JET FRAGMENTATION AT COLLIDER ENERGIES

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A B S T R A C T

We investigate the fragmentation properties of quark and gluon jets at present and future collider energies. Effects due to gluon radiation, as described by leading logarithm QCD parton cascade evolution, are discussed in terms of different model calculations. The longitudinal and transverse properties of jets are shown, in particular the angular energy profile and jet substructure are examined.

1 Introduction

The existence of high- $p_{\perp}$ jets in hadron-hadron collisions have been clearly shown both at the ISR [1] and the SPS $p\bar{p}$ collider [2]. Their rate and distribution in e.g. $p_{\perp}$ have furthermore been found to agree with predictions based on perturbative QCD [3]. The studies of the fragmentation properties of these jets have also recently been started [4,5]. It is therefore interesting to make more detailed investigations on what is expected for jet fragmentation based on current fragmentation model ideas, which provide a working phenomenological framework for lower energy jets in e^+e^- annihilation and deep inelastic scattering.

From an experimental point of view the gluon fragmentation function is badly known, but in virtually all models it has a softer fragmentation than a quark jet. In some models this comes about by the splitting of the gluon into a quark-antiquark pair, thus giving two lower energy jets. In the Lund string model [6] a gluon acts as a kink on a string and hence stretches two strings, resulting in a softer particle spectrum. Considering also QCD based gluon bremsstrahlung a further softening is expected.

At the collider, which predominantly produces gluon jets, these expectations could be further investigated. The first results presented in [5] show a strong similarity between collider (predominantly gluon) jets and TASSO (predominantly quark) jets with regard to the fragmentation function, thus seemingly suggesting that a gluon jet at collider energies has more or less the same fragmentation function as lower energy quark jets. One should keep in mind however, that jet reconstruction is more difficult at the collider because of the complicated underlying event. In particular, it is difficult to correctly assign the low energy particles to the jets and this will lead to distortion effects in the measured fragmentation spectrum. As an example we show in fig. 1 the original fragmentation function of a gluon jet (using the Lund model) at a typical energy for the collider (full line) and the resulting spectrum when particles having fractional momentum, $z=p_{\parallel}/E_{\text{jet}}$, less than 0.05 are not included in the definition of the jet (dashed curve). This loss of particles leads to a loss of energy, which in this case is about 30%, which in turn gives a flatter spectrum for the remaining particles in the jet. As can be seen in

fig. 1 the resulting spectrum is not very different from a typical quark jet at PETRA energies. We note that this kind of effect is more important the more energy is carried by low energy particles. Thus a quark jet is less affected, whereas a gluon jet would be even more distorted if it is still softer as expected based on QCD bremsstrahlung effects. Including that, as discussed below, it would be sufficient to loose only those particles having an angle to the jet axis larger than 35° or fractional momentum below 0.03 to get the same distortion effect as in fig. 1. These distortion effects are at least partly corrected for in [5], but they are difficult to take into account in a model independent way. Their effect can certainly be investigated by letting Monte Carlo generated jets (according to various models) be passed through the experimental analysis chain. From the point of view of fragmentation models it is certainly very important to get a clear result on the gluon fragmentation function at collider energies. In particular, few models would survive if collider gluon jets were indeed as hard as quark jets at PETRA energies!

A future supercollider [7] will be a rich source of very high energy jets which may arise from conventional hard parton-parton scattering or from some new, heavy state decaying into quarks and gluons. An important question to answer is then: What will these jets look like? How hard and wide can we expect them to be, or more precisely, what is the expected fragmentation function and angular energy profile? From a theoretical point of view this is interesting because it may test our ideas for the fragmentation process and thereby improve our understanding of the confinement problem. Different models that more or less agree at low jet energies may differ substantially when extrapolated to extreme energies. For the experimentalist it will affect the ability to measure jets and thereby the accuracy of reconstructed jet-jet invariant masses to be used in the search for possible new, heavy states decaying into jets.

