L3 Note # 1803
July 7, 1995
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Study of Event Shape Variables at Reduced CM Energies from Z Data

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Abstract

We have studied the structure of hadronic events with a hard radiated final state photon ($e^+e^- \rightarrow Z \rightarrow \text{hadrons} + \gamma$) in the event sample recorded by the L3 detector. The event shape variables have been measured in the CM frame of the remaining hadronic system. After correcting for detector effects, various event shape distributions have been compared with the predictions of different QCD Monte Carlo programs at corresponding reduced centre of mass energies. The data are in agreement with the QCD models.

(Submitted to the EPS and the Lepton–Photon Conference, July 1995)

1 Introduction

The study of isolated high energy photons in hadronic Z decays at LEP offers an important probe of the short distance structure of QCD [1]. The high energy photons are radiated early in the process either through initial state radiation or through an early branching in the process of quark bremsstrahlung. On the other hand, the development of hadronic shower takes place over a larger time scale. So one can effectively look at hadron production at a reduced centre of mass energy from a study of $q\bar{q}\gamma$ events.

We report here the results of such an analysis from the hadronic Z decays collected at LEP with the L3 detector during the runs in the period 1991 to 1994. We compare the measured distributions with theoretical models based on leading log approximation of QCD (Parton Shower models). Three such Monte Carlo programs, ARIADNE [2], HERWIG [3] and JETSET [4] have been used for these comparisons. These programs differ in the variables they use for a leading logarithmic expansion of the cross section and also in the modelling of the hadronization effects.

2 Event Selection

The events used in the study have been collected during the LEP running from 1991 to 1994 by the L3 detector [5]. The corresponding integrated luminosity is 110.9 pb^{-1}. The bulk of the data (90.2 pb^{-1}) corresponds to $\sqrt{s} = 91.2$ GeV and the remaining part comes from the LEP energy scan ($\sqrt{s}$: 88 to 93 GeV).

Hadronic events are recorded primarily from calorimetric energy trigger with a trigger efficiency exceeding 99.9%.

The selection of events of the type $e^+e^- \to$ hadrons is based on the energy measurements in the electromagnetic and hadronic calorimeters. Events are accepted if

$$0.6 < \frac{E_{vis}}{\sqrt{s}} < 1.4 \quad , \quad \frac{|E_{\parallel}|}{E_{vis}} < 0.40 \quad , \quad \frac{|E_{\perp}|}{E_{vis}} < 0.40 \quad , \quad N_{cluster} > 12$$

where E_{vis} is the total energy observed in the calorimeters; $E_{\parallel}$, $E_{\perp}$ are the energy imbalances along and transverse to the beam direction and $N_{cluster}$ is the number of clusters with energy larger than 100 MeV. These cuts lead to a total of 2928 K hadronic events from the entire data sample. A study of simulated events reveals that 98% of hadrons are selected by these cuts with a small background of 0.2% from ($\tau^+\tau^-$) and four fermion final states from 2 photon processes.

While jets are reconstructed in the angular region $5^\circ < \theta < 175^\circ$, the photon candidates are selected in the solid angle covered by the barrel and endcap electromagnetic calorimeters ($11.6^\circ < \theta < 36^\circ$, $42^\circ < \theta < 138^\circ$, $144^\circ < \theta < 168.4^\circ$). A loose pre-selection of γ candidates according to the following criteria are applied to the hadronic data sample. A cluster in the electromagnetic calorimeter is considered to be an energetic, isolated 'photon' candidate if

- the energy in the electromagnetic calorimeter is larger than 5 GeV
- the cluster lies in an efficient sector of the tracking chamber and there is no charged track associated with it
- the lateral shower profile is electromagnetic and the cluster is isolated, namely no other cluster with energy ($E_{\alpha_{LI}}$) above 500 MeV is in a cone of half angle (α_{LI}) 15° around the candidate direction.

