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

L3 Collaboration

Abstract

\[ \gamma \]

\[ \gamma \]
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 neutral/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 $gq$ 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 $qg$, $gq$ and $q\bar{q}$ produces a similar effect. Assuming local parton-Hadron Duality which is equivalent to considering the window of final 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 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. We use hadronic events collected with the L3 detector during 1991, 1992 and 1993 at $p_{\text{T}}^\text{beam}/A GeV$.

The results are compared with predictions from the COJETS, HERWIG and JETSET Monte Carlo event generators. These models use a parton shower approach to describe the perturbative phase of gluon emission with differences in the treatment of gluon coherence. The hadronization phase is described by a "string" model in JETSET and a "cluster" model in HERWIG. In COJETS partons are fragmented independently and the effects of gluon coherence are neglected.

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, 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 40% of solid angle coverage of L3 is 99% of 40 GeV.

The BGO energy resolution is better than $2\%$ for electromagnetic particles above 1.5 GeV, while the angular resolution for clusters with energy above 5 GeV is better than $0.12^\circ$. At 4 GeV the jet angular resolution is $2.5^\circ$ and the jet energy resolution is $10\%$.

\[ 1^\text{A discussion of the model parameter tuning for L3 is given in reference [11].} \]
Event Selection

\[ 0 < \frac{E_{\text{vis}}}{\sqrt{s}} < \frac{3}{4}, \quad \frac{|E_\parallel|}{E_{\text{vis}}} < \frac{3}{4}, \quad \frac{E_\perp}{E_{\text{vis}}} < \frac{3}{4}, \quad N_{\text{cluster}} > 1, \]

\[ E_{\text{vis}} \quad E_\perp \quad E_\parallel \]

\[ N_{\text{cluster}} \]

\[ \gamma \]

\[ \circ < \theta < \circ \]

\[ \gamma \]

\[ \circ < \theta < \circ \]

\[ y_{\text{cut}} \]

\[ \pm \]

\[ p_\mu > \]

\[ \pm \]

\[ \gamma \]

\[ \circ < \theta < \circ \]

\[ Q^2 \]

\[ \gamma \]

\[ \sqrt{\frac{s}{s}} \quad \sqrt{\frac{s - E_\gamma \sqrt{s}}{s}} \quad E_\gamma \]

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

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

\[ E_c \quad x, y, z \quad x \]

\[ E_{\gamma c} \quad \epsilon \quad \frac{E_{\gamma}}{E_{\text{jet}3}} \]

\[ |E_c| < \frac{\epsilon}{\epsilon} \quad \epsilon > \]

\[ \pm \pm \gamma \]

\[ p_y \gg p_z \approx \]

\[ E_c \sim \]

\[ \epsilon \quad E_{\gamma}/E_{\text{jet}3} \]

\[ \epsilon \quad \frac{E_{c1}}{E_{c}} \quad \frac{E_{c2}}{E_{c}} \quad \frac{E_{c3}}{E_{c}} \]

\[ \pm \pm \gamma \]

\[ \epsilon \quad \epsilon > \]

\[ \gamma \]

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

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>$R_N$</th>
<th>$R_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\times 6$</td>
<td>$\times 6$</td>
<td>$\times 6$</td>
</tr>
</tbody>
</table>

$R_E$  
$R_N$
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 $R_E = +0.04$.
- When the cut on $y$ from 0.75 to 0.85 is made, the amount of photons emitted at smaller scale than gluons is changed. We observe a change of $R_N = +0.06$ and $R_E = +0.10$. The systematics introduced by the $E_c$ cut are found to be negligible.
- For $q \bar{q}$ events, not recomputing the jet directions without the $q g$ 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 $y_{cut} = 1.2$, 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 $y_{cut}$ in the cut on the angle between the photon and the event plane produce variations $R_N = R_E = +0.07$.

