Energy and Particle Flow in Three-Jet and Radiative Two-Jet Events from Hadronic Z Decays

L3 Collaboration

Abstract
Introduction

The measurement of energy and particle windows in the regions between jets is known to represent an important test of QCD and fragmentation models. In three-jet events produced in $e^+e^-$ annihilations it has been observed that the region between the two quark jets presents lower particle and energy windows relative to that which would be expected from independent-fragmentation models. On the other hand, models based on string fragmentation predicted this effect and have been found to reproduce the data. In these models the string that generates final state particles receives a boost in the gluon direction depleting the $q\bar{q}$ region in favor of the $qg$ and $g\bar{q}$ ones. The success of these models gave origin to the name "string effect" under which the phenomenon is often known. However, it has been observed that in perturbative QCD calculations, coherent emission of soft gluons from the color dipoles $qg$, $g\bar{q}$ and $q\bar{q}$ produces a similar effect. Assuming Local Parton-Hadron Duality, which is equivalent to considering the window of final state hadrons to be proportional to the window of soft gluons, the effect should be observable at the hadron level without invoking any string fragmentation phenomenology. As a consequence a depletion is also expected from parton shower fragmentation models which include soft gluon interference effects.

The experimental comparison of three jet events $q\bar{q}g$ with two jet events having a hard photon in the final state represents a clean and model independent way of studying the "string effect." In fact, for similar kinematics the particle and energy yields in the $q\bar{q}$ region are expected to be lower for $q\bar{q}g$ than for $q\bar{q}$.

In this paper we present a comparison of the energy and particle window distributions in the event plane of $q\bar{q}g$ and $q\bar{q}$ events for similar topologies and kinematics.

The L3 Detector

The L3 detector consists of a time expansion chamber for tracking charged particles, a high resolution electromagnetic calorimeter of BGO crystals, a barrel of scintillation counters, a hadron calorimeter with uranium and brass absorbers and proportional wire chamber readout, and a muon spectrometer. All sub detectors are installed inside a 1.2 m diameter solenoidal magnet which provides a uniform 0.5 T field along the beam direction. The L3 detector is 99% of the $4\pi$.

The BGO energy resolution is better than 1% for electromagnetic particles above 1.5 GeV, while the angular resolution for clusters with energy above 5 GeV is better than 0.12°. At 4 GeV the jet angular resolution is 0.5° and the jet energy resolution is 1.0%.

Event Selection

The selection of hadronic events is based on the energy measured in the electromagnetic and hadronic calorimeters. Events are accepted if:

\[ E_{\text{vis}} < n_3c \]

\[ j \left| E_{\text{vis}} \right| > n_3c \]

\[ E_{\text{vis}} > 0 \]

where \( E_{\text{vis}} \) is the total energy observed in the detector, \( E_{jj} \) is the energy imbalance along the beam direction, and \( E_{\text{trans}} \) is the transverse energy imbalance. An algorithm is used to group neighboring calorimeter signals, which are likely to be produced by the same particle, into clusters. Only clusters with a total energy above 100 MeV are used. The number of clusters produced is proportional to the number of particles in the event, so the cut on the number of clusters, \( N_{\text{cluster}} \), rejects mainly low multiplicity non-hadronic events. Applying the same cuts to simulated events, we find that 98% of the Z hadronic decays are accepted. This efficiency has been found to be constant within errors for photon energies up to 45 GeV.

In the selection of q/qg and q/qd events we pay particular attention to have similar kinematics and productive volumes for the two classes of events and to obtain a high purity q/qd sample. While jets are reconstructed in the angular region \( 5^\circ \leq \theta \leq 175^\circ \) being the angle with respect to the LEP beam axis, photons in q/qd event candidates are selected only in the barrel region of the electromagnetic detector. We select q/qg events by applying the JADE algorithm with \( \gamma \) cut = 0.05 and \( E_{\text{rec}} \) recombination scheme to our hadronic event sample, retaining three jet events, and then identify the gluon as the softest jet. The purity is estimated to be 28.7% using JETSET with the Matrix Element option.

