards [8]; the value $\sin^2\theta_W = 0.229$ is now used rather than 0.217.

Whereas both a matrix element and a parton shower treatment are available, as before, the default has been shifted from the former to the latter choice. While an improvement in many respects, some features are lost thereby. In particular, the full electroweak structure for the angular orientation of three-jet events is available with the matrix element approach, whereas the orientation of parton shower events is only based on the original outgoing quark-antiquark pair.

6.2. Strong Decays of Onia Resonances

As with the continuum events, a parton shower approach is now obtained by default, starting from the two (in ggγ events) or three (in ggg ones) outgoing gluons. For three radiating partons, the maximum mass of each parton is taken to be its energy in the CM frame. Contrary to the case of continuum events, there is no attempt to match on to the next higher order results, here four-jet production. If ever toponium is found in a mass range where decays to ggg are dominant (rather than weak decays of top quarks), the predicted 4-jet/3-jet ratio should therefore be taken with a grain of salt (but it is still more relevant than what is obtained without the use of parton showers).

6.3. Parton Showers

The new parton shower algorithm is described in [3]; a summary is given in the following. From a practical point of view, the main improvement is that one single algorithm now is used both for the conventional and the coherent evolution, so that the effects of angular ordering (the main feature of coherence) can be separated from other effects in a more consistent manner. Further, different definitions of the z splitting variable and the Q^2 scale may be used. In the coherent evolution scenario, these aspects are fairly well constrained (in accordance with the default values) by theoretical studies [9], whereas there is more freedom for conventional evolution.

Parton showers are based on an iterative use of the basic q→qg, g→gg and g→$q\bar{q}$ branchings, as given by the Altarelli-Parisi equations

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

for the probability that a branching a→bc will take place during a small change dt, where $t = \ln(m_a^2/\Lambda^2)$. Starting from the maximum allowed mass for parton a, t may be successively degraded until a branching occurs, at a given mass and with a given z. The products b and c may be allowed to branch in their turn, and so on. The parton branching is stopped when a parton mass is

evolved below some minimum cutoff. For this purpose, one may define effective parton masses $m_{eff,g} = m_{min}/2$ and $m^2_{eff,q} = m^2_{min}/4 + m^2_q$. Here $m_u = m_d = 0.325$ GeV, $m_s = 0.5$ GeV, $m_c = 1.6$ GeV and $m_b = 5.0$ GeV. The minimum mass for a gluon to branch (into two gluons) is then $m_{min,g} = 2m_{eff,g} = m_{min}$ and for a quark to branch (into a quark and a gluon) $m_{min,q} = m_{eff,q} + m_{eff,g}$.

In the Altarelli-Parisi splitting functions $P_{a\to bc}(z)$, the variable z gives the energy fraction (or, more generally, fraction of some combination of energy and momentum) taken by b, with 1-z taken by c. The exact interpretation of z is not uniquely specified in the leading log approximation, so four somewhat different alternatives are available in the program. These may be obtained by combining a "local" or a "global" z definition with a "constrained" or an "unconstrained" maximum daughter virtuality, as follows.

Consider a system of two radiating partons, e.g. $e^+e^- \to \gamma_0 \to q_1\bar{q}_2$, where the indices are used to number the related four-momenta $p_i = (E_i,\bar{p}_i)$. The total four-momentum of the system is given by p_0; in general there need not be a specific particle with that momentum. Now, in the local z definition, z is interpreted as energy fraction in the rest frame of the respective "grandmother". For $q_1 \to q_3g_4$ this is $z_1 = (p_0p_3)/(p_0p_1)$, for $q_3 \to q_5g_6$ $z_3 = (p_1p_5)/(p_1p_3)$, for $q_5 \to q_7g_8$ $z_5 = (p_3p_7)/(p_3p_5)$, etc. In the global definition, z is always energy fraction in the rest frame of the radiating system (this need not be the same as the overall CM frame, consider e.g. high-p_T interactions, where the total system also contains spectator quarks), i.e. $z_1 = (p_0p_3)/(p_0p_1)$, $z_3 = (p_0p_5)/(p_0p_3)$, $z_5 = (p_0p_7)/(p_0p_5)$, etc. For the branchings of the two original partons 1 and 2 the two alternatives coincide.