The aim of this paper is thus to investigate jet fragmentation properties at present and future collider energies. To get quantitative results we use Monte Carlo implementations of models for the development of parton cascades based on perturbative QCD in the leading logarithm approximation and for the final nonperturbative hadron formation. These models, which are discussed in section 2, will differ somewhat when extrapolated to large jet energies even

though fitting data at lower energies. Section 3 gives the resulting fragmentation functions and multiplicities and in section 4 the widths of jets are investigated together with the possible jet substructure. Finally, we end by some concluding remarks in section 5.

2 Jet fragmentation models

Standard jet fragmentation models deal with the transition from high momentum partons into the observable hadrons independently of the way these partons were produced. The simplest approach is to treat each parton as a separate jet and make a parametrization of the fragmentation function. This is the case with the original Field and Feynman model [8]. In such an approach the gluon fragmentation function can be freely varied even if the quark fragmentation function has been fixed. Depending on the actual model the gluon can be treated as a quark jet of random flavour (possible with a softer fragmentation function) or, as is often done, be split into a quark-antiquark pair using the Altarelli-Parisi equations for the longitudinal momentum sharing and then fragment this pair as independent quark jets.

In another scheme, the Lund string model [6], the basic assumption is rather that coloured partons never hadronize independently but are part of a colour singlet jet system including some colour charged partons and their intermediate colour force fields (strings) and that it is these fields that break up to form the hadrons. The dynamics of the fields are modelled by the massless relativistic string which forms a causal and relativistically covariant theory. The gluon is in this case represented by a kink on the string and there is therefore no additional freedom for the gluon fragmentation function once the breakup of the colour triplet field has been determined from quark jets. Furthermore, the form of the fragmentation function is not arbitrary, but given by basic symmetry requirements in the fragmentation process [9]. The system of partons building up the jet system is not given by the standard string model, which only deals with the hadronization of the system once it has been formed from some hard scattering process described by electroweak interactions and/or perturbative QCD. Normally, the leading (or even next to

leading) order perturbative QCD is used to provide the partonic system. We should point out however, that there has recently been some very interesting developments in getting nonperturbative cross sections based on the string model [10], which eventually could provide an effective description of the initial string configuration similarly as perturbative QCD does it by giving the parton system. Since this possibility is at a too early stage of development to be used practically it is not considered further here.

Thus one should in general try to calculate partonic cross sections to as high order in perturbation theory as can be done with reasonable safety, to be used as the starting point for the hadronization process. Usually one can only calculate exact matrix elements to leading or next-to-leading order in α_s because of the rapidly growing complexity of the calculations. By suitable approximations one can however effectively take higher order corrections into account. It is in this connection that the recently developed parton cascade models becomes of interest and to which we now turn.

Two partons emerging from a large Q^2 process can be very much off mass shell, up to $Q/2$, and are therefore expected to emit bremsstrahlung gluons and thus produce a shower of partons as illustrated in fig. 2. Such a parton level cascade has been discussed by several authors [11-14]. The common feature is that first order QCD matrix elements in the leading logarithm approximation are used for each separate branching. Provided that the offshellness of the partons are strongly ordered, i.e. $m_1^2 \gg m_2^2 \gg m_3^2$ etc in fig. 2, the cross section factorises into a product of the probabilities for each separate branching. This results in an iterative process, suitable for Monte Carlo simulation techniques, which is stopped when the offshellness of all partons is below a chosen cut off value, t_{cut} . Together with Λ_{QCD} this cut off regulates the amount of bremsstrahlung emitted.

One should bear in mind that this approximation is not expected to work properly for hard gluon emission at large angles where interference terms between diagrams where the gluon was emitted from different partons become important, e.g. clear 3-jet events in e^+e^-

annihilation will not be correctly described. These methods are rather intended for studies of e.g. jet broadening due to the emission of several, but not very hard gluons at large angles. Even so these models may be used also for studies of multiple jet phenomena simply because better higher order calculations are lacking at present; the general features will certainly be right even though the rates and some distributions will not be exactly correct.

