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Charged Particle Production in the Fragmentation of Quark and Gluon Jets

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Abstract

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CHARGED PARTICLE PRODUCTION IN THE FRAGMENTATION OF QUARK AND GLUON JETS

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Recent results on the total production and angular distribution of charged particles originated from the fragmentation of quark and gluon jets are presented. Experimental studies of the multiplicity as a function of the quark and gluon jet energy, the inter-jet particle flow and the individual fragmentation functions are reviewed and compared to the expectations from QCD.

1 Introduction

In Quantum Chromodynamics (QCD), quarks (q) and gluons (g) are coloured objects that carry different colour charges. The strength of the quark-gluon and gluon-gluon couplings is directly related with the colour charges and, in consequence, the probability to emit additional gluons is also different for both quarks and gluons. Reconstructed quark and gluon jets are expected to inherit their parton origin and, therefore, they should exhibit differences in their multiplicities, energies and angular distributions. It is well known, however, the existing difficulties to measure these differences in quantitative agreement with the predictions from perturbative QCD, as partons, quarks and gluons, are not directly observed in nature and only the stable particles, produced after the fragmentation process, are experimentally detected. Earlier measurements of the ratio of the gluon jet multiplicity w.r.t the quark jet multiplicity, $r = \langle N_g \rangle / \langle N_q \rangle$, of the coherence phenomena in the inter-jet $q\bar{q}$ region w.r.t. the qg region, etc., have established qualitative evidence for these differences but have failed in describing them quantitatively as predicted by QCD.

At present, more than 16 million hadronic decays of the Z boson have been collected by the LEP experiments. These high statistics allow applying restrictive selection criteria to select quark and gluon jet samples with high purities. The selected data samples are almost background free and small corrections to account for impurities are needed. A smaller model dependence than ever is now achieved, bringing the possibility to perform quantitative studies of quark and gluon fragmentation according to perturbative QCD.

Studies on quark and gluon jet fragmentation have been carried out at LEP by the OPAL[1] and ALEPH[2] collaborations selecting three-jet symmetric configurations in which the quark and gluon jet properties were compared at a fixed energy scale. A new analysis from DELPHI[3] using symmetric and non symmetric three-jet event configurations show these properties as a function of the jet energy. The hadronic part of radiative $q\bar{q}\gamma$ events as a function of the reduced center of mass energy, $s' = s \cdot (1 - 2E_\gamma/\sqrt{s})$, has also been investigated using event shape variables by L3[4] and using charged multiplicity distributions by DELPHI[3]. All these studies are quite extensive and a proper description covering all details is out of the scope of this short review. Here only results from analyses, which use heavy flavour tagging in $q\bar{q}g$ events to identify gluon jets and radiative $q\bar{q}\gamma$ events to identify quark jets, are reported. Other presentations of similar content based on other type of jet tagging procedures were also discussed in the conference[5]. The differences of quarks and gluons as a function of the jet reconstruction algorithm and of the three-jet event configuration: jet energies, the particle flow in different inter-jet regions and the scaling violation effects, are the subject of our discussion following.

2 Quark and gluon jet selection

Gluon and quark jets are selected using hadronic three-jet events. Jets are mainly reconstructed using the DURHAM algorithm (OPAL, ALEPH, L3, DELPHI) although the JADE and CONE algorithms have also been used[1,3], in particular to observe the effects due to different angular particle acceptance of the various algorithms and to compare with the results from hadron colliders.

In the gluon splitting process ($g \to q\bar{q}$), the heavy quark production is strongly suppressed[6]. This opens the possibility to select gluon jets from $q\bar{q}g$ events in which two of the jets, the quark jets, are seen to satisfy the experimental signatures of being initiated by b quarks, leaving the remaining jet to be associated to the gluon jet without further requirements. Algorithms for tagging b jets exploit the fact that the decay products of long lived B hadrons have large impact parameters and/or contain inclusive high momentum leptons coming from the semileptonic decays of the B hadrons. Gluon purities of 94% and 85% are achieved when using these techniques, respectively. Obviously, the quark jets belonging to these events cannot be used to represent an unbiased quark sample. Thus the quark jets whose properties are to be compared with the gluon jets must be selected from other sources which in any case should preserve the same kinematics. Two possibilities have been proposed in the current literature. One consists in selecting symmetric three-jet event configurations[1,2,3] in which one (Y) or the two (Mercedes) quark jets have similar energy to that of the gluon jet. The quark jet purities reached are ~48% and ~66%, for Y and for Mercedes events, respectively. In a second solution[1,3,4] radiative $q\bar{q}\gamma$ events are selected, allowing a sample of quark jets with variable energy to be collected. In this latter case, misidentifications of γ's due to the π^0 background and radiative $\tau^+\tau^-\gamma$ contamination give rise to quark jet purities of ~92%. This method gives a higher purity but unfortunately suffers from the lack of statistics.