In a branching $a \to bc$ the kinematically allowed range of z values, $z_{a-} < z_a < z_{a+}$, is given by

$$z_{a\pm} = \frac{1}{2}\left\{1 + \frac{m_b^2-m_c^2}{m_a^2} \pm \beta_a \frac{\lambda^{1/2}(m_a^2,m_b^2,m_c^2)}{m_a^2}\right\} \qquad (6)$$

Here $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$ and $\beta_a = |\bar{p}_a|/E_a$ is the velocity of parton a, in the rest frame of the grandmother for the local z definition and in the rest frame of the system for the global one. With constrained evolution, the bounds above are respected. The cutoff masses $m_{eff,b}$ and $m_{eff,c}$ are used to define the maximum allowed z range, within which z_a is chosen, together with the m_a value. In the subsequent evolution, only pairs of m_b and m_c values are allowed, for which the fixed z_a is within the actual limits given by eq. (6). For unconstrained evolution, one may start off

by assuming the daughters massless, so that the allowed z range is

$$z_{a\pm} = \frac{1}{2}\left\{1 \pm \beta_a\, \theta(m_a - m_{min,a})\right\} \qquad (7)$$

($\theta(x) = 1$ for $x > 0$, $= 0$ for $x < 0$). The decay kinematics into two massless four-vectors p_b^0 and p_c^0 is then straightforward. Once m_b and m_c have been found from the subsequent evolution, subject only to the constraints $m_b < z_aE_a$, $m_c < (1-z_a)E_a$ and $m_b+m_c < m_a$, the actual massive four-vectors may be defined as

$$p_{b,c} = p^0_{b,c} \pm (r_cp_c - r_bp_b)$$
$$r_{b,c} = \frac{m_a^2 - \lambda^{1/2}(m_a^2,m_b^2,m_c^2) \pm (m_c^2-m_b^2)}{2m_a^2} \qquad (8)$$

In other words, the meaning of z_a is somewhat reinterpreted post facto.

Since the β_a values generally are larger if evaluated in the rest frame of the radiating system rather than in the rest frame of the grandmother, the allowed z range and hence the amount of evolution is larger with the global z definition. Needless to say, unconstrained daughter masses also give more evolution than constrained ones. The standard, coherent option is with global z and unconstrained daughter masses, i.e. maximal evolution.

The kinematics of a branching $a \to bc$ is almost uniquely specified by the four-momentum of a, the z value and the masses of b and c. What remains is an azimuthal angle ϕ, i.e. a rotation of the bc system around the a axis. This angle is chosen isotropically.

Theoretical studies have shown that coherence effects lead to an angular ordering, so that the angles of successive branchings are steadily decreasing. The kinematics described so far leads to a conventional shower, in which angular ordering is not always fulfilled. With the conventional shower as a starting point, angular ordering may be introduced as follows, however. The opening angle θ_a for $a \to bc$ is approximately

$$\theta_a \approx \frac{p_{Tb}}{E_b} + \frac{p_{Tc}}{E_c} \approx \{z_a(1-z_a)\}^{1/2} m_a \left\{\frac{1}{z_aE_a} + \frac{1}{(1-z_a)E_a}\right\} = \frac{1}{\{z_a(1-z_a)\}^{1/2}} \frac{m_a}{E_a} \qquad (9)$$

so the requirement $\theta_3 < \theta_1$ is reduced to

$$\frac{z_3(1-z_3)}{m_3^2} > \frac{1 - z_1}{z_1 m_1^2} \tag{10}$$

where $E_3 = z_1 E_1$ has been used to eliminate the energy factors. If a branching of parton 3 does not fulfill this ordering condition, the branching is rejected and the evolution in mass continued.

Angular ordering provides no constraints on θ_1 and θ_2, since the opening angle between the two original partons is $\theta_0 = 180^\circ$ (since the event is considered in the rest frame of these partons). For the special case of e^+e^- annihilation, this freedom may be used to match on to the three-jet matrix element, as follows. A three-jet event $q(x_1)\bar{q}(x_2)g(x_3)$, with $x_i = 2E_i/s^{1/2}$ in the CM frame, can be obtained either by $\gamma_0 \to q_{1^*}\bar{q}_2$ followed by $q_{1^*} \to q_1 g_3$ or by $\gamma_0 \to q_1\bar{q}_{2^*}$ followed by $\bar{q}_{2^*} \to \bar{q}_2 g_3$. In the first case one obtains

$$m^2 = m_{1^*}^2 = (1 - x_2)s \quad \Rightarrow \quad dt = \frac{dm^2}{m^2} = \frac{dx_2}{1 - x_2}$$
$$z = \frac{p_0 p_1}{p_0 p_{1^*}} = \frac{x_1}{x_1 + x_3} = \frac{x_1}{2 - x_2} \quad \Rightarrow \quad dz = \frac{dx_1}{2 - x_2} \tag{11}$$

