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QCD studies in high energy e^+e^- annihilation with the L3 detector

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abstract

The main results obtained from studies of the structure of hadronic events produced in high energy e^+e^- annihilations at LEP with the L3 detector are reviewed. This includes the determination of the strong coupling constant α_s at 133 GeV, 161 GeV and 172 GeV. The energy dependence of α_s is studied by comparing these values to values obtained from the same experiment at lower energies between 30 GeV and 91 GeV.

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1. INTRODUCTION

At LEP the process $e^+e^- \to$ hadrons offers a certain number of advantages for QCD studies: the hard partons produced give collimated jets of particles, the initial state is very well defined and the hadronisation corrections should be small. This means the observations can be compared easily with perturbative QCD calculations.

During 5 years LEP has been running at center of mass energies around 91 GeV (near the Z pole). Since 2 years the LEP machine has been running at higher energy where e^+e^- annihilations occured at 130 GeV, 136 GeV, 161 GeV and 172 GeV.

Due to its nonabelian nature the theory of the strong interaction (QCD) predicts the strong coupling constant α_s to decrease with increasing energy. This characteristic is reflected in the energy dependence of the global structure of hadronic events which has been studied at LEP with the L3 detector. The main results from these studies are reviewed in this article. This includes the determination of the strong coupling constant α_s at high energies and the comparison with values obtained at much lower energies within the same experiment.

2. HADRONIC EVENT SELECTION

The event samples correspond to integrated luminosities of 5 pb^{-1}, 11.05 pb^{-1} and 10.2 pb^{-1} collected by the L3 detector [1] at mean center of mass energies ($\sqrt{s}$) of 133 GeV, 161 GeV and 172 GeV respectively.

The selection of $e^+e^- \to$ hadrons events, based on the energy measured in the calorimeters only, requires a large number of energy deposits (more than 13) and a large visible energy.

A large fraction of the events collected above 91 GeV corresponds to events with hard initial state radiation (ISR) which bring the center of mass energy to the Z resonance where the production rate is very high. These events are called 'return to the Z' events. In order to reduce this contamination it is necessary to apply cuts to reject hadronic events with an energetic photon seen in the detector (more than 15 GeV at 133 GeV center of mass energy or more than 30 GeV for higher center of mass energies) or with a large missing momentum along the beam direction corresponding to an ISR photon lost in the beam pipe.

After this selection the main sources of background left are due to W^+W^- decays for center of mass energies above 161 GeV and to two-photon collisions ($e^+e^- \to e^+e^- +$ hadrons). At 172 GeV, well above the W pair production threshold, the event sample contains about 17% of W^+W^- background. This level of contamination is quite substantial and additional cuts are therefore used to reduce the level of this W^+W^- background.

Table 1 summarises the final number of events and the main background content at the different energies.

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Table 1
Background fractions estimated from Monte Carlo in the selected event samples.

	$\sqrt{s}$ = 133 GeV	$\sqrt{s}$ = 161 GeV	$\sqrt{s}$ = 172 GeV
# of events	402	443	341
ISR ($E_\gamma \geq$)	20.0% (15 GeV)	11.4% (30 GeV)	8.5% (30 GeV)
$e^+e^- \to W^+W^- \to$ ffff	0.0%	4.4%	8.9%
$e^+e^- \to e^+e^-+$ hadrons	2%	3.3%	2.8%

3. EVENT SHAPE DISTRIBUTIONS

The jet structure of hadronic events can be analysed using global event shape variables. The charged particle multiplicity distribution is obtained from reconstructed tracks while the other event shape distributions are obtained from reconstructed calorimetric clusters which are treated as massless particles.

The procedure to obtain a distribution of a given variable is the following: after subtracting the background events estimated according to the standard model cross sections and the recorded luminosity, the distributions are corrected for detector effects, acceptance and resolution bin by bin comparing the detector level result with the particle level result for the same event sample. The effect of initial and final state photon radiation is corrected bin by bin using the PYTHIA Monte Carlo event generator. The correction factors are typicaly between 0.5 and 1.5 for most of the variables. The systematic errors in the distributions of event shape variables arise mainly due to uncertainties in detector calibration and in estimating the background. The comparison of the corrected distributions to the predictions of several QCD models tuned at 91 GeV have shown reasonable agreement within the statistical errors. Figure 1 shows the thrust distribution T as measured by L3 at 172 GeV compared to PYTHIA, HERWIG, ARIADNE and COJETS Monte Carlo models. The agreement is satisfactory.

