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The influence of fragmentation models in the production of hadron jets in electron–positron annihilation

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Abstract. The analysis of electron–positron annihilations to hadrons at high energies shows that apart from two-jet events, there are also signs of three-jet events which are interpreted according to the QCD, as a gluon radiated by a quark. In this paper, we investigate the fragmentation of quarks and gluons to hadron jets. We show that gluon jets have a higher multiplicity compared to quark jets of the same energy. Furthermore, inclusion of different flavours in the distributions shows that quark jets are flavour-dependent, but gluon jets are not. The differences between quark and gluon jets also manifest themselves in the fragmentation functions. We observe that the fragmentation for gluon jet is softer than that for quark jet, because the radiation of soft gluons is larger for gluon jets and that gluon cannot be present as a valence parton inside a produced hadron. We provide possible explanations for these features in this paper.

Keywords. Annihilation; hadron jets; quark; gluon.

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1. Introduction

Quantum chromodynamics (QCD) successfully accounts for many features observed in high-energy e^+e^- annihilation data, examples of which include violation of scaling in inclusive particle distributions [1,2], jet broadening [3,5] and multijet events [2,4,5]. In the world of QCD, the sources of the experimentally observed jets are quarks and gluons. Jets initiated by quarks or antiquarks were studied in great detail in various experiments. However, little is known about jets which originate from high-energy gluons. Bartel *et al* [6] have presented evidences that particle distribution in three-jet events originate from hard gluon bremsstrahlung ($e^+e^- \to q\bar{q}g$) are only described by models in which jets of the same energy have different gluon contents.

In this paper, we study the quark and gluon jet fragmentation properties, using JADE, the most well-known algorithm [7–18]. In §2 we describe observables, followed by physics results in §3. Section 4 includes our conclusions.

2. Definition of observables

Jets are defined by means of JADE clustering algorithm. For each pair i and j, the quantity y_{ij} is calculated as

$$y_{ij} = \frac{2E_i E_j(1 - \cos\theta_{ij})}{E_{\text{vis}}^2}, \tag{1}$$

where E_i and E_j are the energies of particles i and j, θ_{ij} is the angle between the momentum directions and E_{vis} is the total visible energy in the event. The pair with the smallest value of y_{ij} is found, and if this is below a given resolution parameter Y_{cut}, the pair is replaced by a pseudoparticle with four-momentum $P^\mu = P_i^\mu + P_j^\mu$. The procedure is then repeated using the new set of particles and pseudoparticles. When all the values of y_{ij} are greater than Y_{cut}, the clustering procedure stops. Each particle in the event is uniquely associated with a cluster (jet).

The distribution of jet multiplicities obtained by these clustering algorithms depends on the jet defining parameter Y_{cut}. For small Y_{cut} many jets are found because of the hadronization of fluctuation process, whereas for large Y_{cut}, mostly two-jet events are found and the $q\bar{q}g$ events are not resolved. However, Monte Carlo studies show that there is a range of cluster parameters, for which QCD effects can be resolved and the fragmentation effects are sufficiently small. In the following, the parameter $Y_{\text{cut}} = 0.02$ is used which is found to be the most efficient Y_{cut} for 3-jet events (see figure 1).

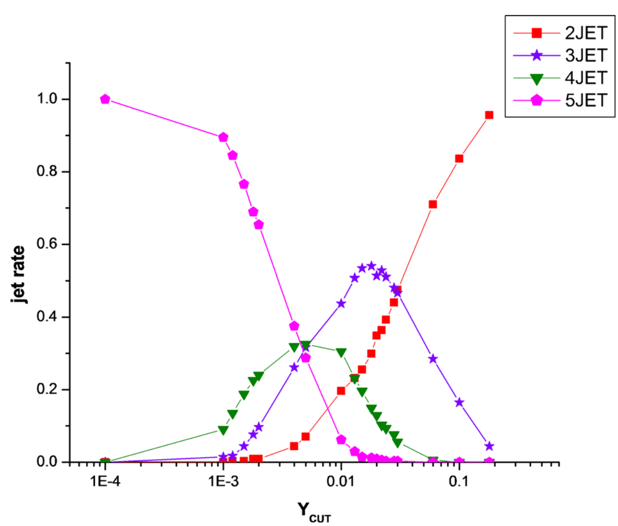

Figure 1. The distribution for 2-, 3-, 4- and 5-jets against the jet rate for different Y_{cut}s.