In the definitions of x_1 and x_2, masses other than m_{1^*} are neglected. Combined with the second possibility, with labels 1 and 2 exchanged, eq. (11) gives the same singularity structure as the first order three-jet matrix element

$$\frac{1}{\sigma}\frac{d\sigma}{dx_1 dx_2} = \frac{2}{3}\frac{\alpha_s}{\pi}\frac{A(x_1,x_2)}{(1-x_1)(1-x_2)} \tag{12}$$

$$A_{shower}(x_1,x_2) = 1 + \frac{1-x_1}{(1-x_1)+(1-x_2)}\left(\frac{x_1}{2-x_2}\right)^2 + \frac{1-x_2}{(1-x_1)+(1-x_2)}\left(\frac{x_2}{2-x_1}\right)^2 \tag{13}$$

$$A_{matrix}(x_1,x_2) = x_1^2 + x_2^2 \tag{14}$$

In the limit $x_1 \to 1$ ($x_2 \to 1$) $A_{shower} = A_{matrix} = 1 + x_2^2$ ($= 1 + x_1^2$), with $A_{matrix}(x_1,x_2) \leq A_{shower}(x_1,x_2)$ everywhere. It is therefore possible to reproduce the matrix element by generating the branchings of partons 1 and 2 according to the shower algorithm, but only accept these branchings with probability $A_{matrix}(x_1,x_2)/A_{shower}(x_1,x_2)$. One should note that some implicit differences remain. In a parton shower the probability of a first branching at a given m is reduced by the probability that no branching has taken place at a larger virtuality, i.e. by the Sudakov form factor. Further, α_s may be allowed to run during the evolution of the parton shower.

The derivation above is implicitly made under the assumption that the maximum parton virtuality is given by the CM energy, i.e. that a $m_{1^*}^2 \approx s$ is allowed. In high-p_T interactions this need not apply; it is then more natural to relate the maximum parton masses to the p_T of the hard interaction.

The Q^2 scale in α_s may be chosen to be either $m_a^2/4$ or $z_a(1-z_a)m_a^2$ ($\approx p_T^2$) for a branching $a \to bc$, with the latter in agreement with results from coherence studies. The factor 1/4 in the former has been chosen to make Λ values determined by the two options more comparable ($z(1-z) \leq 1/4$). It should be emphasized that these values can not be directly compared with $\Lambda_{\overline{MS}}$ values obtained with matrix elements. The number of active flavours n_f in the expression for α_s

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f)\ln(Q^2/\Lambda^2)} \tag{15}$$

is always assumed to be at least 3 (u,d,s); heavier flavours are included if $m_a^2 > 4m_q^2$. Note that the requirement of finite α_s values implies that $Q^2 > \Lambda^2$, a nontrivial requirement on the allowed phase space for branchings when $Q^2 = z_a(1-z_a)m_a^2$. Finally, for completeness, an option with fixed α_s values is also available.

Production of heavy flavours from $g \to q\bar{q}$ is allowed when $m_a^2 > 4m_q^2$. For constrained evolution, the phase space factor $\lambda^{1/2}/m_a^2$ gives an approximate $(1-4m_q^2/m_a^2)^{1/2}$ suppression ($P_{g\to q\bar{q}}(z)$ is essentially flat in z). In the unconstrained case, an explicit suppression factor $(1+2m_q^2/m_a^2)(1-4m_q^2/m_a^2)^{1/2}$ is included in the production probability.