Since α_s used in each separate branching depends on the momentum transfer in that branching, i.e. the offshellness m_i^2 of the parent parton or the p_i^2 in the branching, it grows larger the longer the shower is evolved. Clearly, the perturbative approximation will then break down at some point when the parton offshellness become small. The parameter t_{cut} thus determines the border line between the region where perturbative QCD is considered to be trustworthy and the following nonperturbative region which, of course, must be taken into account to get to the physically observable final state of hadrons. There is no theoretical motivation for the choice of a particular t_{cut} -value, it is more related to ones confidence in the perturbative QCD shower approach and the method used for the final hadronization step. It is desirable, however, that a complete model is constructed in such a way so as to have as little dependence as possible on the exact value chosen.

A further, and very interesting, sophistication of this kind of models is that the interference effects between soft gluons can be taken into account by imposing an angular ordering in the emission [14], i.e. $\theta_1 > \theta_2 > \theta_3$ etc in fig. 2. This has the effect that (for a given t_{cut} value) fewer soft partons will be emitted which can easily be understood since a soft gluon having a large wavelength can not resolve the individual colour charges in the cascade, which therefore act coherently as a single colour charge for soft gluon emission. This strict angular ordering also takes certain next-to-leading corrections effectively into account.

Following the perturbative parton shower the final hadronization step can be performed in different ways. The simplest is to let all the produced partons fragment independently using e.g. the Field-Feynman parametrization [8]. As will be shown below, however, the

hardness of the resulting momentum spectra will then clearly depend on how far the parton shower is evolved, i.e. on the cut off parameter. Another procedure, which has also often been used, is to force the gluons to split into quark-antiquark pairs and then form colour singlet clusters from matching $q\bar{q}$ pairs. (Note that this splitting is not given by QCD but is done in order to be able to form the clusters in this kind of model.) These clusters are then decayed into ordinary hadrons (including resonances) using pure phase-space. The cluster mass spectrum will be continuous and obviously depend on the parton shower cut off value. The occurrence of large mass clusters decaying isotropically using phase space will produce too spherical events as compared to e^+e^- data. This is not only a problem for large cut offs, since even with a small t_{cut} large mass clusters do occur although with a reduced probability. This is usually solved by splitting heavy clusters, with a mass larger than some given minimum value around 3 to 4 GeV, into lower mass clusters using a longitudinal "string-like" decay. Another potential problem with this method is that the particle composition may change with the cut off value since with a lower t_{cut} the cluster masses will become smaller and the rate of heavier particles, like baryons, may be reduced because of the reduced phase space available.

A third and new method which we like to explore in this paper is to connect all the partons, whose colour ordering is perfectly known from the perturbative cascade, by a colour triplet string and apply the Lund fragmentation model for the final hadronization step. This means that the emitted gluons need not be (artificially) split into $q\bar{q}$ pairs, but they will as usual produce energy-momentum carrying kinks on the string. Thus, the string can have a rather complicated topology, e.g. being stretched from a quark via several gluons before ending up on an antiquark. Only if $q\bar{q}$ pairs have been produced in the perturbative evolution, as in fig. 2, will there be more than one colour singlet string system.

The result is therefore a single string (or a few separate ones) with a large invariant mass which hadronize according to the usual principles of the Lund model since the breakup of the force field by $q\bar{q}$ creation is a local phenomenon in the field. We therefore use the standard probabilities concerning flavours etc, as well as the usual "splitting" or scaling function for the energy-momentum fraction taken by a formed hadron. There are, however, complications due to the

occurrence of the many gluon-kinks and the improvements of the model presented in [15] are therefore needed to handle short string segments between nearby partons. This constitutes the string-based treatment of the hadronization of a partonic system having parton pairs with small invariant masses, which naturally occurs from the parton shower and becomes important for small t_{cut} values. This scheme has the advantage of being less sensitive to the parton shower cut off value since, if the shower is driven further, the extra gluons emitted will only produce small disturbances on the string configuration obtained, had they not been emitted. For the same reason the particle composition is also expected to be stable against t_{cut} changes.