With these criteria, we obtain 63729 events of which 43172 have the cluster in the barrel electromagnetic calorimeter ($42^\circ < \theta < 138^\circ$). The energy spectrum of the 'photon' candidates is shown in figure 1(a). This energy distribution can be translated to the energy distribution of the remaining hadronic system

$$\sqrt{s'} = \sqrt{s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)}$$

as shown in fig 1(b). We divide the $\sqrt{s'}$ spectrum into six subdivisions so that each energy region has reasonable statistics. The energy regions and the corresponding number of preselected events are summarized in table 1.

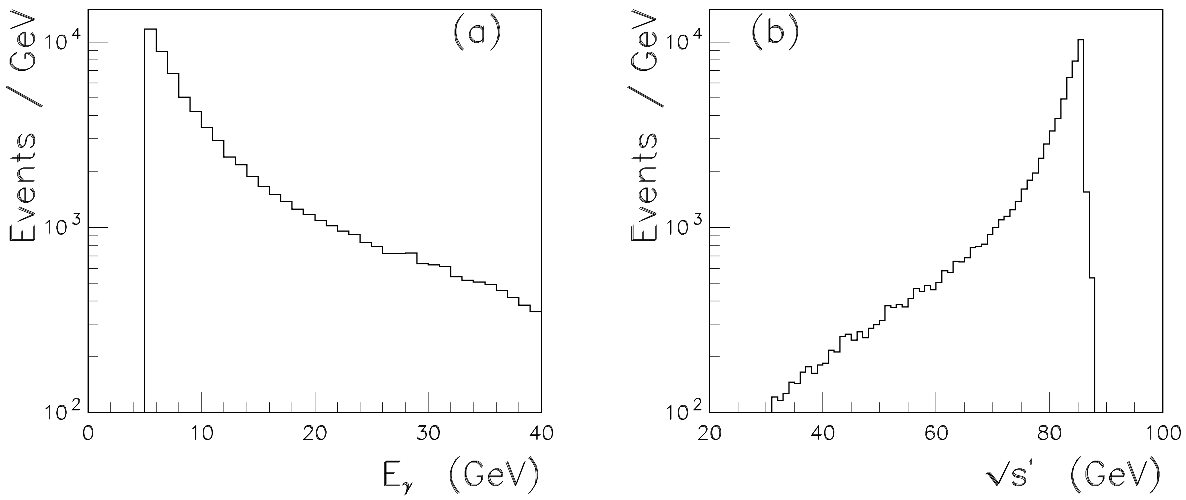

Figure 1: Measured distribution of (a) energy of the 'photon' candidate, (b) CM energy of the remaining hadronic system ($\sqrt{s'}$)

The background to the direct photons is dominated by photons coming from π^0 and η decays where the γ's are either not resolved or are well separated. To reduce this background, we require that the shower should be isolated and the shower shape is compatible with single γ electromagnetic shower. We use a shower shape discriminator ϵ_γ based on artificial neural network [6] to distinguish multi-photon showers from single γ ones in the electromagnetic calorimeter.

The cut values for the following parameters are tuned separately for photon candidates in the six different energy ranges :

- neural network discriminator ϵ_γ
- size of the local isolation cone α_{LI}
- angle to the nearest jet α_{JI} (reconstructed from the remaining hadronic system using the JADE algorithm [7] with $y_{\mathrm{cut}} = 0.05$)
- energy of individual clusters within the local isolation cone $E_{\alpha_{\mathrm{LI}}}$

The purity of the photon signal and the efficiency of selection are optimized using 3 million JETSET 7.3 parton shower events processed through the L3 detector simulation program. The isolation angles have to be chosen energy dependent to get the best performance in the efficiency-purity plot, whereas the energy cutoff $E_{\alpha_{LI}}$ is chosen to be 50 MeV and $\epsilon_\gamma < 0.95$ (keeping 95% of γ's passing all other cuts) for all energy points. One achieves γ (from FSR or ISR) selection efficiency between 65% and 75% depending on its energy whereas the purity is better than 80% at all energies. The cuts as well as the number of events are summarized in table 1.