In most applications, there are two radiating partons emerging from a hard interaction, as described above. Sometimes, like in $qg \to q\gamma$ in high-p_T interactions, only one of the outgoing particles is allowed to radiate. If specified as a system, energy and momentum may be shuffled between the sides, so that the energy of the γ is reduced if the recoiling q acquires a mass. Also the directions of the original particles are affected in the process. The natural procedure is here to preserve these directions in the rest frame of the system, be that with one or both particles radiating. Some showers may be viewed as initiated by a single radiating parton, like the scattered quark in leptoproduction or timelike partons emitted in initial state radiation [10]. For these it is not possible to conserve the four-momentum. The choice has been made to conserve energy and jet (momentum) direction, but allow the momentum vector to be scaled down if the radiating parton acquires a mass. (If

one rather desires momentum to be conserved, this can be obtained afterwards by a boost along the jet direction.) The "rest frame of the system", used e.g. in the z definition, is taken to be whatever frame the jet is given in.

Sometimes one may wish to consider systems starting out with three radiating partons, the most obvious case being three-gluon decays of Υ or toponium. The definition of rest frame and hence z is then straightforward, but one is left with the issue how the energy sharing variables x_1 and x_2 from the massless matrix elements should be reinterpreted for a massive three-parton configuration. We have made the arbitrary choice of preserving the energy of each parton, which means that relative angles between the original partons is changed. Mass triplets outside the allowed phase space are rejected and the evolution continued.

In string (as well as cluster) fragmentation scenarios, it is not only necessary to trace the evolution of showers in momentum, but also to keep track of the colour arrangement, i.e. the way the string is to be drawn between the final partons. In the leading log approximation, with only simple $q \to qg$, $g \to gg$ and $g \to q\bar{q}$ branchings, this is straightforward. For $q \to qg$ the gluon becomes a kink on the string ending at the q, for $g \to gg$ an additional string piece is stretched between the gluons and for $g \to q\bar{q}$ the gluon kink is resolved into two quark string endpoints. A dependence on the azimuthal angle with respect to surrounding partons is conceivable for the $g \to gg$ case, where two different string drawings are possible, but this has not been considered. In e^+e^- annihilation the original $q\bar{q}$ (or ggg) pair is in a colour singlet, but the shower formalism works equally well when this is not the case, e.g. in high-p_T interactions.

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

7.1. e^+e^- Continuum Event Generation

SUBROUTINE LUEEVT(IFL,ECM)

The emphasis of LUEEVT has been somewhat shifted but, apart from the comments below, the old description is still valid.

Purpose : to generate a complete event $e^+e^- \to \gamma/Z^0 \to q\bar{q} \to$ parton shower $\to$ hadrons according to QFD and QCD cross-sections. As an alternative to parton showers, second order matrix elements are available for $q\bar{q} + q\bar{q}g + q\bar{q}gg + q\bar{q}q'\bar{q}'$ production.

Remark : Since Sudakov form factors are no longer pretabulated, reinitializations are only needed because of changed electroweak parameters (see MSTE(9)) in connection with initial state photon radiation.

7.2. A Routine for Onium Decay

SUBROUTINE LUONIA(IFL,ECM)

This routine now includes a parton shower evolution, starting from the ggg or ggγ configuration given by the lowest order matrix element. The evolution may be switched off, see MSTE(1).

7.3. A Routine for Timelike Shower Evolution

SUBROUTINE LUSHOW(IP1,IP2,QMAX)

The routine LUSHOW is completely rewritten, but can be used exactly as the old one. Some new alternatives have been introduced; the revised description follows.

Purpose : to generate timelike parton showers, conventional or coherent. The performance of the program is regulated by the switches MSTE(11) - MSTE(15) and parameters PARE(21) and PARE(22).

IP1 = 0, IP2 = 0 : no action is taken (previously used for initialization of Sudakov form factors, but this is no longer needed).

IP1 > 0, IP2 = 0 : generate a timelike parton shower for the parton in line IP1 in commonblock LUJETS, with maximum allowed mass QMAX. With only one parton at hand, one can not simultaneously conserve both energy and momentum; we here choose to conserve energy and jet direction, while longitudinal momentum (along the jet axis) is not conserved.

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

IP1 > 0, IP2 < 0 : generate timelike parton showers for the -IP2 (at most 3) partons in lines IP1, IP1+2, ..., IP1+2*(|IP2|-1) in the commonblock

LUJETS, with maximum allowed mass for each parton QMAX. The actions for IP2 = -1 or IP2 = -2 correspond to the ones obtained with the two alternatives above, but additionally IP2 = -3 may be used to generate the evolution starting from three given partons (e.g. in toponium → ggg). Then the three partons are boosted to their CM frame, energy is conserved for each parton individually and momentum for the system as a whole.

