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A Study of Rapidity Gaps in e^+e^- Annihilations

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Abstract

Distributions of rapidity gaps in hadronic decays of the Z have been studied using data collected with the ALEPH detector in 1991 and 1992. First, the inclusive gap distribution is made from a sample of hadronic Z decays in which the tau background has been removed carefully. Second, events are sought in four topological categories in which rapidity gap events might be expected. A comparison is made to Monte Carlo predictions, and no significant discrepancy has been found, despite the fact that certain four-quark states, which should be produced at a non-negligible level in Z decays and which would exhibit large rapidity gaps, are not included in those models.

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1 Introduction

Events with large rapidity gaps have been observed at HERA and the TEVATRON at a rate much larger than predicted by the standard QCD-based Monte Carlos. These events are thought to be produced through the exchange of a colorless hadronic object in the t channel. Such an object cannot be exchanged in e^+e^- interactions, so one would not expect to observe an anomalous number of events with large rapidity gaps in Z decays.

Bjorken, Brodsky, and Lu suggested a different mechanism for the production of rapidity gap events in Z decays [1]. Four-quark final states occur when a hard gluon splits. There is a special configuration within perturbative QCD in which the secondary quarks pair up with the primary quarks to make two colorless diquarks flying apart from each other. The main diagram is shown in Figure 1.

In a normal event, the color 'string' stretches across the center-of-mass, *ie* across the entire rapidity range. This leads to a particle population filling in all rapidities between the extremes. Ideally, all such particles are detected, and the rapidity differences between the slowest particles in each event hemisphere is usually small. In contrast, no string stretches across an event containing only two colorless diquarks, so particle production is limited to the kinematic extremes. The rapidity difference is large for such events. The dramatic differences between these two topologies are illustrated in Figure 2, for an ideal case. [1]

Bjorken *et.al.* calculated the rate of their rapidity gap events (henceforth termed 'BBL events') normalized to the rate of hadronic Z decays as a function of the rapidity gap. They included an approximate penalty for the width of a jet, but did not estimate backgrounds, resolution, etc. They found that events with large gaps are rare, of order 10^{-5} or less, even under ideal conditions.

Recently, the problem of rapidity gaps has been examined in more theoretical detail by Ellis and Ross, who confirm that the event rates for large rapidity gap events produced through perturbative mechanisms are small [2].

Hadronic decays of the Z have been examined for evidence of events with large rapidity gaps beyond those predicted by the JETSET Monte Carlo model. The data sample consists of roughly one million events recorded with the ALEPH detector with 35 pb^{-1} delivered in 1991-2. Two approaches were taken:

1. Compare the inclusive rapidity gap distribution of the JETSET model to the observed one.

2. Eliminate the ordinary hadronic events as modelled by JETSET and look for events surviving with large rapidity gaps.

The results of these preliminary analyses are described briefly in the following

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[1] The definition of rapidity gap is given in Section 2, Equation 2.

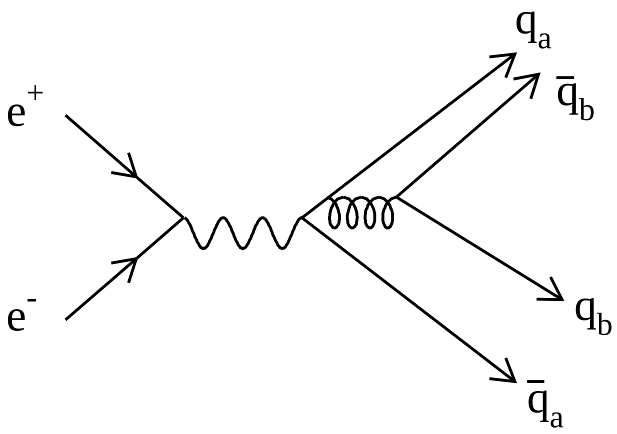

Figure 1: Main Feynman diagram for the four-quark state which, according to Bjorken, Brodsky, and Lu, should lead to events with large rapidity gaps.

sections. They have been presented previously in the Second Workshop on Small-x and Diffractive Physics at the Tevatron [3].

