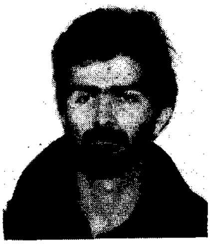
$Z^0 \rightarrow$ HADRONS NEW RESULTS FROM OPAL



Neil Geddes
Rutherford Appleton Laboratory
Chilton
Oxon.
England

representing
The OPAL Collaboration

Abstract

Results of recent studies of intermittency and quark and gluon jet fragmentation in hadronic decays of the Z^0 are presented. A factorial moment analysis of rapidity distributions shows that intermittency in the hadronic decays of the Z^0 is well reproduced by QCD based fragmentation models. Lepton tagging in 3-jet events has been used to distinguish between quark and gluon jets. This technique has been used to provide a model independent observation of the so called string effect. Also, evidence for differences in the fragmentation of quarks and gluons is presented.

1 The Data Sample

The OPAL detector has been described in detail elsewhere[1)]. The main features of the detector are a large volume central tracking chamber, an electromagnetic calorimeter, a hadron calorimeter and muon detection chambers. The detector has a high efficiency for detection of Z^0 multihadronic decays [2)], and for isolation of high momentum muons and electrons within these events[3)][4)].

The analyses presented in this paper are based on 140,000 multihadronic events recorded during the 1990 LEP run. To reduce non-hadronic backgrounds events were selected for analysis if they contained at least 5 charged tracks associated with the interaction vertex, and were well contained within the detector (assessed via restrictions on visible energy balance and event axis orientation)[4)][5)].

2 Intermittency

Intermittency refers to the existence anomalous fluctuations in phase space distributions of hadronic events, in particular the existence of "self-similar" fluctuations, which may hint at a fractal structure in hadronic final states[6)]. Assessing the statistical significance of rare or anomalous fluctuations is a difficult problem, however, a quantitative measure is provided by the method of *factorial moments* as proposed by Bialas and Peschanski[7)]. This technique is normally applied to the experimental rapidity distribution as follows. The central rapidity plateau Y is divided into M bins of size $\delta y = Y/M$. If the number of particles in the m^{th} bin is n_m then the factorial moment of order j is given by:

$$F_j(M) = \frac{1}{(\bar{n}_m)^j}\langle\frac{1}{M}\sum_{m=1}^{M} n_m(n_m - 1)...(n_m - j + 1)\rangle$$

$$\bar{n}_m = \frac{1}{M}\sum_{m=1}^{M} n_m$$

where the angle bracket indicates an average over all events. With this definition it is trivial to extend the calculation to other distributions such as the two dimensional rapidity vs azimuth (azimuthal angle around the reference axis) distribution. In this case the distribution is split into $\sqrt{M}$ rapidity × $\sqrt{M}$ azimuthal bins and the moments calculated according to the definition given above.

Factorial moments of order 2 to 5 have been determined from the OPAL multihadronic Z^0 decay sample. The analysis is restricted to charged particles in the range $-2 < y < 2$ (y is defined with respect to the sphericity axis and all particles are assumed to be pions). The excellent momentum resolution and two particle separation provided by the OPAL detector allow us to measure the factorial moments with rapidity bin size down to 0.01 units. The measured moments for both the rapidity and rapidity versus azimuthal angle are shown in Fig. 1 compared with the predictions of the HERWIG[8)] and JETSET[9)] (using both parton shower and ERT[10)] matrix element formalism) Monte Carlo programs. There is good agreement between all three models and the data[5)]. Detailed investigations of the source of the observed signals in the Monte carlo programs reveals that the major source is the jet structure of the events and the presence of 3 and 4 jet events.