QMAX : the maximum allowed mass of a radiating parton, i.e. the starting value for the subsequent evolution (In addition, the mass of a single jet may not exceed its energy, the mass of a jet in a system may not exceed the invariant mass of the system.)

7.4. Routines for Event Analysis

SUBROUTINE LUCELL(NJET)

Some new options have been introduced in LUCELL (but the old scheme is retained as default). The complete revised description follows.

Purpose: to provide a simpler cluster routine more in line with what is currently used in the study of high-p_T collider events. A detector is assumed to stretch in pseudorapidity between -PARE(35) and +PARE(35) and be segmented in MSTE(24) equally large η (pseudorapidity) bins and MSTE(25) ϕ (azimuthal) bins. Transverse energy E_T for undecayed entries are summed up in each cell. For MSTE(27) nonzero, the energy is smeared by calorimetric resolution effects, cell by cell. This is done according to a Gaussian distribution; if MSTE(27)=1 the standard deviation for the E_T is PARE(39)$\cdot E_T^{1/2}$, if MSTE(27)=2 the standard deviation for the E is PARE(39)$\cdot E^{1/2}$, E_T and E expressed in GeV. The Gaussian is cut off at 0 and at a factor PARE(40) times the correct E_T or E. All bins with E_T > PARE(36) are taken to be possible initiators of jets, and are tried in falling E_T sequence, to check whether the total E_T summed over cells no more distant than PARE(38) in $\{(\Delta\eta)^2+(\Delta\phi)^2\}^{1/2}$ exceeds PARE(37). If so, these cells define one jet, and are removed from further consideration. Contrary to LUCLUS, not all particles need be assigned to jets.

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

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

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

K(N+i,1) = i, the jet number, with the jets arranged in falling order in E_T;

K(N+i,2) = the number of particles assigned to jet i.

Further, for MSTE(26) = 1

P(N+i,1), P(N+i,2) : position in η and ϕ of the center of the jet initiator cell, i.e. geometrical center of jet;

P(N+i,3), P(N+i,4) : position in η and ϕ of the E_T-weighted center of the jet, i.e. the center of gravity of the jet;

P(N+i,5) : sum E_T of the jet;

while for MSTE(26) = 2

P(N+i,1) - P(N+i,5) : the jet momentum, constructed from the summed E_T and the η and ϕ of the E_T-weighted center of the jet as $(p_x,p_y,p_z,E,m) = E_T(\cos\phi,\sin\phi,\sinh\eta,\cosh\eta,0)$;

and for MSTE(26) = 3

P(N+i,1) - P(N+i,5) : the jet momentum, constructed by adding vectorially the momentum of each cell assigned to the jet, assuming that all the E_T was deposited at the center of the cell. The jet mass in P(N+i,5) is calculated from the summed E and p as $m^2 = E^2 - p_x^2 - p_y^2 - p_z^2$.

7.5. The LUDATE Commonblock

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

Status codes and parameters with new options or changed default values are the following.

MSTE(1) : (D=3) gives the type of QCD corrections used for continuum events.

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

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

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

= 3 : a parton shower is allowed to develop from an original $q\bar{q}$ pair, see MSTE(11)-MSTE(15) for details.

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

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

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

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

for =-1 applies.

Note: PARE(1) is now also used for onium resonance events, with

<2 : ggg + ggγ events are generated according to lowest order matrix elements.

>3 : a parton shower is allowed to develop from an original ggg or ggγ configuration, see MSTE(11), MSTE(12), MSTE(14) and MSTE(15) for details.

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

= 0 : no LUEXEC calls, i.e. only matrix element treatment.

= 1 : LUEXEC calls are made to generate fragmentation and decay chains.

= -1 : no LUEXEC calls and no collapse of small jet systems into one or two particles (in LUPREP); if this is followed by a LUEXEC call later, a harmless warning may be generated that a jet system is too small.

MSTE(9) : (D=1) initialization of total cross-section and radiative photon spectrum (initialization of LUSHOW no longer needed).

= 0 : never; can not be used together with radiative corrections.

= 1 : calculated at first call and then whenever IFL or MSTE(2) is changed or ECM is changed by more than PARE(17).

= 2 : calculated at each call.

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

MSTE(11) : (D=2) branching mode for timelike parton shower.