2 Inclusive Rapidity Gap Distribution

The inclusive distribution of rapidity gaps presented here is the closest analogue to the quantities studied at HERA and the TEVATRON. The rapidity of each particle is calculated using the event thrust axis ($\vec{T}$) to define the longitudinal component of the particle momentum:

$$y = \frac{1}{2}\ln\Big[\frac{E + p_{||}}{E - p_{||}}\Big] \qquad \text{where} \qquad p_{||} = \vec{p}\cdot\vec{T}. \tag{1}$$

The energy is computed using the pion mass for charged particles, and zero mass for reconstructed photons. The residual neutral hadronic energy helps define the thrust axis, but individual clusters bear only a poor correspondence to individual neutral hadrons, and are not considered in the rapidity gap analysis.

The rapidities for all charged particles and photons in an event form a set of ascending values $\{y_i \, : \, i = 1, \ldots, N \, ; \, y_{i+1} > y_i\}$, for which y_{ave} is the average for that event. There is one member of the set which is the first value greater than y_{ave}; call it y_k. Then y_{k-1} is the last value less then y_{ave}. The rapidity gap for the event is defined to be

$$G \equiv y_k - y_{k-1}. \tag{2}$$

This definition was used for the plots in Figure 2.

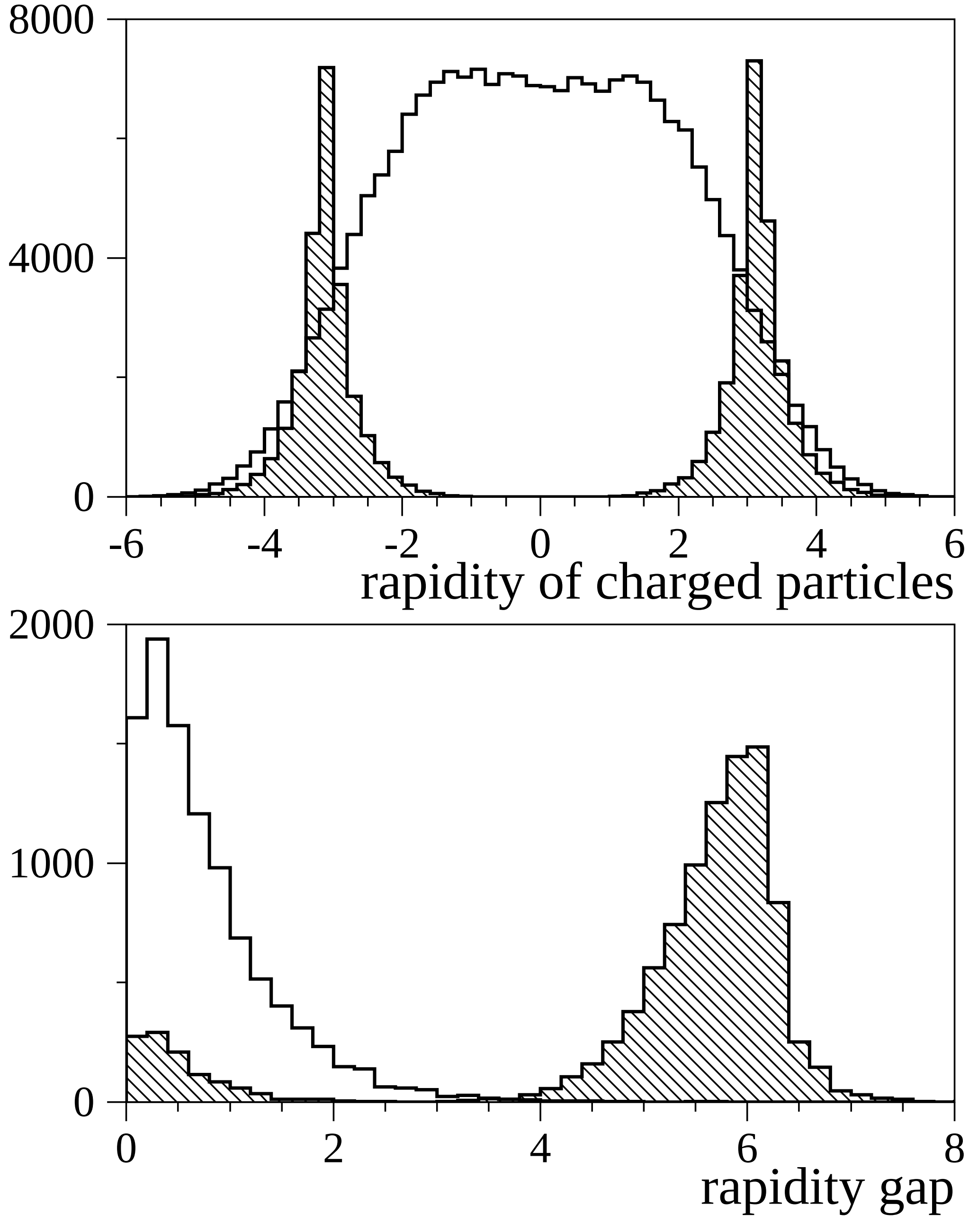

Figure 2: The top plot shows the rapidity distribution of all stable charged particles as predicted by the LUND fragmentation model. The open histograms show normal events, and the shaded histograms, the events described by Bjorken, Brodsky, and Lu [1]. The bottom plot shows the distribution of rapidity gaps (one per event). The plots were made with 10^4 events of each type.

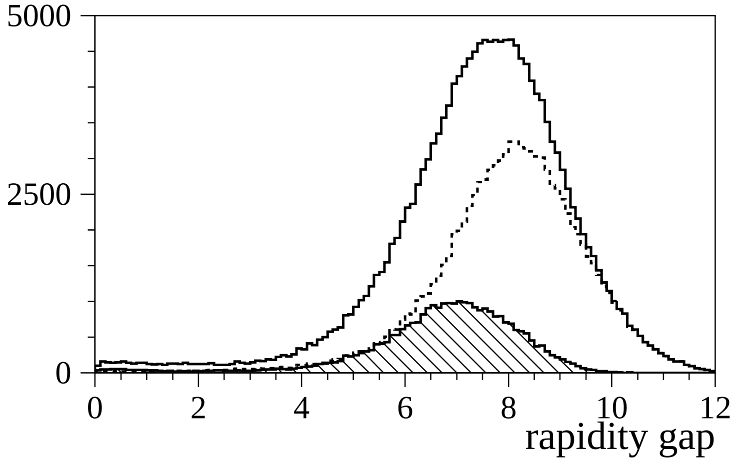

Figure 3: Rapidity gaps calculated from good charged tracks, for 2×10^5 simulated tau-pair events. The plot shows the distribution from all events (solid line), from two-prong events (dashed line), and from events containing at least one $a_1 \to 3\pi^\pm$ decay (shaded histogram).