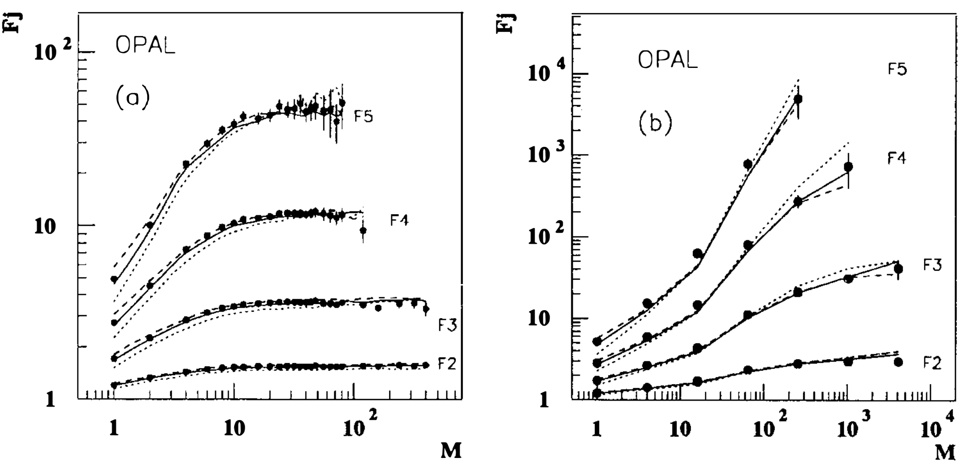


Figure 1: The corrected 2^{nd} to 5^{th} factorial moments , F_j (solid circles) versus number of bins, M for the rapidity (a) and rapidity vs azimuth (b) distributions compared with the predictions of the JETSET v7.2 parton shower (solid line), HERWIG v4.3, (dashed line) and JETSET/ERT matrix element (dotted line) Monte Carlo programs.

3 Tagging Quark and Gluon Jets.

The semi-leptonic decays of charm and bottom quarks can be used to separate quark and gluon jets in 3-jet events$^{4)}$. The principle known sources of high momentum leptons in hadronic electron-positron annihilation events are the weak decays of charm and bottom quarks. Furthermore these heavy quarks are produced almost exclusively at the electroweak vertex rather than during the subsequent fragmentation stage. Thus gluons jets will only rarely contain high momentum leptons and the observation of the latter may thus be used to tag quark (or anti-quark, no distinction is made here) jets.

To select a sample of 3-jet events the "JADE" jet finding algorithm was applied to the multihadronic event sample (the "P-scheme" recombination method was used with a resolution parameter $y_{cut} = 0.03$). All events where exactly 3 jets are reconstructed are retained. The following quality cuts are applied to ensure well reconstructed jets:

- The sum of the angles between the jets must be greater than 358°.
- Each jet must contain at least 3 charged tracks and have a measured energy of at least 5GeV.
- The measured jet energies must be consistent with those calculated from the relative jet angles.

Semi-leptonic decays are further selected by requiring that either;

- Two of the jets contain a high momentum muon ($p > 3$GeV) or electron ($p > 2$GeV). These jets are then "tagged" as the quark/anti-quark jets and the third jet is assumed to be the gluon jet.

or

- One jet, which must not be the highest energy jet (assumed to be the non-radiating quark/anti-quark), contains a high momentum muon or electron. The highest energy jet and the jet containing the lepton are then tagged as the quark/anti-quark jets.

These two samples are combined to provide a set of 3 jet events where the source of each jet (quark or gluon) is known with high probability. Monte Carlo estimates using the JETSET program give the probabilities that the jets are correctly labelled as; 96%, 88% and 84% respectively for the highest and lowest energy quark jets and the gluon jets.

To permit direct comparisons of the quark and gluon jets and the regions between them, a set of "symmetric" events is selected where the angles between the highest and lowest energy quark jets and between the highest energy quark jet and the gluon jet are both $150° \pm 10°$. This gives a sample of events where the lowest energy quark and gluon jets have essentially equal energies and event environments. This final sample contains 188 events.

4 String Effect

The so called string effect refers to an asymmetry in the particle populations for regions between quark and antiquark and between (anti)quark and gluon jets in 3-jet events[4)]. This effect arises naturally in models which explicitly contain "strings", such as the Lund model[9)], where the particles produced along the string are naturally boosted towards the gluon. The effect may also arise, however, as a result of interference terms in soft gluon radiation or as a result of dynamical differences between quark and gluon jet fragmentation. Here "string effect" is used to indicate the experimental observation of an asymmetry with no interpretation implied.

The "particle flow", $(1/N)dn/d\psi$, is shown in figure 2 for the symmetric tagged 3-jet sample described above. Here ψ is the angle in the event plane between a particle and the highest energy quark jet, N is the total number of events and dn is the number of particles in a bin of width $d\psi$. The event plane is defined by the two eigenvectors of the sphericity tensor associated with the two largest eigenvalues. The points in figure 2 show the particle flow starting at the higher energy quark axis then proceeding through the lower energy quark jet ($\phi \simeq 150°$) to the gluon jet ($\phi \simeq 210°$) and back to the higher energy quark jet. The histogram shows the particle flow for the same data, again starting at the higher energy quark axis, but proceeding in theoppositee sense: first through the gluon jet ($\phi \simeq 150°$) then through the lower energy quark jet. ($\phi \simeq 210°$). Thus the points for $0° < \psi < 180°$ are the same as the histogram curve for $360° < \psi < 180°$ and vice versa. The data are all shown for the detector level, no corrections have been applied.