The most important source of background is due to misidentified hadrons or photons coming from hadronic decays. This has been studied using JETSET 7.3 PS Monte Carlo with complete detector simulation. As observed in our earlier studies [8], the absolute rate of the background is not well described in the Monte Carlo. This has been reestimated from the data by selecting a background sample with the same energy and isolation cuts as the γ sample (using $\epsilon_\gamma > 0.90$) and then comparing with Monte Carlo assuming the signal part is well described. This gives an overall normalization factor between 2.2 $\pm$ 0.1 and 2.9 $\pm$ 0.2 depending on the reduced CM energy. Backgrounds due to $\tau^+\tau^-$ and 2γ events have been estimated using Monte Carlo samples normalized to the same luminosity. The level of backgrounds in the six energy regions are also summarized in table 1.

Table 1: Summary of event selection and background estimation

$\sqrt{s'}$ (GeV)	30−50	50−60	60−70	70−80	80−84	84−86
# of events after preselection	3828	3961	6634	15746	17147	16683
Local isolation angle (α_{LI})	15°	15°	15°	15°	21°	24°
Jet isolation angle (α_{JI})	20°	20°	20°	20°	21°	24°
# of events after final selection	962	828	1248	2569	2072	1763
Selection Efficiency	0.74	0.73	0.72	0.72	0.67	0.64
Factor for hadronic BG	2.4 $\pm$ 0.2	2.9 $\pm$ 0.2	2.6 $\pm$ 0.2	2.2 $\pm$ 0.1	2.4 $\pm$ 0.1	2.5 $\pm$ 0.1
BG due to hadrons	18 %	13 %	10 %	7 %	6 %	9 %
BG due to $\tau^+\tau^-$	2.7 %	2.8 %	3.3 %	2.5 %	1.7 %	1.3 %
BG due to e^+e^-+ hadrons	0.1 %	0.1 %	0.1 %	0.1 %	0.3 %	0.1 %

3 Event Shape Variables and Corrections

Event shape variables of the hadronic system are calculated after boosting the event in the CM frame of the hadronic system using the well measured energy and angle of the isolated photon. The variables studied here are event thrust (T) [9], scaled heavy jet mass ($\rho \equiv M_H^2/s$) [10] and total (B_T) and wide (B_W) jet broadenings [11]. The measured distributions are then corrected for backgrounds and detector effects (resolution and acceptance).

Figure 2 shows uncorrected thrust distributions measured at the six energy bins compared to Monte Carlo prediction after normalizing to the same number of hadrons. The different shaded areas indicate the backgrounds from fragmentation in hadronic sample, $\tau^+\tau^-$ and (e^+e^-+ hadrons). One sees reasonable agreement between the measured distribution and the expectation from Monte Carlo programs (in this comaprisons, the hadronic. background has not been rescaled). Similar behaviour is observed in all the measured distributions. The backgrounds are subtracted on a bin-by-bin basis.