Large rapidity gaps are an event feature which appear whenever two colorless objects are produced in an event with a large relative momentum. Hence, they can be useful for Higgs searches at the LHC. Tau leptons produced in Z decays produce clean events with very large rapidity gaps, as illustrated in Figure 3.

Special care was taken to reduce the background from tau decays. An event was rejected if it contained fewer than five good tracks, or if the total event energy was less than 60 GeV. Both hemispheres were required to have at least one good charged track, and the invariant mass of charged tracks in at least one hemisphere was required to be greater than 1.8 GeV. To reduce the background from taus in which a hadron interacts inelastically in the inner detectors, the impact points of all charged tracks calculated in the transverse place (d_0) were examined. An event with fewer than twelve tracks but more than three in at least one hemisphere was rejected if the median d_0 was greater than 3 mm.

The remaining tau contamination is 1.8×10^{-4}, according to a detailed simulation. It consists mainly of a single energetic track with neutrals recoiling against a multi-prong tau decay in which one ore more tracks has been reconstructed poorly. Since some of these events are found at large rapidity gaps (see Figure 4), any signal would have to be substantial (at least 10 events or so) for $G > 6$.

The distribution of rapidity gaps from data is displayed on a log scale in Figure 5, to be compared to the distribution obtained from the standard ALEPH $q\overline{q}$ Monte Carlo simulation. The agreement is good over five orders of magnitude, and, in complete contrast to the results from HERA and the TEVATRON, no

