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Differences between quark and gluon jets at LEP

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ABSTRACT

In this paper we show a method capable of seeing at LEP the theoretically predicted differences between quark and gluon jets. The method uses multihadronic events in electron-positron annihilation at three- and four-jet topologies. It handles the energy of a jet in an adequate way and studies a large part of the multi-jet events. Another advantage of our method is that it can be carried out by analysing hadronic events gained at one centre-of-mass energy e^+e^- annihilation, thus only one detector and one experimental group are needed.

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QCD has been proposed as a theory for the strong interactions. Its fundamental particles are the quarks and gluons. On the other hand, high energy experiments (e.g. electron-positron annihilation) produce hadrons. We only have phenomenological models describing these fragmentation processes. Uncertainties in these models present a major obstacle to the detailed testing of Quantum Chromo Dynamics. Hadrons forming a jet are believed to mark the path of a quark or a gluon. There has been remarkable success in correlating the data for two-, three-, or even four-jet variables with theoretical predictions based on partons (see e.g. [1] and references therein). The next step to having a deeper insight into QCD is to see less inclusive processes. Thus we should determine the parton ancestor of a jet. Discrimination between quark-induced and gluon-induced jets is required to understand several phenomena. Two of the numerous examples: a fairly precise identification is needed to establish the existence of the three-gluon vertex [2], or to determine the strong coupling constant using azimuthal asymmetries [3]. Gluons carry a stronger colour charge than quarks, and one expects this to produce a difference in their fragmentation, namely higher multiplicity, softer hadron spectrum, and broader p_t distribution. There has been an intensive theoretical study to calculate variables sensitive to the differences between quark and gluon jets [4]. On the other hand, there are several theoretical papers giving methods by which the experimental data may be analyzed and the above-mentioned differences between quark jets and gluon jets can be seen [5,6,7].

Electron-positron experiments have produced a large amount of information on the fragmentation of quark and antiquark jets, while our knowledge of the fragmentation of high energy gluon jets is quite poor. The experimental problem in these studies is that in e^+e^- annihilation quark jets occur predominantly in the two-jet ($q\bar{q}$) topology, but gluon jets occur only in three or more jet topologies ($e^+e^- \rightarrow q\bar{q}g, \Upsilon \rightarrow ggg$). There is thus a large kinematic difference superimposed on any dynamical difference.

In $p\bar{p}$ collisions two-jet topologies are a mixture of $q\bar{q}$, qg and gg events.

Because of these problems most studies of gluon jet fragmentation led to inconclusive results.

One can study "nearly" symmetric three-jet events and compare the results with the results of the two-jet events gained at $\frac{2}{3}$ CM energies [8]. The HRS collaboration has analysed the average multiplicities of quark and gluon jets. They have found for the ratio: $\bar{n}_q/\bar{n}_g = 1.29^{+0.20}_{-0.41}$. The MARK II Collaboration has studied inclusive charged particle distributions in terms of the fractional momentum. Their study apparently favours a softer gluon fragmentation. On the other hand, the TASSO Collaboration has repeated these studies but their result does not confirm the above-mentioned MARK II result.

There are several approaches based on studies of jets with different energies [9]. The JADE Collaboration has seen that particles coming from the least energetic jet (the one most likely to be a gluon jet) in three-jet events tend to carry on the average larger p_t . In the studies of the CELLO Collaboration, where they have compared the least energetic jet in three-jet events at $W=35$ GeV to two-jet events at $W=14$ GeV (thus they have compared a gluon enriched sample of jets to a quark enriched

sample), they report $\bar{p}_{t3}(35)/\bar{p}_t(14) = 1.03 \pm 0.03 \pm 0.04$, not seeing any increase in p_t for gluon jets. The AMY Collaboration has seen differences between quark and gluon-jets in terms of the concentration of energy near the jet core, the rapidity of the leading particle, and the distribution of the energy-energy correlation for quark jets and gluon jets.

Despite a considerable amount of experimental effort, unambiguous differences between quark and gluon-induced jets have not yet been established.

It is our purpose in this paper to introduce a method capable of seeing how an energy dependent jet-variable $A_{q/g}(E_j)$ (e.g. multiplicity, average p_t , rapidity etc.) differs between quark (q) and gluon (g) jets at a given jet energy (E_j) studying three-jet and four-jet events in e^+e^- annihilation.