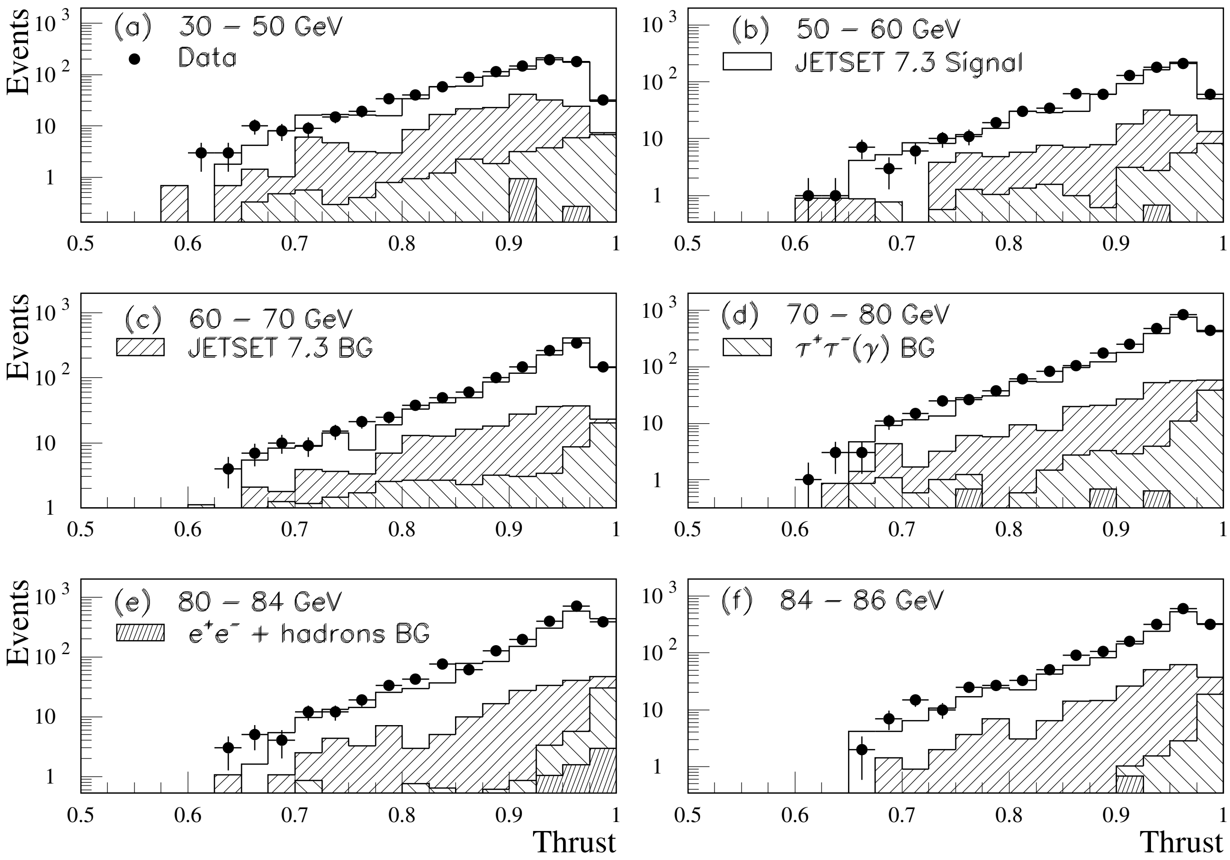

Figure 2: Measured thrust distributions at different reduced CM energies (a) 30 – 50 GeV, (b) 50 – 60 GeV, (c) 60 – 70 GeV, (d) 70 – 80 GeV, (e) 80 – 84 GeV, (f) 84 – 86 GeV. The solid lines correspond to the overall expectations from theory. The shaded areas refer to different backgrounds and the clear area refer to signal predicted by JETSET

The effects of the detector resolution and acceptance have been studied by comparing the event shape variables of accepted JETSET 7.3 PS Monte Carlo events before and after detector simulation. The fluctuations in the ratios at different energy bins are smoothed and the corrections are applied on a bin-by-bin basis.

4 Comparison with QCD Models

Figure 3 shows the corrected distributions for total jet broadening (B_T) at the six energy ranges. These distributions are compared with predictions from ARIADNE [2], HERWIG [3] and JETSET [4]. Events are generated using a parameter set tuned with the L3 data at the Z peak [12]. The initial and final state radiation has been switched off and one uses the CM energy spectra as observed in the data. As can be seen in the figure, the agreement is rather good. This is also the case for the other event shape variables.