In figure 1, we show the distribution for 2-, 3-, 4- and 5-jet rates for different Y_{cut}s for AMY data. The y-axis indicates the jet rate production (the number of events with each kind of jets, divided by the total number of events) in our data. To obtain a better resolution for separating quark and gluon jets in 3-jet events, the events with more than four particles were considered. Detailed description of the event selection is described in ref. [19]. The decrease of 3-jet rate at large Y_{cut} is clearly visible [15].

3. Physics results

The difference between quark and gluon jets manifests itself in the fragmentation function defined as the energy fraction carried by each particle:

$$x_E = \frac{E_{\text{part}}}{E_{\text{jet}}}, \tag{2}$$

where E_{part} is the energy of each particle inside a jet and E_{jet} is the total energy of that jet in the event. The inclusive quark (gluon) fragmentation functions represent the probability for a parton (i.e. quark, gluon) to fragment into a particular hadron carrying a certain fraction of the parton's energy.

We have separated the quark and gluon jets according to the JADE algorithm defined in §2. In figure 2, the inclusive quark fragmentation function is compared to that of gluon jet. The latter is observed to be softer which can be explained by the fact that the radiation of soft gluons is larger for gluon jets and that gluon cannot be present as a valence parton inside a produced hadron.

Our results are also consistent with the results obtained from other experiments, as shown in figure 3 [20].

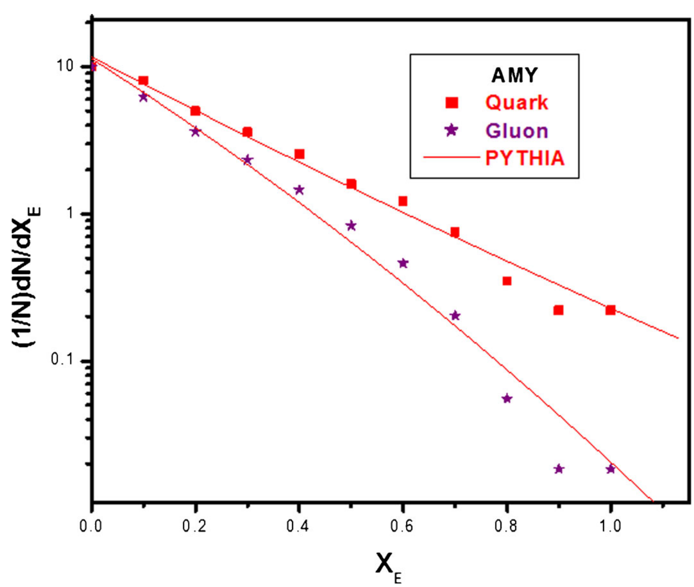

Figure 2. Fragmentation distributions for quark and gluon jets.

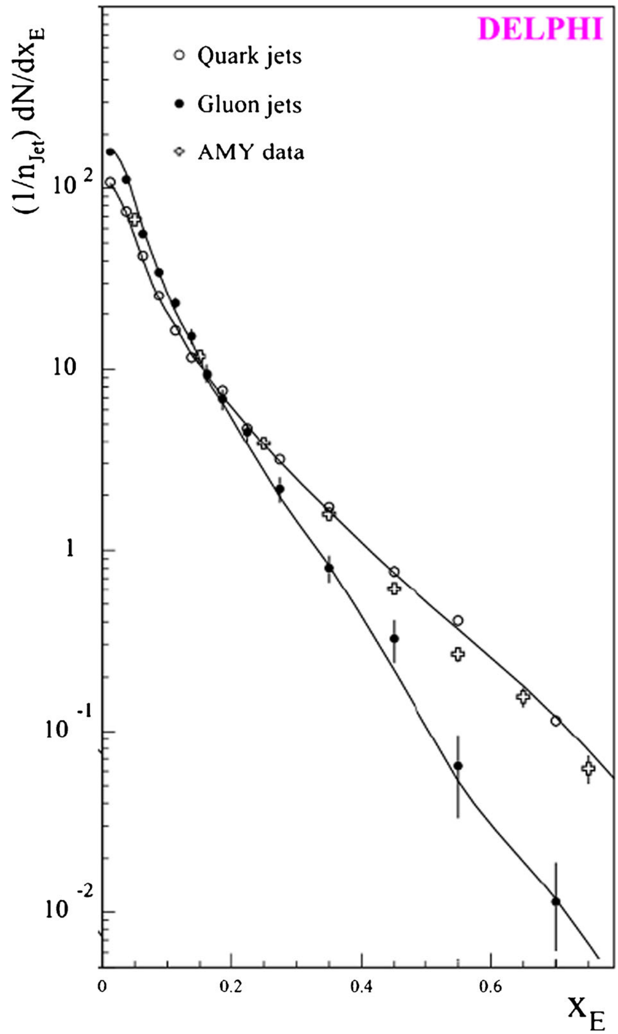

Figure 3. Fragmentation distributions for quark and gluon jets [20].