3.1. Energy dependences of the Mean Values

An important test of the QCD models is to check the predicted energy evolution of the shape

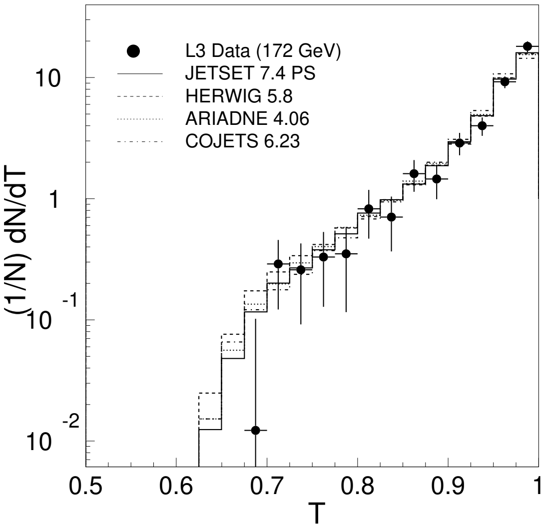

Figure 1. Corrected distributions of thrust, T at $\sqrt{s}$ = 172 GeV in comparison with QCD model predictions. The experimental errors are statistical only.

distributions using the same Monte Carlo parameter values. This energy evolution comes mainly from the logarithmic dependence of α_s and from the hadronisation process leading to a dependence proportional to 1/E. The mean values of thrust, T, and charged particle multiplicity, n_{ch}, measured by L3 are given in table 2. The mean charged particle multiplicity is shown in figure 2, together with measurements at the Z resonance as well as those at low energy e^+e^- colliders.

Also shown are the energy dependences of these quantities as predicted by several QCD Monte Carlo models with constant parameter values over the full energy range. These models use different approaches to describe the perturbative and non perturbative phase of QCD evolution. All models are in agreement with the present measurements of the thrust distribution. We also find

Table 2
Measured mean values. The first error is statistical and the second is systematic.

$\sqrt{s}$(GeV)	$< T >$	$< n_{ch} >$
130	0.948±0.004±0.007	24.9±0.5±0.8
136	0.943±0.005±0.008	24.2±0.7±0.8
161	0.946±0.003±0.002	25.5±0.4±0.3
172	0.949±0.003±0.002	26.6±0.5±0.3

similar agreement for scaled heavy jet mass and the jet broadening parameters. The situation is different for charged particle multiplicity. The JETSET 7.4 ME model fails to describe the energy dependence of $< n_{ch} >$. This is understood as a consequence of low parton multiplicity before fragmentation compared to the other models incorporating multiple gluon emission. The COJETS model based on independent fragmentation overestimates $< n_{ch} >$ at high energies.

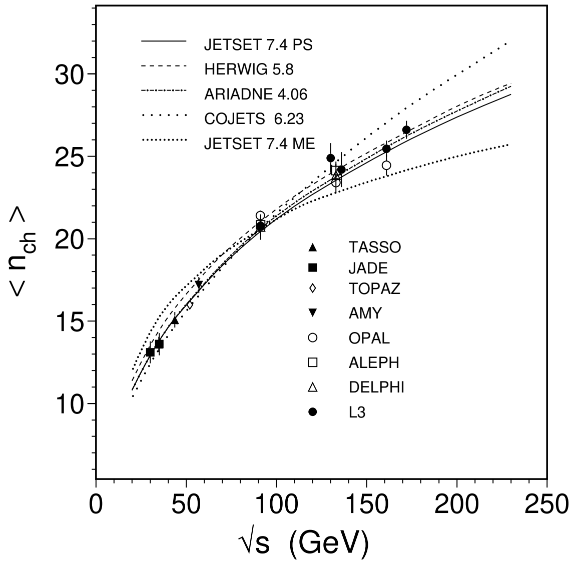

Figure 2. Distribution of mean charged particle multiplicity, $< n_{ch} >$, as a function of the center of mass energy, compared to several QCD models.

4. α_s DETERMINATION

The measurements of the strong coupling constant α_s above the Z have been performed by fitting combined O(α_s^2)+NLLA QCD calculations to the corrected thrust, scaled heavy jet mass (ρ), total (B_T) and wide jet (B_W) broadening distributions for which the theoretical descriptions are the most complete.

The hadronisation corrections have been applied to the theoretical distributions using the JETSET model.

The α_s values from the four distributions are affected differently by higher order corrections and hadronisation effects. To obtain a combined value of the strong coupling constant we take the unweighted average of the four α_s values at each energy. The results for the three energies are:

$$\alpha_s(133\text{GeV}) = 0.107 \pm 0.005 \pm 0.006$$
$$\alpha_s(161\text{GeV}) = 0.103 \pm 0.005 \pm 0.005$$
$$\alpha_s(172\text{GeV}) = 0.104 \pm 0.006 \pm 0.005$$

where the first error is experimental and the second error is theoretical. This may be compared with our measurement at 91 GeV [2] obtained using the same analysis procedure and variable. The result is:

$$\alpha_s(91\text{GeV}) = 0.122 \pm 0.002 \pm 0.007$$

It should be noted that the theoretical errors are strongly correlated between these four measurements. The higher order uncertainties should be the same and the hadronisation corrections should be of similar size at these energies. To study the energy dependence of α_s, one can therefore consider the variation taking into account only the experimental errors.

