DIFFERENCES BETWEEN QUARK AND GLUON JETS AT LEP1

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ABSTRACT

A report is given here on the differences between quark and gluon initiated jets as measured in LEP1. Various measurements, agree qualitatively on the differences between quark and gluon jets. However a direct quantitative comparison among the measurements as well as comparisons between the measurements and analytical calculations are difficult. This is due to the dependence of the results on the selected event topologies and used jet finding algorithms. Topology dependence of the charged particle multiplicity in quark and gluon jets is studied by ALEPH and transverse momentum-like scales are proposed to account for it. OPAL produced the first quantitative test of QCD analytic prediction for the ratio of the mean particle multiplicity between gluon and quark jets valid, at least, for 39 GeV jets.

1. Introduction

Differences between quark and gluon initiated jets are expected in QCD. They are due to different relative probabilities for a gluon or a quark to radiate an additional gluon, given by the SU(3) group constants $C_A = 3$ and $C_F = 4/3$, respectively. The various measurements from the LEP experiments of these differences are found to agree qualitatively with the theoretical predictions: gluon jets are measured to have a larger mean particle multiplicity, a softer fragmentation function and a larger angular width than light quark jets [1]. But, they are found to be quite like the b quark jets at LEP energies. [2].

QCD analytic predictions exist for the ratio between the mean hadron multiplicity of gluon and quark jets [3]. It is equal to $r = C_A/C_F = 9/4$ at the leading order and it is lowered by higher terms and energy conservation.

Experimentally, the measurement of the ratio r relies on jet finding algorithms to select exclusive samples of three jet events. Results are found to depend on jet algorithms, selected event topologies and average jet energy [4]. Analytic calculations use inclusive definitions of jets and do not employ jet finders to assign particles to jets; this makes their predictions not directly comparable to most of the available experimental measurements. In this report, study of topology dependence of charged particle multiplicity in three-jet events, test of QCD analytic predictions for the multiplicity ratio between gluon and quark jets and study of identified particles in gluon and quark jets are summarised.

2. The topology dependence of charged particle multiplicities in three-jet events

In this work [5] it is demonstrated that the energy of a quark or a gluon jet is an inappropriate scale to uniquely specify its mean multiplicity. From the coherence of QCD radiation (as seen in the string effect for example), it is clear that the position of a jet relative to the other jets is important in determining its properties. for a three-jet ($q\bar{q}g$) event, at the first order, the gluon carries an equal and opposite anticolour charge of that of the quark; likewise the antiquark. In this picture one expects that as the quark and gluon come close to each other the colour charges mutually shield one another, and the amount of subsequent gluon radiation, hence the particle multiplicity, is reduced.

The colour shielding suggests that the scale for quarks (likewise antiquarks) is : $Q_{qg} = E_q \sin\theta_{qg}/2$ rather than $Q_{qg} = E_q$, where E_q is the quark's energy and θ_{qg} the quark-gluon opening angle. This scale depends only on the direction of the gluon and tends to E_q when the quark and gluon are back to back (minimal colour screening) and vanishes as the quark and gluon become parallel (maximal screening). Since the gluon is approximated by a pair of colour anticolour charges so that using two scales, one for each colour line, seems appropriate to describe the gluon: $Q_{qg} = E_g \sin\theta/2$ and $Q_{\bar{q}g} = E_g \sin\theta/2$. The two scales can be combined into one as : $\bar{Q_g} = \sqrt{Q_{gq} Q_{g\bar{q}}}$.

Three-jet events are selected using the Durham jet clustering algorithm with a resolution parameter $y_{cut} = 0.01$, and the jet energies are recomputed from their relative opening angles assuming massless planar kinematics. The quark and gluon jet properties are measured in a sample of 5.4×10^5 events. First a $b\bar{b}g$ enriched subsample of 5×10^4 events is obtained using an impact parameter tag. The gluon jet is defined as the jet with highest probability to be from the primary vertex. The resulting purity of the gluon jet varies between 50% at a jet energy of 40 GeV and 97% at 5 GeV. The gluon jet charged multiplicity is determined as a function of its energy and the angles to two the other jets. This allows investigation of the topology dependence. Charged particle multiplicity in quark jets are linearly unfolded from the untagged three-jet event sample using the obtained gluon results and quark/gluon composition determined from the leading order QCD matrix element. The angle θ_{qg} is taken to be the θ_{min}, i.e. the smallest angle between the gluon jet and the two other jets. For different bins of jet energies the mean quark and gluon jet charged particle multiplicities are measured for several values of $\Delta\theta$. A strong dependence on $\Delta\theta$ is observed in each jet energy bin; the overall dependence on energy can not be parametised with a simple analytical form. The mean charged multiplicity for quark and gluon jets measured in bins of the scales $Q = Q_{qg}$ and $Q = \bar{Q}_g$, respectively, shows a smoother dependence on $\Delta\theta$ in each Q bin. The overall dependence on Q can be reproduced for the gluon jet by a QCD-inspired analytical form and it can be smoothed (fitted) by a quadratic form in log(Q) for both the gluon and the quark jets.