We show in figure 4 the multiplicity distributions separately for quark and gluon jets, both for the AMY data and the Monte Carlo PYTHIA in 60 GeV centre-of-mass energies. By taking into account the statistical errors, the figures indicate that within a few standard deviations, the particles in the gluon jet have higher multiplicities than the particles in the quark jet. We also see that the Monte-Carlo data reproduce the trend of the real data. So, it is appropriate to use the simulated data at some different energies if required.

In QCD, gluons have a colour factor that is larger than that of quarks by a factor of $(C_{\mathrm{A}}/C_{\mathrm{F}}) = 2.25$, if the asymptotic condition $E_{\text{particle}} \ll E_{\text{jet}}$ is fulfilled [21]. This leads us to a conclusion that gluon jets show a different behaviour when compared to the quark jets of the same energy. In particular, the higher colour factor should result in gluons

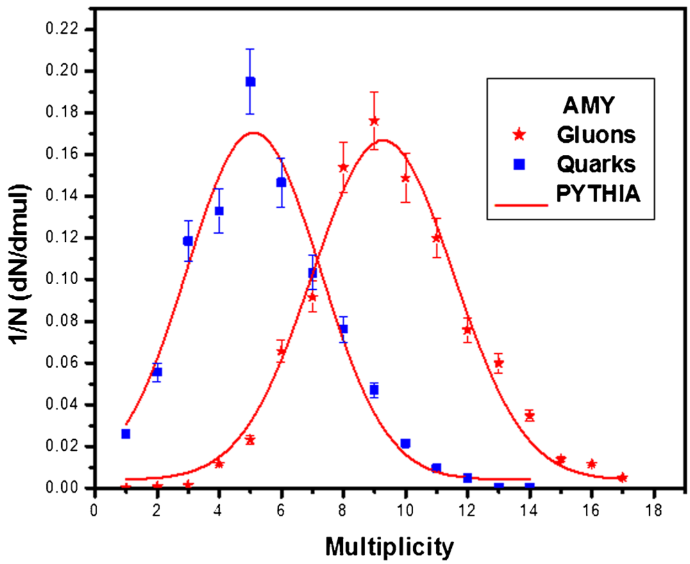

Figure 4. Multiplicity distribution for quark and gluon jets.

radiating more soft gluons, and this fragments into more particles, resulting in softer and fatter jets.

There is also a large theoretical interest in the ratio of mean multiplicity of the two kinds of jets, $r = (\langle N\rangle_g/\langle N\rangle_q)$ which is claimed to be equal to the ratio of the two colour factors, (C_A/C_F) [21]. Table 1 shows the ratio, obtained from the AMY as well as Monte Carlo simulated data in the range of 20–172 GeV. The Monte Carlo result at 60 GeV is in good agreement with experimental data at the same energy. In addition, a slight increase with energy in the ratio is observed but such energies are not high enough to fulfill the asymptotic value of 2.25 (figure 5).

At this stage we investigate the effect of jet energy on the mean charged particle multiplicity separately for quark and gluon jets (figure 6). The increase of multiplicity at large jet energies is clearly visible. Furthermore, both quark and gluon jets follow a similar trend as the jet energy increases. Our results are consistent with those obtained from ALEPH, OPAL, DELPHI and HRS-PEP experiments (figure 7 and ref. [21]).

Next we study the effect of different flavours on multiplicity for quark and gluon jets. To achieve this, we present in figure 8 the mean charged particle multiplicity of quark jet against the energy of each jet by using different flavours in generating the simulated hadronic data. For a given jet energy, we observe that the mean charged particle multiplicity grows considerably as the quark mass increases. This is more prominent for bottom

Table 1. The ratio of mean charged particles in gluon jet to quark jets (PYTHIA).

E_{cm} (GeV)	20	60 (AMY)	60	91.2	133	161	172
r	1.58 ± 0.038	1.62 ± 0.034	1.64 ± 0.033	1.65 ± 0.042	1.67 ± 0.037	1.69 ± 0.039	1.71 ± 0.041