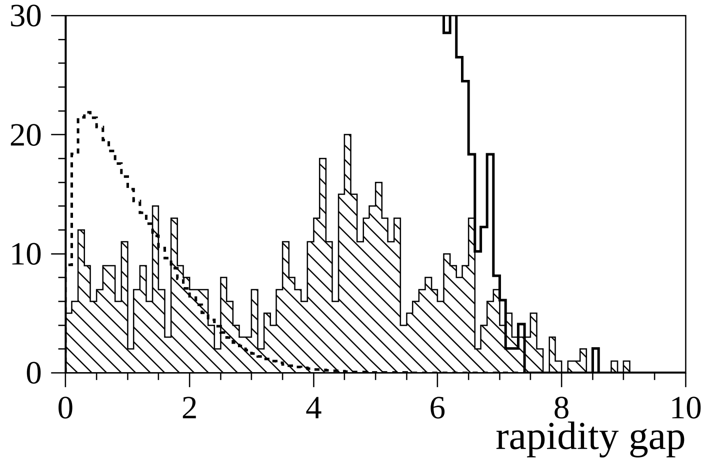

Figure 4: Distribution of rapidity gaps for events surviving the tau rejection requirements. The shaded histogram shows tau events, and the heavy solid line, the $q\overline{q}$ Monte Carlo. (These are both normalized to an integrated luminosity of 100 pb^{-1}.) The $q\overline{q}$ distribution, scaled by factor of 10^{-4}, is shown as the dashed line.

plateau is observed at large gaps.

A close-up of the tail of the distribution is provided in Figure 6. The slight excess in the data (represented by the filled circles) compared to the simulation (the solid line) is due to residual tau-pair background. Clearly there is no *large* excess is observed at large gaps. The lower plot shows that the simulation reproduces the data at the level of 20%. A comparison of the open squares and the dashed line shows that the tau-pair background is not poorly modelled by the simulation.

The standard ALEPH $q\overline{q}$ Monte Carlo program is based on JETSET [4]. The main parameters have been tuned to reproduce general features of hadronic Z decays. Rapidity gaps were not used in the tuning procedure.

The JETSET model produces four-quark final states via the splitting of a hard gluon. The invariant mass of the secondary quark tends to be small, leading to events with three quarks in one hemisphere and one in the other. The rapidity gap distribution of such events is even softer than that for two-quark final states.

The events with large rapidity gaps ($G > 5$) are not caused by multi-quark final states, according to the Monte Carlo. They result from unusual fluctuations in the hadronization process and the limited detection efficiency for very soft particles. For example, a two-quark event may produce a couple of hard tracks in each hemisphere, and only soft neutral hadrons in the central rapidity region which escapes detection. The decay of central vector resonances, or even the weak