Like pure 2-jet events without any gluon radiation is an unrealistic model at PETRA energies we expect that the simple extrapolation of a single quark or gluon jet without gluon emission effects is not adequate at collider energies. Nevertheless, we have included such an example in some cases below (using standard Lund fragmentation) for the reason of comparison and to show the effects of the parton shower more clearly.

To get quantitative results we use Monte Carlo implementations of these models. For the parton shower we mainly use the scheme of Marchesini and Webber [14] which takes the soft gluon interference into account as mentioned above, but also for comparison use the one by Gottschalk [12] which does not have that angular ordering in the emission. For the hadron formation we have tried all three options but will mainly employ the string case to investigate this new method.

In order to get clearer results we have simplified the situation by neglecting the underlying event and only consider a pair of high- $p_{\perp}$ partons created at a given Q^2 -value. The source, e.g. hard parton-parton scattering or the decay of a heavy object, need not be exactly specified at this stage. Since gluon jets are expected to dominate we will mostly discuss those, but also show results for quark jets for comparison. Thus we simulate the evolution up to the final hadronic state of an initial back-to-back gluon-gluon or quark-antiquark system of a given invariant mass Q . This could then be viewed as two jets at zero rapidity and having $E_{\perp}=Q/2$.

3 Fractional energy spectra of partons and hadrons

Defining an energy fraction variable $z=2\cdot E_p/Q$ as usual and a "fragmentation" function $D(z)=1/N_{\text{event}}\cdot dN_p/dz$, where the subscript p can refer to either parton or particle, we show in fig. 3 the distributions of $z\cdot D(z)$ for partons after the perturbative branching process and the final state hadrons from an initial gluon-gluon system with invariant mass $Q=100$ GeV. Looking first at the parton level result one can clearly see the difference between having and not having included the soft gluon interference effects. For given parameter values, $t_{\text{cut}}=5$ GeV² and $\Lambda_{\text{QCD}}=300$ MeV, the scheme without proper interference effects [12] (dotted line) gives substantially more low energy partons as compared to the scheme [14] including the destructive soft gluon interference effects (dashed line). This means that in the latter model one can lower the cut off without getting flooded by low energy gluons; there is rather a characteristic dip at small z (which is not only due to the fact that $z\cdot D(z)$ is plotted here). In fact, the standard value used in [14] is $t_{\text{cut}}=0.5$ GeV² (full line). The possibility to extend the perturbative region by having a low cut off is an advantage in a model with cluster formation and phase space decay, since that brings the cluster masses down to be closer to the hadron world. The principle problem with α_s getting large are however still present.

The two parton curves in fig. 3, dashed and full lines for a higher and lower cut off respectively in model [14], are rather different, but since partons are not observable this does not necessarily mean very much. The interesting thing is rather how different the corresponding hadron level spectra will be in different fragmentation schemes. Starting from these two parton level cases we apply independent and string fragmentation with the results as shown in fig. 3. Since the concept of independent fragmentation is not well defined it has to be further specified. Here we take it to mean the separate fragmentation of all partons in the overall CM frame and keeping the same fragmentation function as in the string case; having verified that a change in the fragmentation function to e.g. the Field-Feynman parametrization does not change the conclusions drawn below. For the case of independent fragmentation there is a large difference, both at small and large z , between using the different values of t_{cut} . This can be understood intuitively since there is no way that the

energy, being divided into two gluons by driving the parton shower further, can be added up again. For the string case, where two nearby gluons can enter the same hadron and therefore the energy from them be added again, there is much less dependence on the t_{cut} value. The spectra are almost identical at low z , at larger z there is naturally still some dependence on the cut off value.