3 Multiplicities of quark and gluon jets

Results on the charged multiplicity of quark and gluon jets[1,2] using symmetric Y configurations and reconstructed with DURHAM at 24 GeV gluon jet energy, give a ratio of $r \approx 1.23 \pm 0.04$(stat.+syst.) which does not depend on the cut-off parameter (y_{cut}) selected to reconstruct jets[1]. It is significantly higher than one, which indicates that quark and gluons in fact fragment differently, but it remains far from the asymptotic lowest order expectation of $C_F/C_A = 9/4$, suggesting that higher order corrections and non-perturbative effects are very important to understand the measured value. A next-to-leading order correction[7] in MLLA (Modified Leading Log Approximation) at $\mathcal{O}(\sqrt{\alpha_s})$ already lowers the prediction towards r values slightly below two and exhibits a small energy dependence due to the running of α_s. However this is still insufficient to explain the value of r determined by the experiments. Solutions based on the Monte Carlo method give a better approximation[3]. The parton shower option of the JETSET generator[8] which uses the Altarelli-Parisi splitting functions for the evolution of the parton shower reduce the theoretical prediction[3] for r. At parton level, at 24 GeV jet energy, the expected value is ~1.4 and it is further reduced to ~1.3 if the value of r is computed after the fragmentation process. In both cases there is a clear dependence of r with the jet energy[3] which can be parametrized using straight lines with slopes of $\Delta r/\Delta E = (+90 \pm 3(\text{stat.})) \cdot 10^{-4}$ GeV^{-1} at parton level and $\Delta r/\Delta E = (+76 \pm 2(\text{stat.})) \cdot 10^{-4}$ GeV^{-1} after fragmentation. The absolute value of r predicted at parton level is however largely affected by the choice on the Q_0 parameter (cut-off at which the parton evolution stops) but has negligible influence on its relative variation with the energy, i.e. the slope. The DELPHI analysis uses symmetric and non-symmetric three-jet event configurations with quark and gluon jets of variable energy, allowing thus all these properties and predictions to be tested. A value of $r = 1.24 \pm 0.03$ (stat.+syst.) is measured corresponding to an average jet energy of ~27 GeV. The energy dependence of r is also suggested at 2.7σ significance level, with a fitted slope of $\Delta r/\Delta E = (+86 \pm 32(\text{stat.+syst.})) \cdot 10^{-4}$ GeV^{-1}.

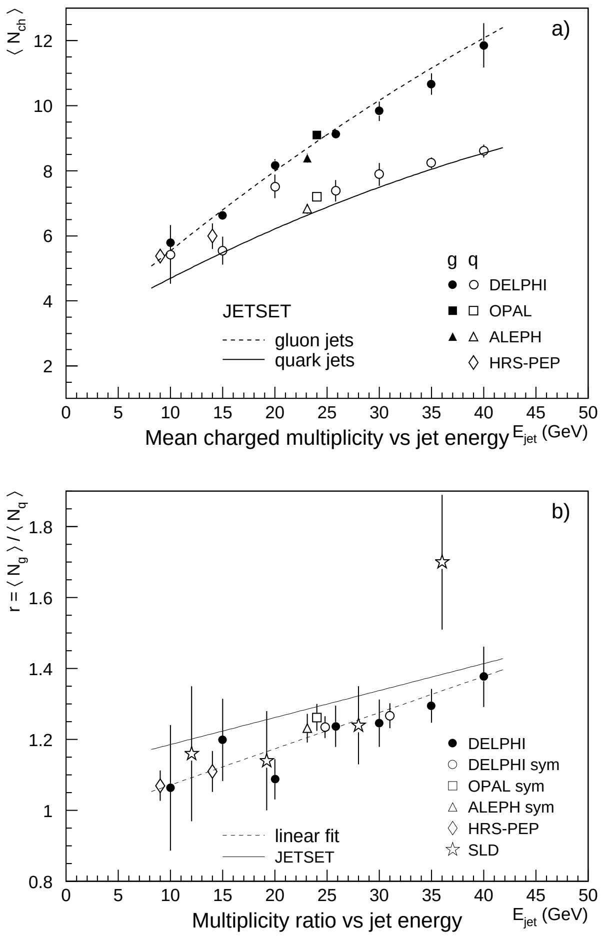

Figure 1: (a) Mean charged multiplicity of quark and gluon jets as a function of the jet energy. Original results are corrected to account for the same flavour composition of 11% b's and 33% c's. Solid and dashed lines represent the JETSET event generator prediction. (b) Multiplicity ratio r as a function of the jet energy. The solid line represents the JETSET prediction after fragmentation and the dashed line is the best fit to data. Values corresponding to the same energy are separated for having a better display.