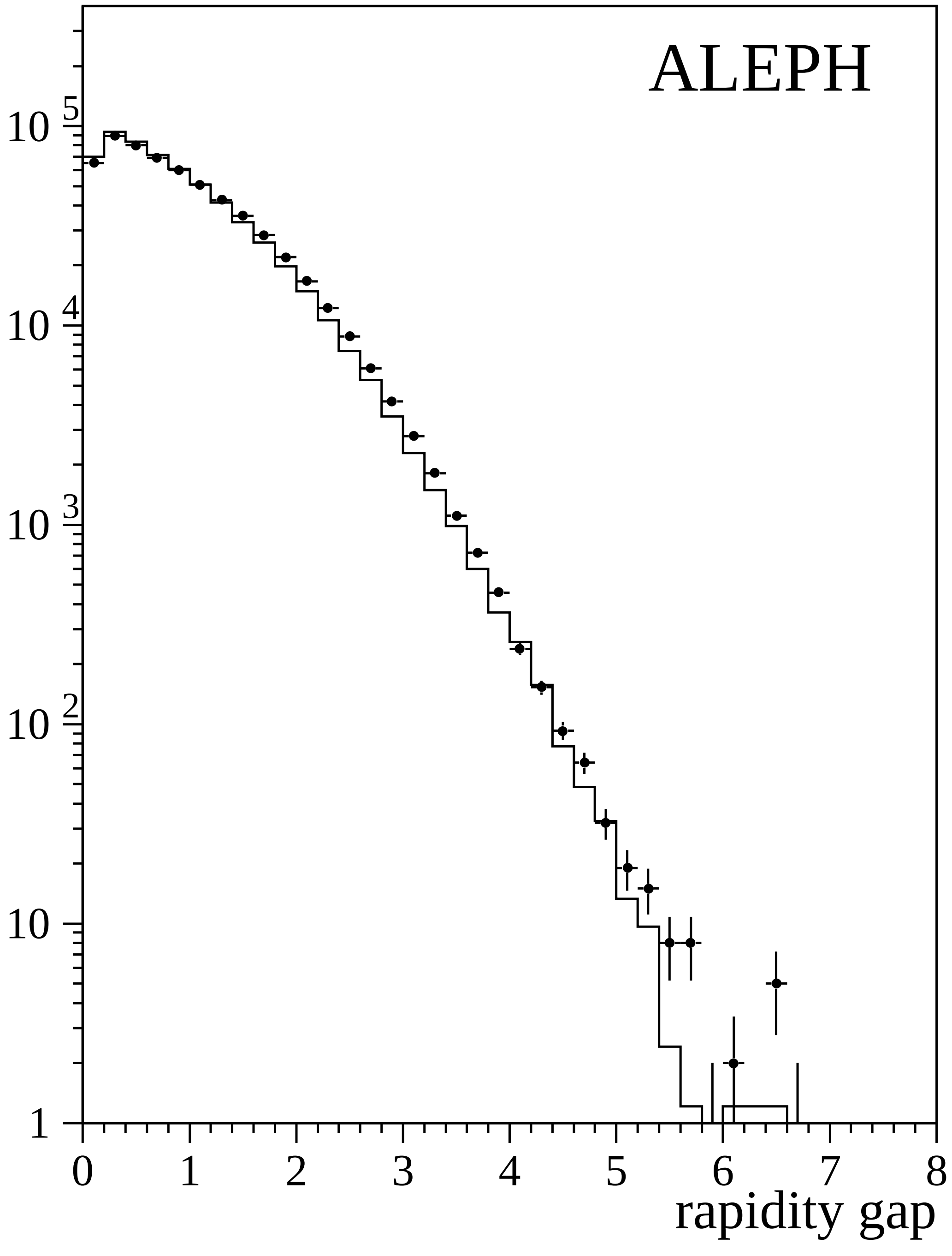

Figure 5: Rapidity Gap Distribution for ALEPH data (points) and a full simulation of $q\overline{q}$ events using JETSET (solid line). The number of entries in the two histograms is the same.