As a cross-check, we perform a gluon identification by requiring the event to have an muon with momentum \( p < 4 \) GeV in the second or third most energetic jet and identify the two quark jets as the most energetic jet and the one including the muon. The remaining jet is assigned to the gluon. This technique results in a higher gluon identification purity of 85.2%, but the semileptonic tag selects quark jets that include a neutrino and hence some missing energy. This makes the event kinematics different from the q/qd case, so we use this second method only as a cross-check.

In both cases the plane including the two quark jets is taken as the event plane and events are selected in such a way to have the gluon jet within 10° from it. Similar to the photon in q/qd events only gluon jets inside the central region of the detector are accepted.

The analysis faces the problems of distinguishing genuine single photons from energetic neutral hadrons and of suppressing photons emitted by the quarks at low Q^2. Events with a photon radiated at a smaller scale than a gluon should be considered as background, while events with hard photons from initial state radiation are not a background and are not removed from the sample.

In the case where the photon is emitted before any gluon radiation takes place one can make the approximation that the q/qd event is equivalent to a two-jet event boosted by the photon emission. If one disregards the photon, in the q/qd center-of-mass system the event should have the properties of a two-jet event with a total energy \( p_s = q_s = 2 \left( E_{\text{vis}} \right) \), where \( E_{\text{vis}} \) is the photon energy in the laboratory frame.
\[ E_\gamma = E_{\gamma c} - E_\gamma - \frac{E_{c1} E_{c2} E_{c3}}{E_{c1} E_{c2} E_{c3}} \]

\[ p_x, p_y, p_z \quad -p_x, -p_z, -p_y \]

\[ E_c \quad E_{\gamma c} \quad E_\gamma \quad \epsilon \]

\[ E_{\gamma c} = E_\gamma - \frac{E_{c1} E_{c2} E_{c3}}{E_{c1} E_{c2} E_{c3}} \]

\[ p_y \gg p_z \approx E_c \]

\[ E_{\gamma c} / E_{\text{jet3}} \]

\[ |E_c| < \epsilon \]

\[ \epsilon > \]

\[ \pm \pm \]

\[ \epsilon \]

\[ \gamma \]

\[ A_{12} \quad A_{13} \]
### Results

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/ $\gamma$
The following sources of systematics have been estimated:

- The subtraction of the residual neutral hadron background in the amount predicted by JETSET or HERWIG increases the $R$ values by $R_N = +0.05$ and $R_E = +0.04$.

- Varying the cut on " from 0.75 to 0.85 with the aim of changing the amount of photons emitted at smaller scale than gluons. We observe a change of $R_N = -0.06$ and $R_E = -0.10$.

- The systematics introduced by the cut are found to be negligible.

- The use of the DURHAM algorithm with $y_{\text{cut}} = 0.2$ in the analysis, rather than the JADE algorithm, results in a 2% increase of both $R_N$ and $R_E$. This is compatible with a 5% reduction of gluon purity as predicted by JETSET. Hence we do not add this effect to the systematic error.

- For $q/qd$ events, not recomputing the jet directions without the candidate increases the number of events by 0.8% and increases the angle between the quark jets by 0.4° on average. The resulting changes in the ratios are $R_N = +0.05$ and $R_E = +0.08$.

- The definition of a calorimetric object was modified by introducing a preclustering procedure which uses the JADE algorithm with $y_{\text{cut}} = 1.2$, corresponding to a mass of about 100 MeV at LEP energies. This causes a change of $R_N = +0.10$ and obviously no change in $R_E$.

- Changes of 2° in the cut on the angle between the photon and the event plane produce variations $R_N = +0.1$ and $R_E = -0.0$.

- The data composition of $q/qd$ and $q/qg$ events is different because of the different quark charges resulting in different couplings to the photon. We therefore reweighted, in JETSET events, the composition of $q/qg$ events to match the data composition of $q/qd$ ones. This was found to have no effect on $R_N$ or $R_E$.

- By a study of Monte Carlo events at generator level we have also tested the influence of cracks in the detector acceptance. The magnitude of the phenomenon is left unchanged by the addition of a blind region covering 6° around the beam axis. This is the consequence of the fiducial region adopted for jet 3 in both the $q/qd$ and $q/qg$ cases.