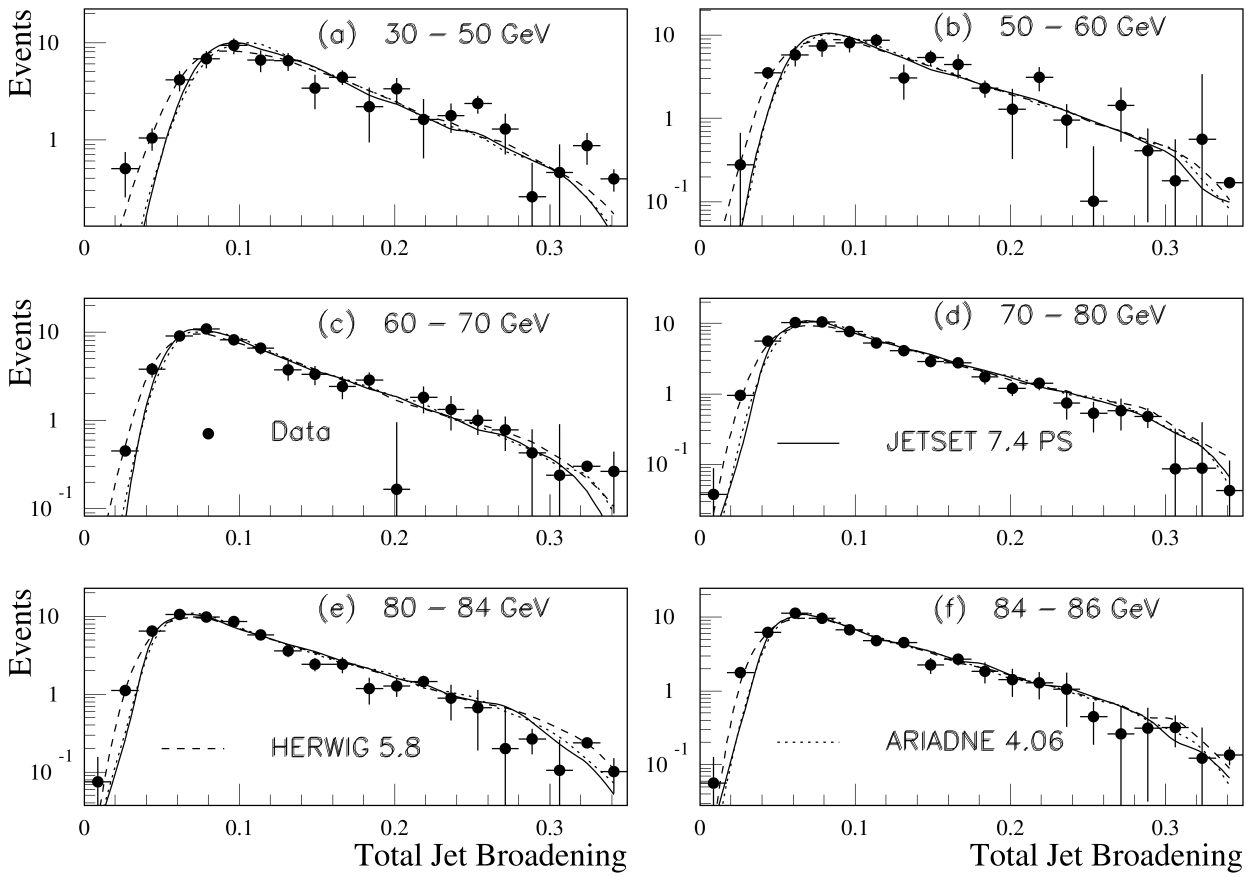

Figure 3: Corrected total jet broadening distributions at different reduced cm energies (a) $30-50$ GeV, (b) $50-60$ GeV, (c) $60-70$ GeV, (d) $70-80$ GeV, (e) $80-84$ GeV, (f) $84-86$ GeV. The smooth lines correspond to the predictions of different QCD models

Figure 4 shows the energy evolution of the mean event shape variables, thrust, scaled heavy jet mass and jet broadenings. We also include the L3 measurement of these parameters at $\sqrt{s} = m_Z$ [12, 13]. The energy evolution of these variables are compared with different QCD models and the trend in the data agree with the predictions from different parton shower models. It should be noted that the errors are statistical only. Systematic uncertainties are still to be done.