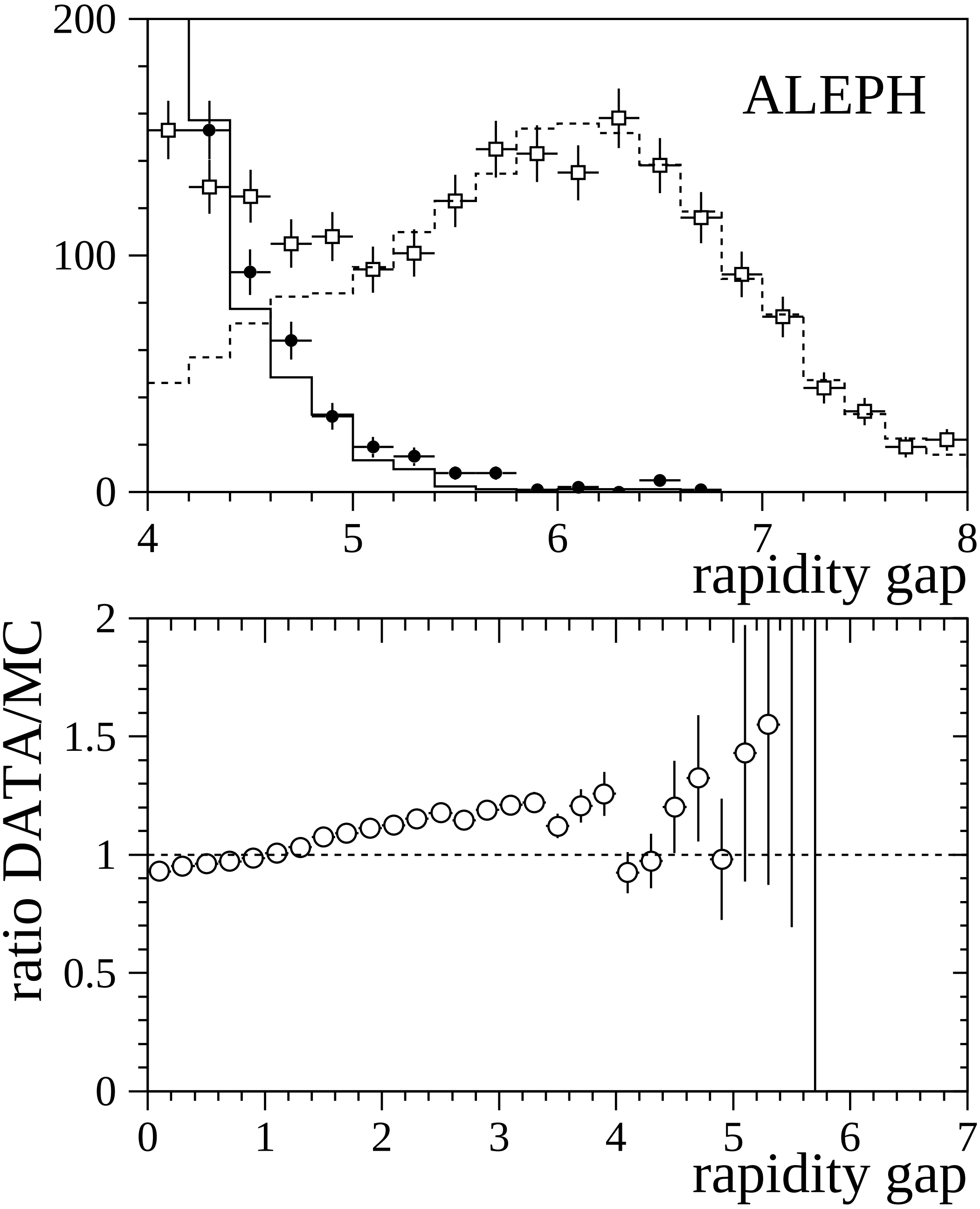

Figure 6: Upper plot: Tail of the rapidity gap distribution, for data (points) and the $q\overline{q}$ simulation (solid line) (same normalization as Figure 5). The open squares (data) and the dashed line (simulation) show the data rejected by the tau rejection cuts. Lower plot: Ratio of the rapidity gap distributions from data and the simulation.

decay of hadrons can produce an apparent gap in the rapidity distribution of a particular event. There is no evidence, based on the JETSET Monte Carlo, that the events with $G > 5$ are of interest in the context of the parton-level processes depicted in Figure 1.

3 Search for Events with Large Rapidity Gaps

The production of BBL events may be too small to be observed in an inclusive rapidity-gap distribution. They are sufficiently distinctive, however, that a sample might be isolated in certain well-defined topologies. Four topological categories have been defined:

1. Low Multiplicity. One hemisphere contains four charged tracks, while the other contains two or four. The total charge of each hemisphere is zero.
2. Two-on-two. Each hemisphere contains two oppositely-charged tracks.
3. Trackless Hemisphere. One hemisphere contains no charged tracks at all, while the other contains any number greater than zero.
4. Broomstick. One hemisphere contains one or two energetic charged tracks, while the other contains at least six.

These categories are motivated by an important feature of BBL events: a colorless, low-mass diquark will produce few particles. If it is boosted in the lab frame, then a thin jet containing a small number of energetic particles will be observed. If both diquarks are low mass, then the acceptance for all charged particles will be good, in which case constraints on the total charge in a hemisphere are effective. The four categories have been designed to have a low background from tau-pair events. Cuts were applied to ensure that the event was well measured. It was checked that the event selection retained a resonable fraction of BBL events, according to a simple Monte Carlo event generator interfaced to JETSET.

Two of these topologies have an important advantage over the inclusive rapidity gap distribution: they allow one hemisphere to have a high multiplicity and mass. As pointed out in Reference [1], the hemisphere masses limit the largest possible gap for a given event. Referring to Figure 1, a configuration in which the lower two quarks have a large invariant mass and multiplicity while the upper two have a small mass and multiplicity would be lost under a huge background of ordinary hadronic events even though they should be more numerous than the ideal rapidity gap events described in the Introduction.