The absolute value of r depends on the reconstruction jet algorithm. For both the JADE and CONE schemes different results are obtained w.r.t. the DURHAM scheme[1,3]. This is due to the combined effect of the different sensitivity of the various jet reconstruction algorithms to soft particles at large angles and of the expected different angular and energy spectra of the emitted soft gluons in the quark and gluon jets. A precise deconvolution of both effects seems, at present, impossible[9]. The energy behaviour of r is however well represented[3].

All published data from various experiments can be used to perform a general study in which more precise results can be attained. Care has to be taken when comparing results from different experiments as not all the analyses consider quark samples of the same flavour content, and this can significantly change the quark jet multiplicity [10,11,12]. To optimize calculus, the results given following are based on the $q\bar{q}\gamma$ analysis from DELPHI which considers that the quark jet sample contains 11% b's and 33% c's. All other results are corrected from their original values to account for the same quark mixture. In figure 1.a the quark and gluon jet multiplicities are shown as a function of the jet energy and compared to JETSET. Available results from LEP[1,2,3] and PEP[13] using symmetric and non-symmetric configurations are entered. In addition to these data figure 1.b also includes measurements from SLD[14]. The value given for r at 10 GeV and 15 GeV is calculated using the quark jet multiplicities from HRS and the gluon jet multiplicities from DELPHI.

Evidence for an energy dependence of r is again observed when using all these data. The measured increase is

$$\frac{\Delta r}{\Delta E} = (+97 \pm 21 \text{ (stat.+syst.)}) \cdot 10^{-4} \text{ GeV}^{-1},$$

representing a $\sim 5\sigma$ effect.

The measured value of r remains systematically lower than the JETSET prediction over the whole energy range, having an average value of

$$r = 1.23 \pm 0.01 \ (\mathit{stat.}) \pm 0.03 \ (\mathit{syst.}),$$

corresponding to an average energy of ~22 GeV. This ratio can be further expressed as

$$r_{uds} = 1.30 \pm 0.01 \ (\mathit{stat.}) \pm 0.04 \ (\mathit{syst.}),$$

if r is computed only for the light quarks u, d and s, extracting the b and c quark contribution to the quark jet multiplicity according to [10,11,12].

4 Inter-jet coherence, the string effect

The measurements of the energy and particle flow in the inter-jet regions of three-jet $q\bar{q}g$ and $q\bar{q}\gamma$ events represent an important test on the non-abelian gauge nature of QCD. Inter-jet coherence effects are expected to be seen in data according to the Local Parton Duality hypothesis (LPHD). Again the possibility to perform either qualitative or quantitative tests depend on the available theoretical predictions[15] and on the selected experimental data sample.

Using Mercedes events DELPHI[3] measures an asymmetry of the particle flow between the qg and $q\bar{q}$ regions of $R_g = N_{qg}/N_{q\bar{q}} = 2.23 \pm 0.37$ (stat.+syt.), proving that the string effect is present in fully symmetric three-jet event configurations in which all jets have the same energy. This rules out those arguments which explain the string effect on the basis of only kinematic considerations.

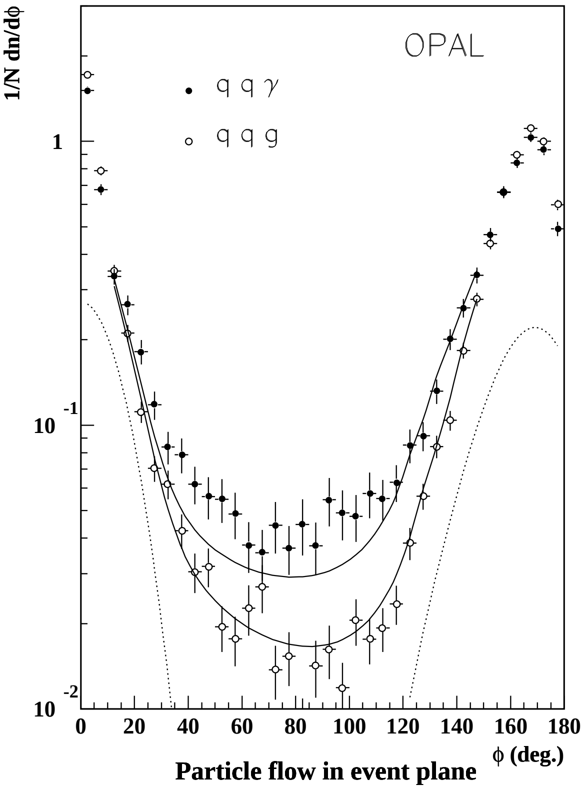

Figure 2: Charged particle flow in the inter-jet $q\bar{q}$ region of $q\bar{q}g$ and $q\bar{q}\gamma$ events as compared to the MLLA prediction. The dotted line represents the estimated intra-jet contribution.