For $q \bar{q}$ and $q g$ events, not recomputing the jet directions without the $q g$ 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 deviation in the cut on the angle between the photon and the event plane produce variations $R_N = R_E = +0.07$.

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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 $6.4$ around the beam axis. This is the consequence of the cut used for jet in both the $q \bar{q}$ and $q g$ cases.

From the above study the total systematic error is $6.0:15$ for both $R_N$ and $R_E$. This gives $R_E = 0.79$ and $R_N = 0.81$, so that the depletion of the region opposite to the gluon compared to the one opposite to the photon has a significance of $5\%$ for both particle and energy windows. The results obtained by identifying the gluon jet with a $-\bar{q}$ give a somewhat larger effect $R_E = 0.73$ and $R_N = 0.75$, which is compatible with the higher gluon purity.

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 $q \bar{q}$ events, having less energy to share, are slimmer and result in lower interjet activity. In fact, we observe a small difference between the $q \bar{q}$ and $q g$ kinematics as a shift of the order of $1.0\%$ 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 central effect. Also, this mass shift is reduced by half if the jets are...
The systematics give negligible contribution to the errors. In order to increase the statistical significance, we select for each event only particles with a large momentum component.

Table 2: Double ratios

<table>
<thead>
<tr>
<th>$P_{out}$</th>
<th>$\rho E$</th>
<th>$N_{out}$</th>
<th>$R_{P_{out}}^{E\mu\tau}/R_{E}$</th>
<th>$R_{N_{out}}^{\tau}/N_{\mu}$</th>
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As noted by several authors, the magnitude of the effect is expected to decrease at LEP energy and to vanish perpendicular to the event plane. This phenomenon, observed by MarkI I and JADE, is predicted by perturbative QCD to decrease at LEP energy and to vanish in the case of the event plane.

The effect is more abundant when a cut is applied in each plane separately. The systematic effect introduced by the above algorithm has been found to be negligible by a study of JETSET at generator level. In the case of the event plane, a precise meaning even in the event rest frame and the statistics used for JETSET, HER WIG and COJETS in the table.

In practice, the investigation of the event plane is partially overcome using the cylindrical symmetry of the event. The energy measurements give a picture consistent with a vanishing dependence on the event plane. This is compatible with perturbative QCD predictions.

In a similar fashion, detector corrections are applied in each plane separately. The systematic effect introduced by the above algorithm has been found to be negligible by a study of JETSET at generator level. In the case of the event plane, a precise meaning even in the event rest frame and the statistics used for JETSET, HER WIG and COJETS in the table.

Data is compared to Monte Carlo generators for energy and particle distributions. The double ratios cancel and are found to be negligible. In a similar fashion, detector corrections are applied in each plane separately. The systematic effect introduced by the above algorithm has been found to be negligible by a study of JETSET at generator level. In the case of the event plane, a precise meaning even in the event rest frame and the statistics used for JETSET, HER WIG and COJETS in the table.

Within the present statistics, the particle distribution shows an enhancement of the effect. In Figures 5c and 5d, we plot the variation of the double ratios.
Conclusions

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References

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  \item $\delta$
  \item $A_{12}$
  \item $A_{13}$
  \item $E_3$
  \item $\gamma$
  \item $\gamma$
  \item $P_{out}$
\end{itemize}
Figure 1: Isolation variables \( n_{28a} \) and \( n_{28b} \) after the cut \( |E_c| < JETSET \) 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.
Figure 2: Energy distribution projected on to the event plane in the q̅qγ rest frame for JETSET q̅qγ events after removal of the photon, which otherwise appears around 260. Angles run from 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 $\varepsilon$. 

a) JETSET q̅qγ

- $\varepsilon > 0.8$
- $\varepsilon$ cut

b) Data
Figure 3: 

(a) Angle $A_{12}$ between the two quark jets and $A_{23}$ between the most energetic jet and the third jet $A_{3}$. 

(b) Energy of the third jet $E_{3}$. 

(c) $N/4$ deg. distribution.
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