5 Summary

We have studied hadronic events with isolated, energetic photons from Z decays. The event shape variables of the hadronic system have thus been examined for different reduced CM energy regions. The resulting distributions are compared with the expectations from several QCD models. The data agree with the energy evolution of the QCD models, JETSET 7.4 PS, HERWIG 5.8, ARIADNE 4.06.

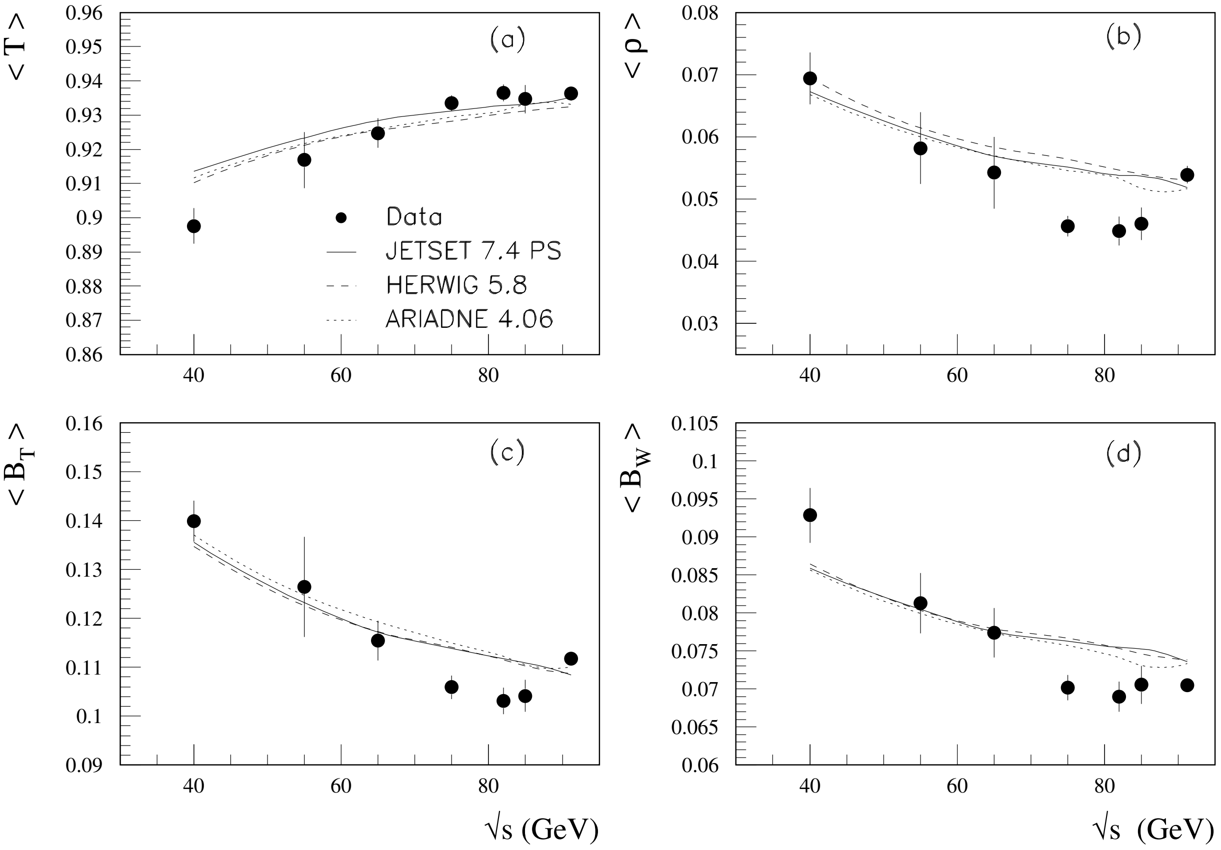

Figure 4: Corrected distributions for mean (a) thrust (T), (b) scaled heavy jet mass (ρ), (c) total jet broadening (B_T), (d) wide jet broadening (B_W) as a function of CM energies. The smooth lines correspond to the predictions of different QCD models

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