A significantly larger population of particles is present in the region between the gluon and higher energy quark jets than in the region between the two quark jets, as is expected for the string effect. The effect of biases due to the event selection criteria have been evaluated and are not found to account for the observed asymmetry. Consistent results are also obtained for other

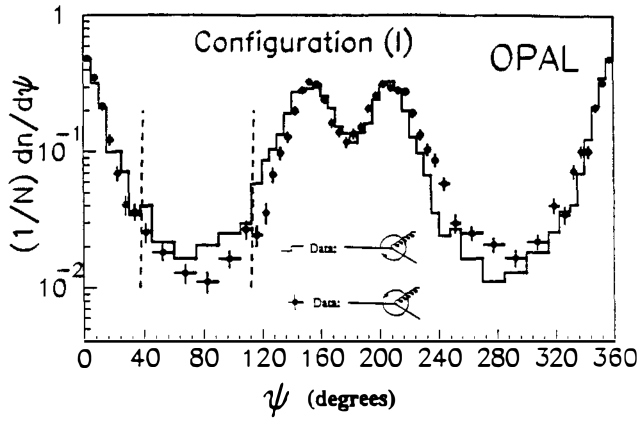


Figure 2: The particle flow distribution, $(1/N)dn/d\psi$. No corrections have been applied to the data. The points with errors show the flow from high energy quark jet to the low energy quark jet then to the gluon jet; the histogram shows the measured particle flow for the same events, again starting at the highest energy quark jet but then proceeding in the opposite sense

samples of 3-jet events$^{4)}$, eg. selected with quark-antiquark and quark-gluon jet separations of 130° rather than 150°. independent, event samples

5 Quark and Gluon Fragmentation

Using the symmetric quark-gluon jet events selected above, it is possible to compare directly the properties of gluon jets and quark jets of similar energies embedded in similar environments. the event plane excluded from the string effect studies. Figure 3 shows the ratio of the particle flow for gluon jets to that for the quark jets in the region around the jet axis. Although the multiplicity of the quark and gluon jets is similar in the central region around the jet axis, the gluon jets clearly have more particles in the wings than the quark jets. Also shown in Figure 3 is the differential energy spectrum for particles in the cores of quark and gluon jets, defined as the region $135° < \psi < 165°$. The quark jet spectrum clearly is clearly harder, implying that particles in the cores of quark jets tend to be more energetic than those in gluon jets.

6 Summary

Intermittency in Z^0 hadronic final states is well reproduced by QCD based Monte Carlo programs. The major source of observed signals appears to be the jet structure of the events.

A definite asymmetry exists between the particle populations of the regions between quark and antiquark and between (anti)quark and gluon jets in 3-jet events. Also, in the jet regions themselves, gluon jets are observed to be softer and wider than quark jets.

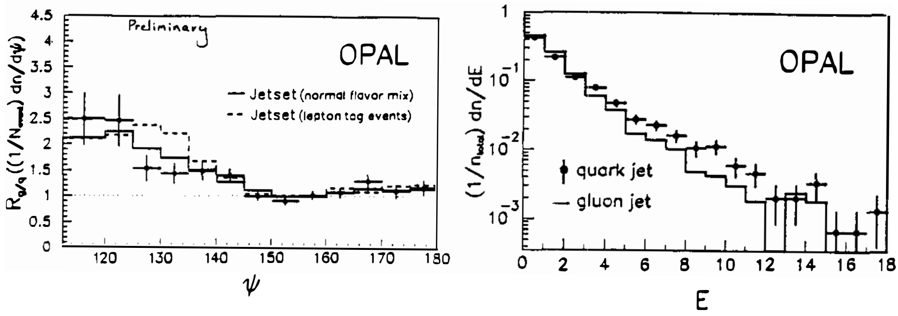


Figure 3: (a). The ratio of $(1/N_{evt})dn/d\psi$ in for gluon jets to that for quark jets in the region around the jet peak. (b). The inclusive energy spectrum $(1/n_{total})dn/dE$ of particles in the jet core regions ($135° < \psi < 165°$).

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