= 0 : no branching at all.

= 1 : conventional branching, i.e. without angular ordering.

= 2 : coherent branching, i.e. with angular ordering.

MSTE(12) : (D=4) choice of z definition in branching.

= 1 : energy fraction in grandmother's rest frame ("local, constrained").

= 2 : energy fraction in grandmother's rest frame assuming massless daughters, with energy and momentum reshuffled for massive ones ("local, unconstrained").

= 3 : energy fraction in CM frame of the showering partons ("global, constrained").

= 4 : energy fraction in CM frame of the showering partons assuming massless daughters, with energy and momentum reshuffled for massive ones ("global, unconstrained").

MSTE(13) : (D=2) corrections for lowest order $q\bar{q}g$ three-jet matrix element at the first branching of either initial parton in a shower.

= 0 : no correction.

= 1 : correction if LUSHOW is called from LUEEVT, else not.

= 2 : always included if scattered partons are $q\bar{q}$.

MSTE(14) : (D=2) choice of α_s scale for shower.

= 0 : fixed at PARE(3) value.

= 1 : running with $Q^2 = m^2/4$, m mass of decaying parton, Λ as stored in PARE(21).

= 2 : running with $Q^2 = z(1-z)m^2$, i.e. roughly p_T^2 of branching, Λ as stored in PARE(21).

MSTE(15) : (D=5) maximum flavour that can be produced in a shower by branchings $g \to q\bar{q}$; also used to determine the maximum number of active flavours in the α_s factor in parton showers (here with a minimum of 3).

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

MSTE(26) : (D=1) form for presentation of information about reconstructed clusters in LUCELL, as stored in /LUJETS/ in lines N+1 through N+NJET.

= 1 : the P vector in each line contains η and ϕ for geometric origin of jet, η and ϕ for weighted center of jet, and E_T of jet, respectively.

= 2 : the P vector in each line contains a massless four-vector giving direction of jet, obtained as $(p_x,p_y,p_z,E,m) = E_T(\cos\phi,\sin\phi,\sinh\eta,\cosh\eta,0)$ where η and ϕ give the weighted center of the jet and E_T the transverse energy of it.

= 3 : the P vector in each line contains a massive four-vector, obtained by adding the massless four-vectors of all cells that form part of the jet, and calculating the jet mass from $m^2 = E^2 - p_x^2 - p_y^2 - p_z^2$. For each cell, the total E_T is summed up, and then translated into a massless four-vector assuming that all the E_T was deposited in the center of the cell.

MSTE(27) : (D=0) smearing of correct energy, imposed cell-by-cell in LUCELL, to simulate calorimeter resolution effects.

= 0 : no smearing.

= 1 : the transverse energy in a cell, E_T, is smeared according to a Gaussian distribution with standard deviation PARE(39)$\cdot E_T^{1/2}$, with E_T given in GeV. The Gaussian is cut off so that $0 < E_{T\text{smeared}} <$ PARE(40)$\cdot E_{T\text{true}}$.

= 2 : as =1, but it is the energy E rather than E_T that is smeared.

MSTE(32) : not used.

PARE(5) : (D=0.229) $\sin^2\theta_W$, weak mixing angle in QFD.

PARE(21) : (D=0.40 GeV) Λ value used in α_s for parton showers.

PARE(22) : (D=1.0 GeV) invariant mass cutoff m_{min} of parton showers, below which partons are not assumed to radiate. For $Q^2 = p_T^2$ (MSTE(14)=2) PARE(22)/2 additionally gives the minimum p_T of a branching. To avoid infinite α_s values, one must have PARE(22) > 2$\cdot$PARE(21) for MSTE(14) ≥ 1

(this is automatically checked in the program, with 2.2·PARE(21) used as lowest value attainable).

PARE(23) - PARE(29) : not used.

PARE(39) : (D=0.5) the calorimeter cell resolution assumed when smearing the transverse energy (or energy) in LUCELL (see MSTE(27)) is taken to be PARE(39)·$E_T^{1/2}$ (or PARE(39)·$E^{1/2}$), for E_T (or E) in GeV.

PARE(40) : (D=2.) maximum factor of upward fluctuation in energy or transverse energy in a given cell when calorimeter resolution is included in LUCELL (see MSTE(27)).

PARE(66) - PARE(80) : not used.

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