As has been suggested in [6], the comparison of jets in two- and in general three-jet events could show the differences between quark and gluon jets. The method is based on the different quark contents of two- and three-jet events. In the former case the quark content is clearly 100%, while in the second case it is a function of the energy fraction carried by the jet. As has been emphasized in [10], the jet environment is somehow relevant. The cone-energy fractions are different for quark jets in two- and three-jet event topologies. Nevertheless the variables suggested in [6]

$$M_{nm}(E_j) = \sum \left(\frac{p_t}{E_j}\right)^n \eta^m \quad (1)$$

(the sum goes over the outgoing particles in a jet, η is the pseudorapidity, p_t is the transverse momentum of a definite particle with respect to the jet axis) are fortunately not too sensitive to these differences, and the large difference between the quark contents of two- and three-jet events makes it possible to determine the differences between quark induced and gluon induced jets. There is a technical problem with this [6] analysis. In general two detectors and two experimental groups are needed, one for two-jet studies at smaller (e.g. PETRA or TRISTAN) energies, and another one for three-jet studies at higher (e.g. LEP) energies. (Actually, the energy range covered by PETRA would have been enough for both, but unfortunately the experiments have not been carried out.)

The basic idea, having two jet samples at a given jet energy but with different quark contents, can be generalised. There are two possibilities.

- a. Compare jets at a given energy and jet number, but at different kinematic configurations.
- b. Create two (or more) jet samples with a given jet energy: $S_n(E_j)$. Each of these samples contains jets from different jet topologies. Thus all the jets with energy E_j in three-jet events can be found in $S_3(E_j)$, etc.

Let us discuss these possibilities in detail.

- a. This method is not applicable for two-jet events at all, since all the scaled energy fractions $x_{jet} = 1$ ($x_{jet} = 2E_j/E_{CM}$ is the scaled energy fraction of the jet and E_{CM}

is the centre-of-mass energy of the electron-positron annihilation). Thus there are no different kinematic configurations with different quark/gluon contents.

For a three-jet event $0 < x_a, x_b, x_c < 1$ and $x_a + x_b + x_c = 2$ thus there are only two independent variables, e.g. the energy fractions of two jets, x_b and x_c . The possible kinematical configurations are: $x_b < 1$; $x_c < 1$; $x_b + x_c > 1$. The upper triangle in x_b, x_c plane $[(1,0); (1,1); (0,1)]$ contains these kinematically allowed final states, shown in Fig. 1. The gluon content of a sample with x_a scaled energy fraction (the two other jets have x_b and x_c scaled energy fractions) is clearly:

$$r_g(x_a | x_b, x_c) = \frac{x_b^2 + x_c^2}{(1 - x_b)(1 - x_c)} \times \left(\frac{x_a^2 + x_b^2}{(1 - x_a)(1 - x_b)} + \frac{x_b^2 + x_c^2}{(1 - x_b)(1 - x_c)} + \frac{x_c^2 + x_a^2}{(1 - x_c)(1 - x_a)} \right)^{-1} \quad (2)$$

(This is a parton level first order result in α_s . The small second order correction does not affect our conclusions.) We have plotted in Fig. 1 the $r_g = 0.2, 0.4, 0.6, 0.8$ curves according to eq. (2). These curves are almost parallel to the line $(1,0)-(0,1)$. Thus a jet sample determined by one of these curves contains jets with almost the same energy. Therefore there are no different jet samples from different kinematic configurations in three-jet events with the same energy but with remarkably different quark/gluon contents. (The analysis of the AMY Collaboration [9] corresponds to a study of different regions of this phase space.)

For four-jet events the problem is even more complicated. There are five independent variables. There is no simple presentation of the phase space as the two-dimensional plot for the three-jet events (Fig. 1). Perhaps one could find a sophisticated projection of this five-dimensional phase space where the constant energy jet assumption could lead to jet samples with different quark/gluon contents, but a serious problem still remains, namely statistics. The number of four-jet events is approximately an order of magnitude smaller than the number of three-jet events (for the resolution parameter y_{min} we have used 0.02). To create clean four-jet samples, with small background from three-parton events, a large d_{join} cluster algorithm parameter [11] is needed. This reduces the number of four-jet events drastically. Thus a 30×3 binning (30 bins for the energy, and 3 bins for the different samples with different quark/gluon contents) means that less than 0.1% of the four-jet events can be found in one bin, while the quark contents are presumably slightly different. It would be extremely difficult to extract the information for quark and gluon jets using these small samples without remarkable differences in their quark contents.