We do not show the result of the cluster approach here since, in particular for the larger cut off value, it depends on the details of the "string-like" decay employed and in a sense one is back to the string model. Using the model of [14] (with $t_{\text{cut}}=0.5 \text{ GeV}^2$) and having its standard cluster method one gets a z -spectrum which is similar to the string case but differs slightly in the large z region by falling somewhat steeper.

In fig. 4 we show the fragmentation function, $z \cdot D(z)$, for quark and gluon jets of energy 50 GeV and 1 TeV. Strictly speaking, what has been simulated is quark-antiquark and gluon-gluon systems at $Q = 100 \text{ GeV}$ and 2 TeV . If there were no parton bremsstrahlung there would just be a single parton giving a δ -function at $z=1$, which after string fragmentation gives the hadron spectra shown by the dotted lines. Turning on the parton shower schemes of [14] and [12] (with their standard parameter values; $t_{\text{cut}}=0.5 \text{ GeV}^2$, $\Lambda=300 \text{ MeV}$ and $t_{\text{cut}}=5 \text{ GeV}^2$, $\Lambda=500 \text{ MeV}$ resp.) gives the parton level spectra shown by the full and dashed curves respectively. Applying the string fragmentation method in both cases gives the corresponding hadron level spectra. As noted before, the two different parton schemes, although different at the parton level, gives similar results after string fragmentation but with some difference at larger z -values. The effect of the parton shower is clearly seen to give sizable deviations from the case where it is excluded, in particular for gluon jets and at higher energies where more gluon radiation is emitted.

By comparing the lower and higher energies one observes that the difference between the no shower and shower at the lower energy is larger than the difference between the shower results at low and high energy. This is in accordance with the logarithmic dependence on Q^2 of the radiation process. The difference in the hadron spectra from the two parton cascade schemes should rather be taken as an

indication of the theoretical uncertainty at this stage, since it does not only depend on soft gluon interference effects but also to some extent on the cut off as seen in fig. 3.

From an experimental point of view an interesting property of jets is the fraction of the jet energy that is carried by particles having more than a given energy. This integral distribution $F(z' > z) = \int_z^1 dz' z' D(z')$ is shown in fig. 5 for quark and gluon jets. The softening of the jets when the parton shower is included and the jet energy is increased is here clearly visible. We also note the large difference between quark and gluon jets, the latter being considerably softer. For a 50 GeV (1 TeV) gluon jet, 50% of the energy is carried by particles having $z \leq 0.05$ (0.025), i.e. $E_h \leq 2.5$ (25) GeV. The corresponding numbers for quark jets are $z \leq 0.1$ (0.06), i.e. $E_h \leq 5$ (60) GeV. The expected mean multiplicities are shown in fig. 6 as a function of the jet energy, i.e. $Q/2$.

An alternative way to get the fragmentation functions would be to make parametrizations of the D-functions with the inclusion of parton emission effects using the evolution equation of the Altarelli-Parisi type, in a similar way as is usually done for structure functions. In [16] we have found that such an approach leads to conceptual problems due to confinement effects, unless partons are assumed to fragment independently. At large enough energy, however, the results should be the same as compared to the Monte Carlo approach, having a not too small cut off value. An advantage of the dynamical simulation of the parton branching processes used here, is that it also gives the transverse properties of the jet evolution which we will now consider.

4 Jet widths and substructure

With the inclusion of parton bremsstrahlung one will, of course, also introduce a larger flow of particles and energy transverse to the initial parton direction or overall jet axis. Again, it turns out that variations in the parton shower gives very similar results after string hadronization, whereas the independent fragmentation scheme depend more on the cut off value. We also note in this connection, that independent fragmentation gives a somewhat larger flow of energy at large angles with respect to the jet axis.