A more convenient way of studying the running of α_s is for example to proceed within the same experiment over a wide energy range and using the same technique in order to cancel some experimental and theoretical uncertainties. We performed such an analysis using hadronic events with a hard photon recorded on the Z resonance [3] at LEP1.

The isolated high energy photons are radiated early in the process either through initial state radiation or through an early branching during the quark bremsstrahlung cascade. On the other hand, the development of the hadronic shower takes place over a larger time scale. So one can effectively look at hadron production at a reduced

Table 3
The measured α_s values at different centre-of-mass energies $\sqrt{s}$ given in GeV.

$<\sqrt{s}>$	$\alpha_s(<\sqrt{s}>)$	$\Delta\alpha_s(\mathrm{exp})$	$\Delta\alpha_s(\mathrm{theo})$
41.2	0.140	± 0.006	± 0.011
55.3	0.126	± 0.007	± 0.010
65.4	0.134	± 0.006	± 0.009
75.7	0.121	± 0.006	± 0.009
82.3	0.120	± 0.006	± 0.009
85.1	0.116	± 0.007	± 0.008
91	0.122	± 0.002	± 0.007
133	0.107	± 0.005	± 0.006
161	0.103	± 0.005	± 0.005
172	0.104	± 0.006	± 0.005

centre of mass energy from a study of $q\bar{q}\gamma$ events. The effective center of mass energy is related to the photon energy via the relation

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

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, scaled heavy jet mass, total and wide jet broadenings.

From the LEP1 data sample it has been possible to obtain enough statistics to obtain 6 energy bins ranging from 30 GeV to 86 GeV. From a fit of the second order QCD calculation with resummed leading and next-to-leading terms to the thrust, scaled heavy jet mass, total jet broadening and wide jet broadening distributions we have determined the strong coupling constants at the six reduced CM energy points. Table 3 summarises the α_s values obtained with L3 from 30 GeV to 172 GeV. Because the variables and the fit ranges used for all the energy points are similar, the theoretical errors coming from missing higher order terms in the perturbative prediction and from the renormalisation scale dependence should be correlated and then can be subtracted to allow a more accurate check of the energy evolution.

The measurements are shown in figure 3 with experimental errors only, together with a fit to the QCD evolution equation, $\alpha_s(M_Z)$ being a free parameter. The fit gives a χ^2 of 12.2 for nine degrees of freedom, corresponding to a confidence level of 0.20, with a fitted value of α_s :

$$\alpha_s(M_Z) \quad = \quad 0.1207 \pm 0.0016 \pm 0.0066.$$

On the other hand, a model with a constant α_s gives a χ^2 of 42.4 (C.L.=0.3×10^{-5}) and is therefore excluded.

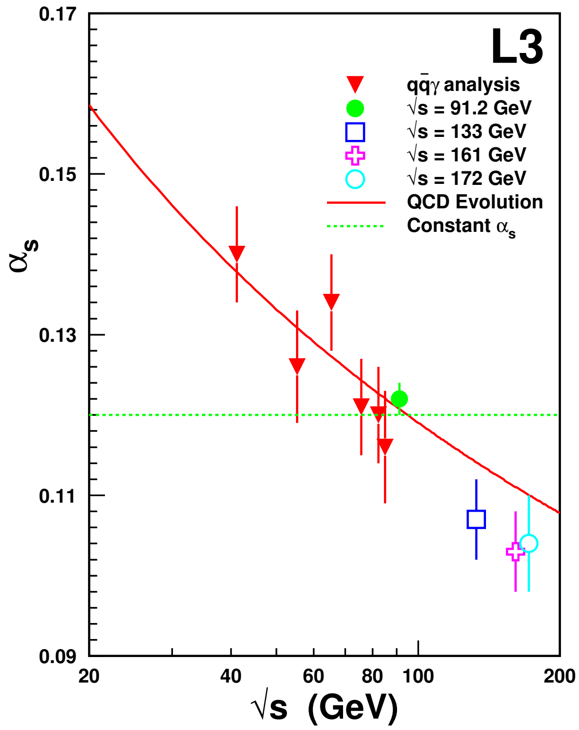

Figure 3. Measured values of α_s from the event shape distributions as a function of the centre-of-mass energy of e^+e^- collisions.

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