b. This method was presented in [6] for two- and three-jet event samples. For two-jet events the quark content is clearly 100%, while for three-jet events it is a function of the energy of the jet and much smaller than 100% for small energy jets. The solution for the previously mentioned technical problem is the comparison of three- and four-jet events at the same E_{CM} with the same detector. The quark contents of the jet

samples from three- and four-jet events as a function of the jet energy are presented in Fig. 2. These quark contents are mixed heavy-quark light-quark contents. (The results are gained from Monte Carlo events at the Z^0 resonance. The MC generator, its parameters, and jet-finding algorithm used will be described later.) The quark content of the four-jet events is clearly higher than that of the three-jet events in this energy region. If the gluons are really softer –as predicted by the previously mentioned theoretical calculations– the experiments would be able to verify it by showing softer three- than four-jet events on the average. (On the other hand there is an additional phenomena to this question. There is a larger space for jets in three-jet events than for jets in four-jet events to fragment, thus jets in three-jet event topologies are softer anyhow. This effect is quite small and can be reduced [12] e.g. by neglecting particles outside a cone around the jet axis. The remaining effect can be easily handled.)

We will discuss this possibility (comparison of jets in three- and four-jet topologies) as the only promising chance.

After determining the energy dependence of a chosen jet variable $[A(E_j)]$ for three- and four-jets $[A_{3/4}(E_j)]$ it is easy to give the energy dependence of this jet variable for quarks/gluons $[A_{q/g}(E_j)]$ using the quark content of the three- and four-jet events $[q_{3/4}(E_j)]$ plotted in Fig.2. and solving a linear system of equations. The result is:

$$\begin{pmatrix} A_q(E_j) \\ A_g(E_j) \end{pmatrix} = \frac{1}{q_3(E_j) - q_4(E_j)} \begin{pmatrix} 1 - q_4(E_j) & q_3(E_j) - 1 \\ -q_4(E_j) & q_3(E_j) \end{pmatrix} \begin{pmatrix} A_3(E_j) \\ A_4(E_j) \end{pmatrix} \quad (3)$$

It is straightforward to give the square of the statistical errors (for simplicity we will not indicate the energy dependence in the following):

$$\begin{pmatrix} D_q^2 \\ D_g^2 \end{pmatrix} = \begin{pmatrix} \frac{(1-q_3)^2}{N_3} & \frac{(1-q_4)^2}{N_4} \\ \frac{q_3^2}{N_3} & \frac{q_4^2}{N_4} \end{pmatrix} \begin{pmatrix} \sigma_3^2 \\ \sigma_4^2 \end{pmatrix} \quad , \quad (4)$$

where σ_4^2 and σ_3^2 are the variances of the jet variables for three- and four-jet events. σ_4^2 and σ_3^2 can be given in terms of the variances of the jet variables for quarks and gluons:

$$\begin{pmatrix} \sigma_3^2 \\ \sigma_4^2 \end{pmatrix} = (A_q - A_g)^2 \begin{pmatrix} q_3 - q_3^2 \\ q_4 - q_4^2 \end{pmatrix} + \begin{pmatrix} q_3 & 1 - q_3 \\ q_4 & 1 - q_4 \end{pmatrix} \begin{pmatrix} \sigma_q^2 \\ \sigma_g^2 \end{pmatrix} \quad (5)$$

In the following we will illustrate the method outlined above to determine special energy-dependent moments of quark and gluon jets. In our approach Monte-Carlo data were generated by Jetset 6.3 [11]. The partonic configuration is calculated from perturbative QCD in the form of a second order matrix element for a finite jet resolution parameter y_{min} . We have changed the QCD part of JETSET 6.3 to get rid of

the GKS [13] approximation, by the method of the MARK J collaboration (for more details see [14]). In our Monte-Carlo analysis we have used the fragmentation parameters fitted to LEP data given by OPAL [15]. We want to study and compare separate jets, (all parton ancestors are well separated) thus the fixed order perturbative results are applicable in this region of the phase space. (The leading-log approximations used in parton shower models are valid close to the soft and collinear configurations, but do not necessarily give a relevant answer for well separated parton states. For example, the three-jet rate in parton shower models is readjusted to reproduce the fixed order matrix element result.)