From the above study the total systematic error is $0.15$ for both $R_N$ and $R_E$. This gives $R_E = -0.79 \pm 0.06$ and $R_N = -0.81 \pm 0.03$, so that the depletion of the region opposite to the gluon compared to the one opposite to the particle has a significance of 5

- It has been remarked that the observed effect could have a purely kinematic origin, being caused by the difference between the massless photon and the effective mass of the gluon jet. In this scenario the quark jets of the $q/qd$ events, having less energy to share, are slimmer and result in lower interjet activity. In fact, we observe a small difference between the $q/qd$ and $q/qg$ kinematics as a shift of the order of 1% in the masses of the two quark jets in our data and in all the Monte Carlo models used. The difference also occurs for COJETS even though it does not reproduce the constraint effect. Also, this mass shift is reduced by half if the jets are...
The systematics give negligible contribution to the errors. Increase by selecting for each event only particles with a large momentum component, left unchanged. We conclude that the effect cannot be explained on these grounds.

Table 2: Double ratios not recomputed after the removal of the photon, while the magnitude of the effect is at lower energies, is predicted by perturbative QCD to decrease at LEP energy and to vanish perpendicular to the event plane. This phenomenon, observed by MARKII and JADE asymptotically. In practice the investigation of the $P$ at large part.

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$P_{out}$

$\gamma$

$P_{out}$

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$P_{out} > \gamma$

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$\alpha$

$P_{out}$

$P_{out}$

$P_{out} > P_{out}^{cut}$

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Conclusions

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References

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$E_c$, $\varepsilon$, $|E_c| <$

$\gamma$, $\delta$, $\varepsilon$

$A_{12}$, $A_{13}$, $E_3$

$P_{out}$
Figure 1: Isolation variables $n_{28a}$ after the cut $j E_c/j^2_{GeV}$ has been applied. Solid points represent the data, while the histogram represents the JETSET prediction. The background contribution from neutral hadrons is shown as the hatched area. The arrows represent the cuts used.

$E_c$, $\epsilon$, $|E_c| <$
Figure 2: Energy distribution projected onto the event plane in the $q\bar{q}\gamma$ rest frame for JETSET $q\bar{q}\gamma$ events after removal of the photon, which otherwise appears around $260^\circ$. Angles run from the highest energetic jet direction towards the second jet. Neutral hadron background is removed and the $E_c$ cut has been applied. Relative energy difference between the photon region and the symmetric one for data as a function of the cut on $\delta$. 

- a) JETSET $q\bar{q}\gamma$
  - $E^{-1}\Delta E/\gamma$ deg. vs. Angle [deg.]
  - no $\varepsilon$ cut
  - $\varepsilon > 0.8$

- b) Data
  - $\delta$ [%] vs. $\varepsilon_{\text{min}}$
Figure 3: 

- **a)** Angle $A_{12}$ between the two quark jets and $q\bar{q}g$. 
- **b)** Angle $A_{13}$ between the most energetic jet and the third jet. 
- **c)** Energy of the third jet $E_3$. 

```
\begin{align*}
A_{12} &\quad q\bar{q}g \\
A_{13} &\quad q\bar{q}\gamma \\
E_3 &\quad E/2 \text{ GeV}
\end{align*}
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Figure /4/: /n28a/n Distribution of the normalized energy /n0do w and /n28b/n particle /n0do w in the lab oratory frame. /n28c/n and /n28d/n are the corresp onding distributions in the q /n16 q cen ter of mass frame/, after the photon has b een remo v ed. The arro ws sho w the angular range used to measure the e/n0bect/.
Figure 5: Bin-by-bin ratios of the $q/n_16 q$ and $q/n_0 d/n_28 a/n_29$ energy and $n_28 b/n_29$ particle down plots after the application of the algorithm described in the text to $q/n_16 q$ events. The theoretical predictions have statistical uncertainties of similar magnitude to the ones shown for data. $c$ and $d$ show the ratios of the distributions with and without a 0.2 GeV $P_{out}$ cut. Systematic errors are not shown in $a$ and $b$, while they are negligible in $c$ and $d$. The arrows show the angular range used to measure the effect.