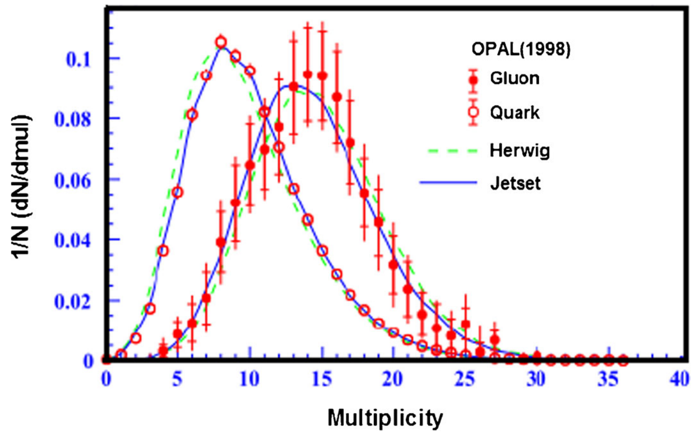

Figure 5. Charged particle multiplicity of unbiased gluon and quark jets [21].

quark which has a higher mass compared to c, s, u and d quarks. On the other hand, the difference between the distributions is not significant for lighter quarks. We conclude that the mean charged particle multiplicity is affected considerably by increasing the quark mass.

Figure 9 illustrates a similar distribution for gluon jets obtained from different flavours. In contrast to figure 8, the inclusion of the flavours does not change the results significantly. This is reliable, because from the QCD theory one can expect that gluons lack

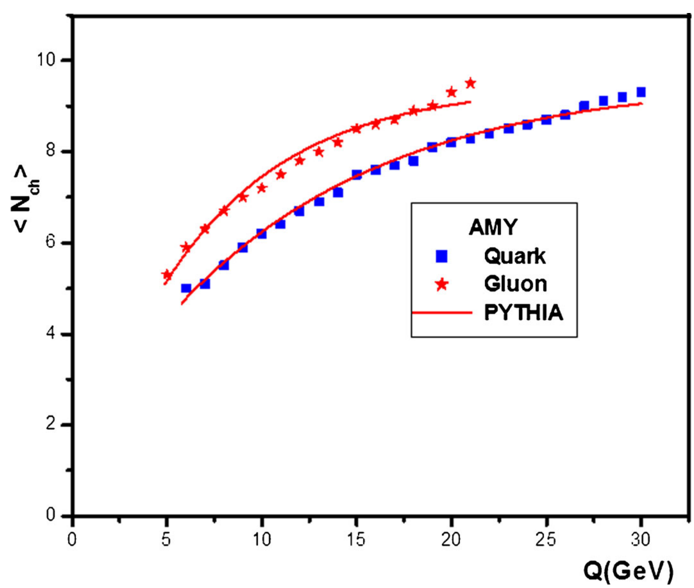

Figure 6. Mean-charged particle multiplicity vs. energy of the jet for quark and gluon jets.

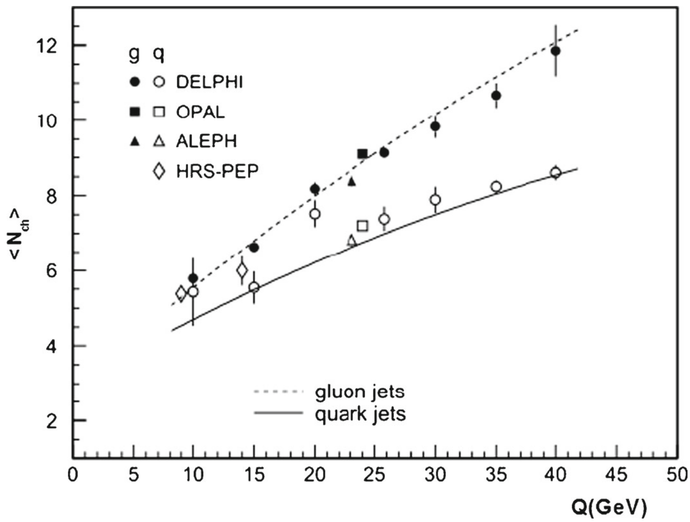

Figure 7. Mean charged particle multiplicity vs. energy of the jet for quark and gluon jets [20].