3. Test of QCD analytic predictions

The analytic calculations employ definitions of the event samples and jets which are entirely inclusive. The gluon jet properties are defined from a sample of gluon gluon (gg) events produced from a colour singlet point source; and similarely a sample of quark antiquark ($q\bar{q}$) events produced in the same way is used to define the quark jet properties. The gluon and quark jet characteristics are given by inclusive sums over the particles in these two samples. Thus, the theoretical results are not restricted to 3-jet events and do not employ a jet finder to assign particles to jets.

A method was proposed [7] for LEP experiments to identify gluon jets using an inclusive definition similar to that used for the analytic calculation. The method is based on rare events of the type $e^+e^- \longrightarrow q\bar{q}g_{incl}$ in which the q and $\bar{q}$ are identified quark jets which appear in the same hemisphere of an event. The quantity g_{incl}, taken to be the gluon jet, is defined by the sum of all particles observed in the hemisphere opposite to that containing the q and the $\bar{q}$. In the limit that the q and the $\bar{q}$ are collinear the gluon jet g_{incl} is produced under the same conditions as the gluon jets in gg events from a colour singlet point source. The g_{incl} therefore corresponds closely to single gluon jets in gg events, defined by dividing the gg events in half using the plane normal to the principal event axis.

In this study [6], a gluon jet is defined inclusively by the particles observed in the hemisphere opposite to that containing an identified quark and antiquark jet. Each event is divided into hemispheres using the plane perpendicular to the thrust axis. Exactly two jets are reconstructed in each hemisphere. A hemisphere is tagged if it is found to contain two tagged b quark jets. After applying the selection criteria [6], a total of 278 events are selected for the final g_{incl} event sample with a purity of 83% estimated using JETSET. The mean gluon jet energy is determined to be $< E >_{g_{incl}} = 39.2$ GeV. The uds quark jets are also defined inclusively using particles observed in event hemispheres opposite to those containing tagged uds jets. Here the (uds) jet energy is equal to that of the beam, i.e 45 GeV.

The measured charged particle multiplicity for the gluon is $< n_{ch} >_{g_{incl}} = 14.63 \pm 0.38(\text{stat}) \pm$

0.59(syst). The corresponding obtained result for uds jets is $< n_{ch} >_{uds} = 10.05 \pm 0.04(\text{stat}) \pm 0.23(\text{syst})$ in agreement with an earlier publication [8]. The measurements are summarised in figure 1. The ratio r_{ch} of the mean charged particle multiplicity of gluon jets divided by the corresponding value for uds quark jets after accounting for larger energy of the later jets is $r_{ch} = 1.552 \pm 0.042(\text{stat}) \pm 0.061(\text{syst})$. This result is substantially smaller than the predictions of analytic calculations which do not include energy conservation in the parton branchings. Analytic calculations [3] which incorporate approximate energy momentum conservation predict a parton level multiplicity difference for 39 GeV gluon and quark jets in the range from 1.64 to 1.83. This latter prediction is in overall agreement with the measurement presented here.

4. Identified particles in quark and gluon jets

The QCD prediction of the enhancement of the particle multiplicity in gluon jets with respect to quark jets is irrespective of the particle type. Measurements at a center-of-mass energy of 10 GeV at the Υ resonance, which mostly decays via three gluons, showed enhanced baryon production while no such effect was observed for mesons [9]. Therefore measurements of identified particles are interesting to improve our understanding of fragmentation processes and to verify hadronisation models implemented in various Monte Carlo generators.

Measurements of K^0_s and Λ production rates in quark and gluon jets in three-jet events are made by OPAL [10] and L3 [11]; DELPHI [12] has made the measurement for K^+, K^0, p, and Λ.

In the OPAL measurement, Λ baryons and K^0_s mesons were reconstructed via their decays into charged particles. The three-jet events were selected by using either the Durham or the cone jet finder and the least energetic jet was identified as the gluon jet; the final results were corrected to 100% gluon jet purity. The energy dependence of particle production in jets of different energy ranges have been compensated by normalising to the charged particle multiplicity. Higher relative Λ production rate in gluon jets than in quark jets have been observed. The increase is up to 40% in the event sample defined the with Durham algorithm and 28% for the cone selection. A smaller enhancement of $8 \pm 3\%$ is observed for K^0_s. JETSET predicts 25% for the relative Λ production in gluon jets when compared to quark jets which is smaller than the measured value.