Candidate events were selected from the data in all four categories. A number of Low Multiplicity events were found; an example is given in Figure 7. The number and rapidity gap distribution was found to be consistent with the $q\overline{q}$

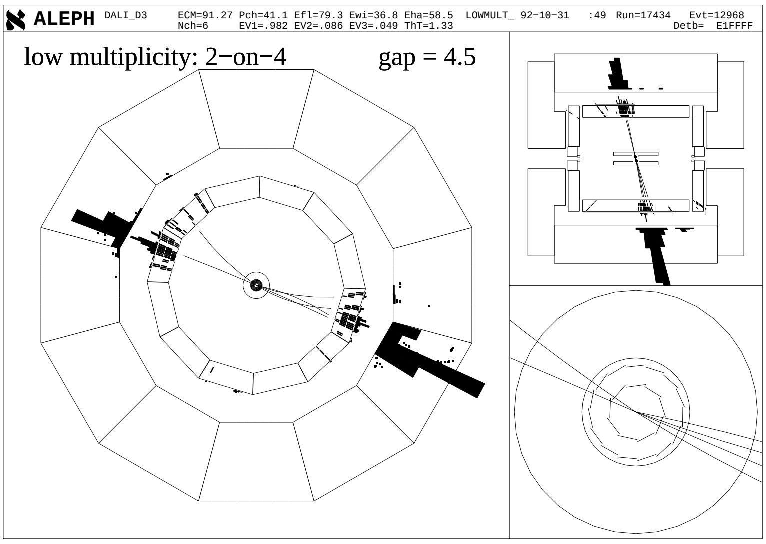

Figure 7: An event from the ALEPH data falling in the Low Multiplicity category.

background. Two-on-two events also were selected at a rate consistent with $q\overline{q}$ and two-photon production. Many events with trackless hemispheres were found, but most of these consist of a pair of leptons recoiling against a 45 GeV photon. An example of an unusual event in this category is shown in Figure 8 in which six energetic tracks recoil against a single photon. This event is possibly a two-photon event in which one photon materializes as a pair of quarks, or a Z decay to two quarks and a very hard final-state photon. Finally, the one-track and two-track Broomstick events tend to have low rapidity gaps, with a tail extending up to $G \approx 8$. This tail is well reproduced by the $q\overline{q}$ Monte Carlo simulation.

All four categories are sensitive to events with large rapidity gaps, and indeed, such events are found. The number and characteristics of these events, while consistent with BBL events, are also consistent with known backgrounds, including hadronic Z decays, tau-pairs, and two-photon processes. No anomalous production of rapidity gap events has been observed.

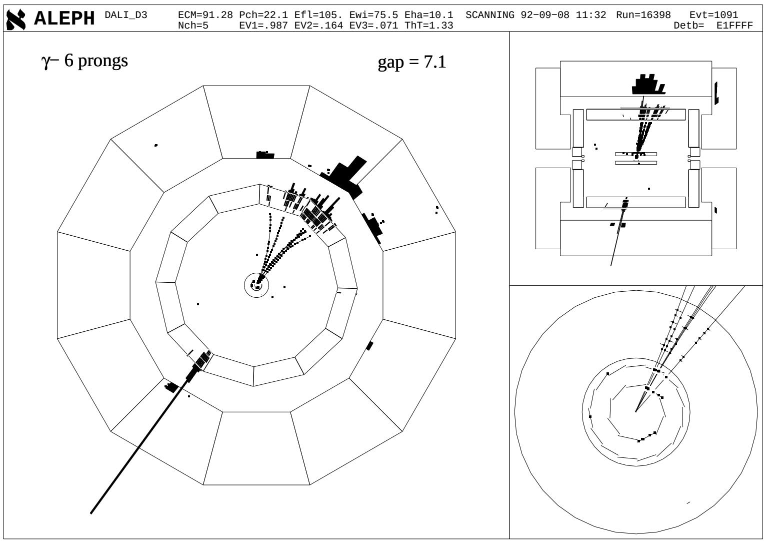

Figure 8: An event from the ALEPH data falling in the Trackless Hemisphere category. A single 45 GeV photon recoils against six energetic tracks and neutral energy.

4 Summary

Events with large rapidity gaps have signalled interesting new physics at HERA and the TEVATRON. In the future, the analysis of LHC data will include searches for events with large rapidity gaps, as this is the signature for new centrally-produced heavy particles.

The ALEPH data have been examined for an anomalous rate of large rapidity gap events. The observed inclusive distribution of rapidity gaps is well reproduced by the JETSET Monte Carlo, after care is taken to remove tau-pair background. Searches for four categories of events with unusual topologies have been carried out. The candidates selected are consistent with known background processes.

No evidence has been found for an anomalous production of rapidity gap events. This result does not contradict predictions based on perturbative QCD as the expected signal is very small [1, 2], and difficult to observe above the backgrounds caused by hadronization fluctuations and detector acceptance.

References

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