We have used 10 000 000 hadronic events in our studies at the Z^0 resonance. In the hadronic final states not only the charged, but the neutral particles have been considered too.

After generating an event we have used the LUCCLUS cluster algorithm [11] to determine the number, the energies and the directions of the jets. The method used in LUCCLUS is to form clusters of particles which are close together in phase space where closeness is defined as the relative p_t of two particles. All particles which are closer together than a definite cut (d_{join}) are clustered into a cluster or jet. Of course the jet number, as determined by the cluster algorithm, does not always coincide with the parton number. Events where it does not are called background.

To reduce this background we have used only those multihadronic events where the jet number was insensitive to the cluster algorithm's parameter in the range of $3.3\text{ GeV} - 4.9\text{ GeV}$. Clearly, this important requirement leads to really "jet-like" jets in the sense that small perturbation of the jet finding algorithm (changes of the d_{join} parameter in this region) cannot split a jet into two jets or cannot join two jets into one. This requirement led to 0.0% and 0.3% background for three-jet events (originated from two- and four-jet events) while the results for four-jet events are 0.0% and 0.2% (from two and three-jet events respectively). This insensitivity assumption gives extremely clean multijet samples. Varying the parameters one can get even cleaner samples, but the statistics is rapidly decreasing. In our case 66% and 65% of the three- and four-jet events remains in the analysis.

In addition we have required, as usual, that no jets have less than 5% of the total centre-of-mass energy.

We have analysed the moments of eq. (1). It is easy to see that M_{00} is the multiplicity of the jet. Clearly these moments are sensitive to the softer fragmentation, higher multiplicity and broader p_t of the gluon jets as compared to the quark jets. Previous studies [6] have shown that the moments M_{10} and M_{14} are the most sensitive to the jet type. Therefore we have analysed these moments and multiplicity.

As we have mentioned above the larger space available for jets in three-jet events (than for jets in four-jet events) leads to softer fragmentation for jets in three-jet event topology than for jets in four-jet event topology. To reduce this effect we have neglected particles outside a cone (with half-opening angle 25°) around the jet axis. Some differences for some moments still remain. (E.g., for the quark jets M_{10} is the same in three- and four-jet event topologies while for other moments there is a few %

difference.)

As an example we have plotted the moment M_{14} for jets in three- and four-jet event topologies as a function of the jet energy (Fig. 3.). Clearly the jets in the three jet events are softer, in good agreement with the higher gluon content. (At least they are softer at the Monte Carlo level. We encourage experimentalists to present this softness using the available experimental data.)

Using eq. (2), and the previously mentioned small corrections, originating from the different space available, we have determined the energy dependence of M_{00} , M_{10} , and M_{14} moments for quark-jets and gluon-jets (Fig. 4.). These results are clearly extracted from the information contained by the three- and four-jet events. On the other hand in MC analyses one can give these energy functions for quark- and gluon-jets using the parton ancestor of a jet. The result of this second study entirely agrees with Fig. 4.

In this paper we have suggested a simple method to see the differences between quark and gluon jets. The differences between them arise from the perturbative QCD prediction of Fig. 2. We have tested our method to calculate special moments of quark and gluon jets in the Lund Model. Remarkable differences can be seen between them. Comparing our method to other methods (eg. symmetric three-jet event studies), we can say that our method compares gluon jets with quark jets having exactly the same energy, thus there is no kinematical difference superimposed on the dynamical ones. The other advantage of our method is that it reaches high statistics. The third and technically most important advantage of the method is that the comparison can be made by the use of only one detector.

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Figure Captions

Figure 1. The available phase space for three-jet events. The curves represent the $r_g = \text{const.}$ samples (see text).

Figure 2. The quark content of the jet samples, gained in three- and four-jet topologies, as a function of the jet energy.

Figure 3. The average M_{14} value for jets in three- and four-jet events as a function of the jet energy.

Figure 4. The average M_{00} , M_{10} , and M_{14} moments for quark and gluon jets as a function of the jet energy (a,b,c).

Fig. 1

Fig. 2

Fig. 3

Fig. 4