The L3 measurement is done using the Luclus algorithm to find three-jet events, and the least energetic jet is identified as the gluon jet. A reduced rate for the K^0_s $(15 \pm 3)\%$ in the least energetic jet follows the observed reduction for charged particles $(15 \pm 1\%)$. This reduction is explained by the smaller phase space available during the fragmentation. Consistent predictions are provided by the JETSET program. For the Λ baryons, this reduction is not seen, but here also the rates are well reproduced by JETSET.

In the DELPHI analysis the Durham jet finder is used and only two event topologies are selected in the three-jet events sample : 1) the "Y events". Here the angles between the highest energy jet and the two other jets is between 135 and 165 degrees, this corresponds to an average jet energy of 24 GeV for the two small energy jets. 2) the "mercedes events" which are symmetrical events with the three inter-jet angles all between 100 and 120 degrees, corresponding to an average jet energy of 30 GeV for any of the three jets. For Λ, K^+ and K^0 the ratio of the average multiplicity in gluon jets with respects to quark jets is found to be consistent with the same ratio measured for charged particles and consistent with the

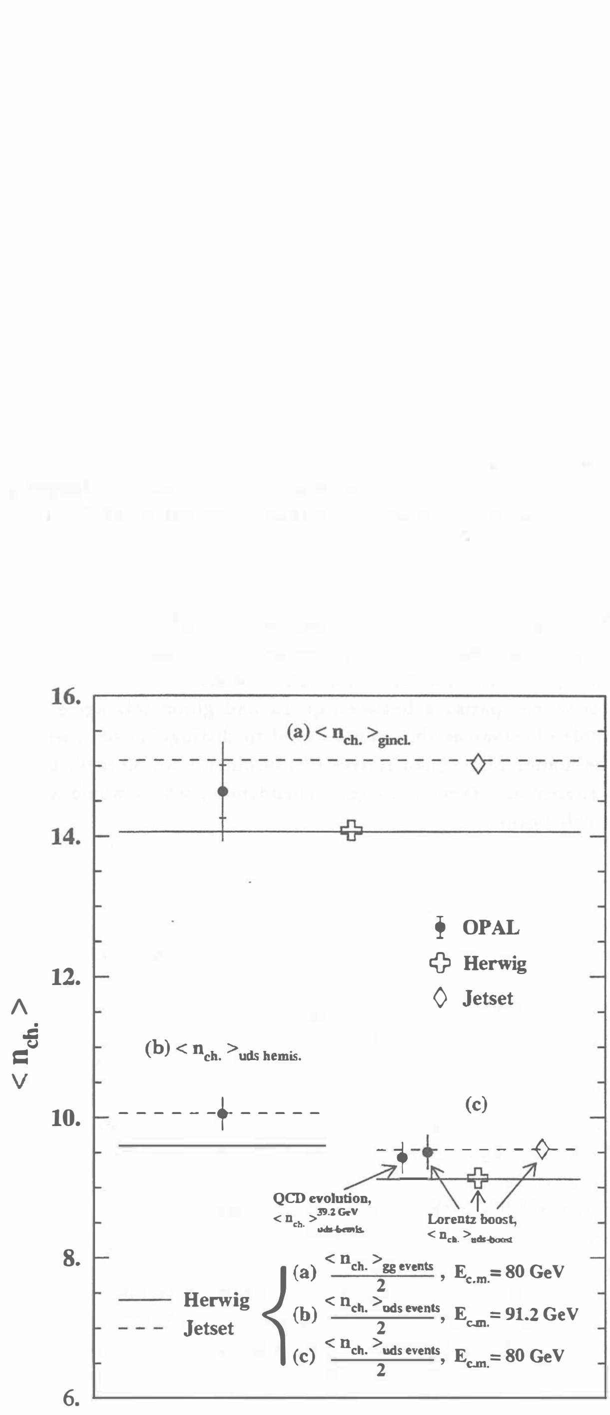

Figure 1: Corrected results for the mean charged particle multiplicity values of (a) 39.2 GeV gluon jets, (b) 45.6 GeV uds jets, and (c) 39.2 GeV uds jets, in comparison to the generator predictions of the Herwig 5.8 and Jetset 7.4 Monte Carlos. The experimental statistical uncertainties are indicated by the small horizontal bars. The statistical uncertainties are too small to be visible in parts (b) and (c). The statistical uncertainties of the Monte Carlo results are much smaller than those of the data.

JETSET predicted ratio. For protons, the ratio normalised to the ratio for charged particles in Y events is about 2 to 3 standard deviations more than predicted by JETSET.

5. conclusion

The Study of quark and gluon initiated jet properties and differences is an important task for the understanding of the hadronisation processes. It provides more inputs for the preparation of Monte carlo generators for future hadron colliders.

Experimental qualitative comparisons between quark and gluon jets agree well on the differences, and measurable observables that can be used to distinguish between quark and gluon jets can already be made. More quantitative measurements are needed, mainly those taking into account jet energy and event topology dependences, which would allow further tests of QCD analytical calculations.

6. References

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