As a measure of the width of a jet we consider the fraction of particles or energy outside a given cone. These mean fractions are shown in fig. 7 as a function of the half-angle of a cone around the jet axis corresponding to the initial parton direction. The dependence on the jet energy is rather weak. Half of the particles are contained within a cone of about 30° (20°) for a gluon jet of 50 GeV (1 TeV). The energy flow is much more collimated; half the jet energy is within 12° (5°) for a 50 GeV (1 TeV) gluon jet. Nevertheless a large cone is needed to contain most of the energy for precise energy measurements.

The fact that the energy of the initial parton is spread out over a sizable angular region does not mean that it is evenly distributed over that region. Due to hard gluon bremsstrahlung one would rather expect it to be localized in a subjet structure. The possibility to resolve such a substructure depends on the experimental apparatus, in particular on the granularity of the calorimeter. In order to study this we have made a simulation where this kind of back-to-back jet system at zero rapidity is thought to be absorbed in a calorimeter with dimensions and properties similar to the UA2 experiment and applied their jet finding algorithm [17] based on a cluster method as follows. The energy of the particles are deposited in a grid of calorimeter cells with $\Delta\phi \times \Delta\eta = 15^\circ \times 0.2$ in azimuth and pseudorapidity. The cells have a Gaussian energy smearing of $\sigma_{em}(E) = 0.14\sqrt{E}$ for electromagnetic and $\sigma_{had}(E) = 0.8\sqrt{E}$ for hadronic showers (E in GeV). For each cell a 4-vector is assigned with the direction from the event vertex to the cell centre and magnitude given by the summed energy of the particles hitting the cell. Then, cells having a common side and energy above a threshold of 0.4 GeV are joined into a cluster. Finally, clusters above a given threshold, here 3 GeV, are recognized as a jet with a 4-vector having direction given by the event vertex and the cluster energy centroid, as given by the cells of the cluster, and momentum equal to the cluster energy.

Applying this method to a gluon-gluon and quark-antiquark system at $Q = 100$ GeV, simulated with the standard parton shower of [14] and string fragmentation, we can now investigate the jet substructure. First we show in fig. 8 how many jets that are actually observed. For

the gg system the mean number is 3.4 whereas it is lower, 2.8, for the $q\bar{q}$ system. Thus a gluon of this energy gives, in the mean, rise to 1.7 separate clusters through the bremsstrahlung process.

The experimentally more important measure of the jet width is then rather the energy flow with respect to each separate jet axis. In fig. 9 we compare the fractional energy outside a cone with half-angle θ measured either with respect to an overall jet axis (dashed lines) or with respect to the various reconstructed cluster axes (full lines). The difference is quite large, demonstrating the importance of good detector segmentation and of an adequate jet reconstruction algorithm. We also note here the difference in width for quark and gluon jets; as can be seen in fig. 9 the latter have a larger flow of energy at larger angles due to more QCD radiation. For comparison a simple jet without parton shower is also shown (dotted lines). A similar study for jets in the TeV energy region has also been made and reported in [18].

The behaviour when two jets are close in angle is not only a question of experimental resolution but also of theoretical interest, since it will give information about what happens in the fragmentation of two nearby partons. In a model with independently fragmenting partons there will just be two superimposed jets and a discontinuous transition, in terms of multiplicity and energy flow, to the case of a single parton giving a single jet of higher energy. In a string model, on the other hand, there will be a smooth transition [15], as is physically expected, because of the short piece of string between the two nearby partons which in the limit acts as a single parton.

5 Concluding remarks

As a check on the reliability of these Monte Carlo simulation techniques, we have in another study [19] compared their results with analytic calculations of another jet-width measure, namely the angular energy-energy correlation. For quark jets, which are on a more firm analytic basis, the results are remarkably close over a large energy region. The more complicated gluon jets tend to be somewhat more narrow in an approximate analytic calculation.

By further studies of jets at collider energies one should be able to gain more information about jet fragmentation, in particular for gluon jets, to test different ideas invoked in the models. We have shown that the effects of a QCD based parton cascade evolution gives sizable effects on longitudinal and transverse spectra which should be observable. A further consequence is the appearance of jet substructure which, when experimentally resolvable, leads to multijet events.