A cleaner verification of the string effect is then evident when comparing the particle flow in the $q\bar{q}$ region of $q\bar{q}g$ events with the corresponding region in $q\bar{q}\gamma$ events. Figure 2 shows the OPAL results[16] for three-jet events using all topological configurations. The angular separation between jets was normalized to allow a proper comparison and the obtained distribution was fitted considering a perturbative QCD contribution as given by the MLLA approach and a non-perturbative intra-jet contribution assumed to be gaussian. The results of the fit are in reasonable agreement with data.

The DELPHI approach[3] is different to that from OPAL as it uses symmetric $q\bar{q}g$ and $q\bar{q}\gamma$ three-jet events. The selected configuration corresponds to Y events which have a $q\bar{q}$ jet separation of 150° ± 10°. The measured ratio of the particle flow corresponding to this region in both type of events is $R_q = N_{q\bar{q}}(q\bar{q}g)/N_{q\bar{q}}(q\bar{q}\gamma) = 0.58 \pm 0.06$ (stat.+syt.), compatible with the MLLA prediction of 0.60. This is the first time in which inter-jet coherence effects are measured to occur according to the perturbative QCD prescription. This is mainly due to two important aspects of the analysis, the highly pure sample of gluon jets (96%) which enhance the effect and the large angle separation between jets which minimizes non-perturbative contributions.

Table 1: Particle flow ratios measured by the LEP experiments using $q\bar{q}\gamma$ events and the characteristics of each analysis.

Experiment	Topology	R_q	Gluon id.
ALEPH	Y	0.75 ± 0.07	Lepton
DELPHI	Y	0.58 ± 0.06	Vertex
DELPHI	Y	0.68 ± 0.07	Lepton
L3	All	0.79 ± 0.06	Lepton
OPAL	All	0.71 ± 0.03	Energy

In table 1 all LEP measurements of the string effect[3,16,17,18] with $q\bar{q}\gamma$ events are summarized. The differences among these results can be understood in terms of the applied gluon selections and the three-jet configurations used in the analyses.

5 Fragmentation functions

The distribution of the energy fraction carried by the generated particles, $x_E = E_{part}/E_{jet}$, is known as the fragmentation function. LEP studies using symmetric Y three-jet event configurations[1,3] demonstrate that the gluon jets contain a softer particle spectrum than their quark jet counterparts of equivalent energy. DELPHI also includes an analyses on fully symmetric three-jet events (Mercedes). A comparison between the obtained distributions at both energy points, 24 GeV for Y and 30 GeV for Mercedes events, shows that the increase in the multiplicity takes place at small momentum whereas the inclusive spectra decreases for large x_E, indicating thus the presence of scaling violations (see figure 3). The measured suppression is larger for gluon jets than for quark jets by a factor 2.4±0.5 (stat.), which is in nice agreement with the lowest order QCD prediction of ~2.5.

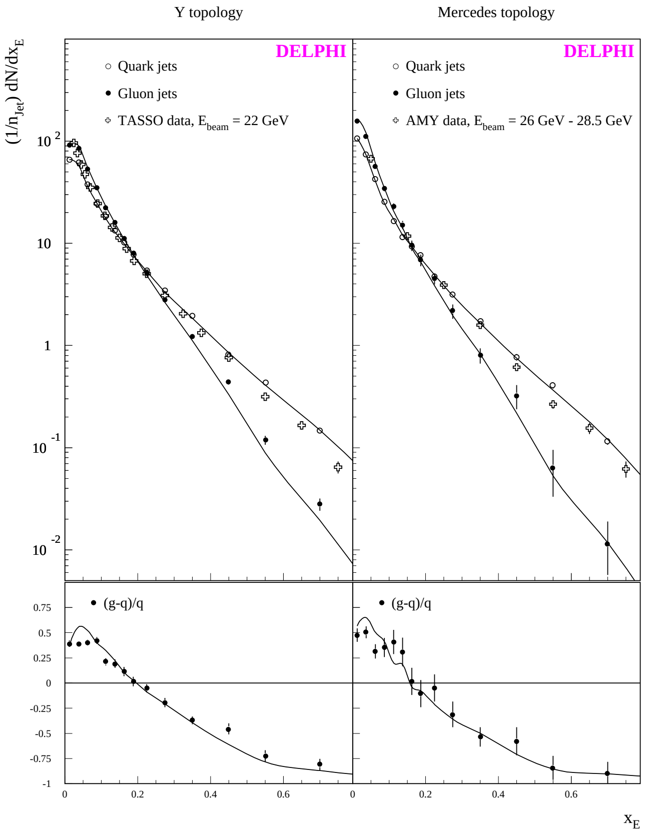

Figure 3: Fragmentation functions for quark and gluon jets selected from symmetric three-jet events. The solid lines are the corresponding JETSET predictions as tuned using DELPHI data.

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