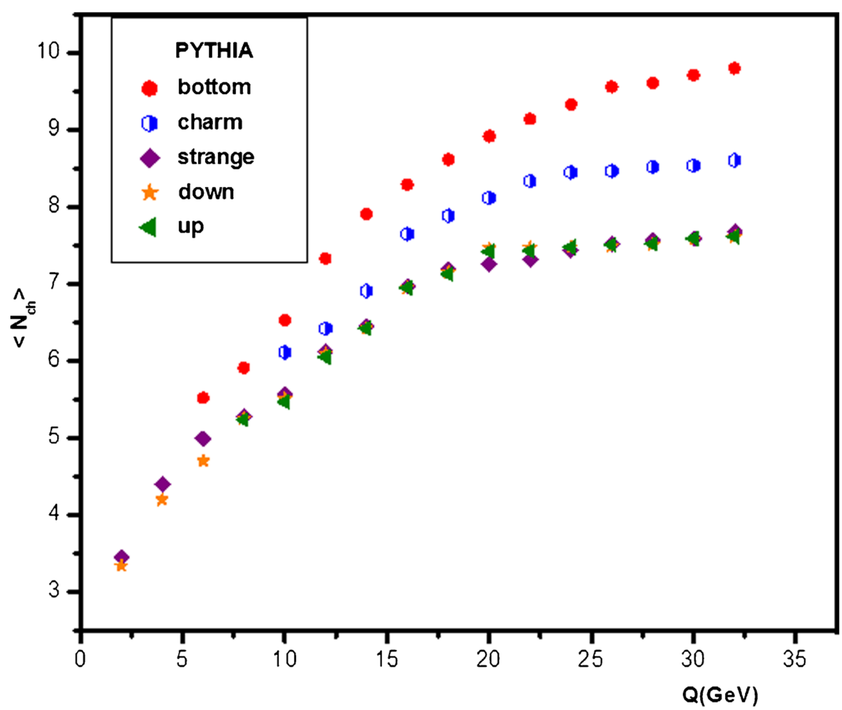

Figure 8. Mean charged particle multiplicity vs. energy of the jet for quark jet, using different flavours.

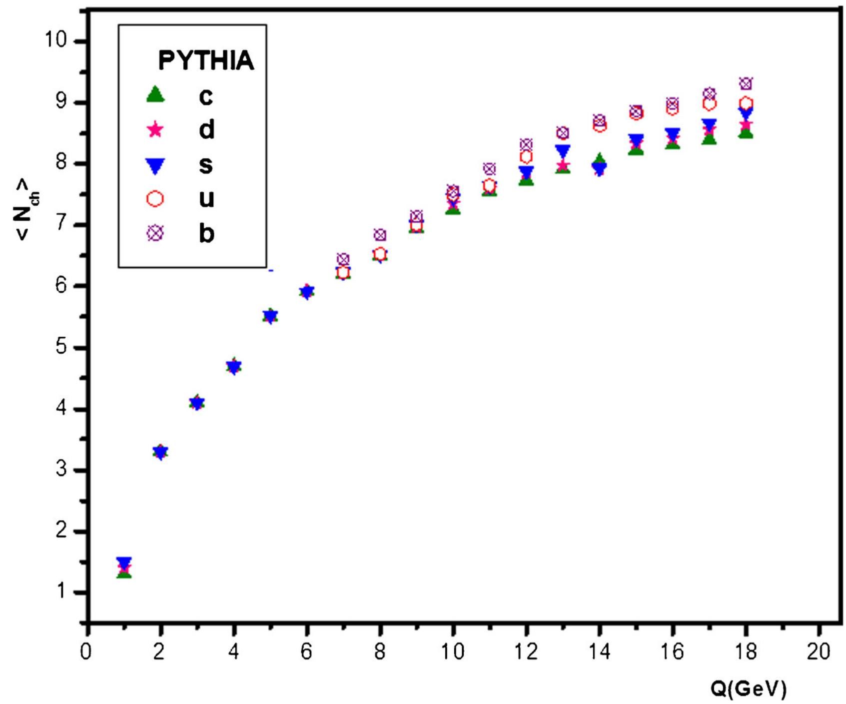

Figure 9. Mean charged particle multiplicity vs. energy of the jet for gluon jet using different flavours.

flavours while, quarks carry flavours. Accordingly, such a behaviour manifests itself as a difference between the quark- and gluon-enriched jets. A small separation seen at the end of the distributions in figure 9 is probably due to the uncertainty in separating the gluon and quark jets. We conclude that our results are consistent with the QCD theory.

4. Conclusions

In this paper we investigated the fragmentation of charged particles in e^+e^- annihilation at 60 GeV centre-of-mass energy in terms of the fragmentation parameter x_E and also in terms of multiplicity distributions.

In QCD, one expects quark and gluon jets to differ because of greater colour charge carried by the gluon. Quantitatively, therefore, one anticipates that gluon jets would have higher multiplicity, softer fragmentation and broader angle.

We also studied the effect of different flavours on multiplicity for quark and gluon jets. We observed that the inclusion of heavy flavours changes the distributions significantly for quark-enriched jets, while it does not considerably affect the distributions for gluon-enriched jets. This is due to the fact that, according to the QCD theory, quark jets carry flavours, whereas the gluon jets lack flavours. Such a behaviour manifests itself as a difference between quark- and gluon-enriched jets. Our results are consistent with QCD theory [12].

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