One should however, watch out for the possible distortion effects that may occur, like the one discussed here. This will almost certainly lead to a situation, like in e^+e^- annihilation, where extensive model calculations via Monte Carlo techniques become necessary. This calls for elaborate models which are not only based on sound physics ideas, but also fulfill requirements on stability with respect to variations of necessary parameters. We have here shown that a model based on a QCD leading logarithm parton cascade evolution followed by a string fragmentation approach has such stability against variations of the border line between the perturbative and nonperturbative regions of the hadronization process.

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FIGURE CAPTIONS

- Figure 1: Fragmentation function of a 34 GeV gluon jet including all particles (full line) and only those with $z (=p_{||}/E_{jet}) > 0.05$ (dashed line), compared with a 17 GeV quark jet (dotted line). Lund model used.
- Figure 2: Schematic representation of a parton cascade evolution from an initial quark-antiquark pair produced at a given Q^2 .
- Figure 3: Distributions of $z \cdot D(z)$, where $z=2 \cdot E_p/Q$, at parton and hadron level from a gluon-gluon system at $Q=100$ GeV. Parton curves are Webbers Monte Carlo [14] with $t_{cut}=0.5$ GeV² (full line); and $t_{cut}=5$ GeV² (dashed line); Gottschalks MC [12] with $t_{cut}=5$ GeV² (dotted line). Hadron curves are from parton shower [14] with $t_{cut}=0.5$ GeV² plus string fragmentation (full line); $t_{cut}=5$ GeV² plus string fragmentation (dashed line); $t_{cut}=0.5$ GeV² plus independent fragmentation (dash-dotted line); $t_{cut}=5$ GeV² plus independent fragmentation (dotted line). In all cases $\Lambda_{QCD}=300$ MeV.
- Figure 4: Distributions of $z \cdot D(z)$ for partons and hadrons from gluon-gluon and quark-antiquark systems at $Q = 100$ GeV and 2 TeV using parton shower [14] (full lines) and [12] (dashed lines) with default parameters; $t_{cut}=0.5$ GeV², $\Lambda=300$ MeV and $t_{cut}=5$ GeV², $\Lambda=500$ MeV respectively. The results without parton bremsstrahlung is shown (dotted lines) for comparison. String fragmentation is used in all cases.
- Figure 5: Fraction of jet energy (E_{jet}) carried by particles (E_h) with $z' > z$ ($z=E_h/E_{jet}$) for (a) gluon and (b) quark jets. The dashed (full) curves are for $E_{jet} = 50$ GeV (1 TeV) using Webbers parton shower [14] and dotted curves are without parton shower (same for 50 GeV and 1 TeV). String fragmentation used in all cases.

- Figure 6: Mean values of total multiplicity (including photons from π^0) and charged multiplicity as a function of jet energy ($=Q/2$) for (a) gluon and (b) quark jets using Webbers parton shower plus string fragmentation.
- Figure 7: Fraction of particles (full lines) and energy (dashed lines) outside a cone with half-opening angle θ , around the jet axis, for gluon-gluon systems at $Q = 100$ GeV and 2 TeV. Webbers parton shower plus string fragmentation.
- Figure 8: Distribution of the number of reconstructed jets per event, using the cluster algorithm described in the text, for a gluon-gluon (full line) and quark-antiquark (dashed line) systems at $Q=100$ GeV. Webbers parton shower plus string fragmentation.
- Figure 9: Energy fraction outside a cone, with half-opening angle θ , around the overall jet axis (dashed lines) or around the reconstructed cluster axis (full lines) for (a) gluon-gluon and (b) quark-antiquark systems at $Q=100$ GeV, shower plus string fragmentation. The dotted lines are without parton shower and θ relative to the overall jet axis.

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 4c

Fig. 4d

Fig. 5a

Fig. 5b

Fig. 6

Fig. 7

Fig. 8

Fig. 9a

Fig. 9b