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abstract

Results of recent QCD studies at LEP for energies different from the Z pole are presented. In a first part we report on the analyses of events produced at a center of mass energy between 130 and 136 GeV which were recorded in 1995. In the second part we review the LEP1 QCD results obtained using the process $e^+e^- \rightarrow q\bar{q}\gamma$ to obtain hadronic systems with a reduced center of mass energy.

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Results of recent QCD studies at LEP for energies different from the Z pole are presented. In a first part we report on the analyses of events produced at a center of mass energy between 130 and 136 GeV which were recorded in 1995. In the second part we review the LEP1 QCD results obtained using the process $e^+e^- \rightarrow q\bar{q}\gamma$ to obtain hadronic systems with a reduced center of mass energy.

1 Introduction

At LEP the process $e^+e^- \rightarrow$ 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 correction should be small. This means the observation can be compared easily with perturbative QCD calculations.

During 5 years the center of mass energy of LEP was around 91 GeV (near the Z pole). The 4 experiments (ALEPH, DELPHI, L3 and OPAL) have each collected until now more than 4 million hadronic Z decays. The theory of the strong interaction (QCD) has been quite successful in describing many aspects of jet structure found in these hadronic final states produced in e^+e^- annihilation. Due to its nonabelian nature 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. The 130-136 GeV e^+e^- annihilations produced at LEP at the end of 1995 have given a data set which is ideal to test QCD evolution predictions. The theory predicts α_s to decrease by about 5% at these energies compared to 91 GeV. In addition to the strong coupling measurement the comparison of the event shapes with the predictions of QCD models and with some analytical calculations is a good test of the overall consistency of QCD in this new energy regime.

2 Above the Z resonance

A large fraction of the events collected above the Z correspond 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 a visible energetic photon seen in the detector or with a large missing momentum along the beam direction corresponding to an ISR photon lost in the beam pipe.

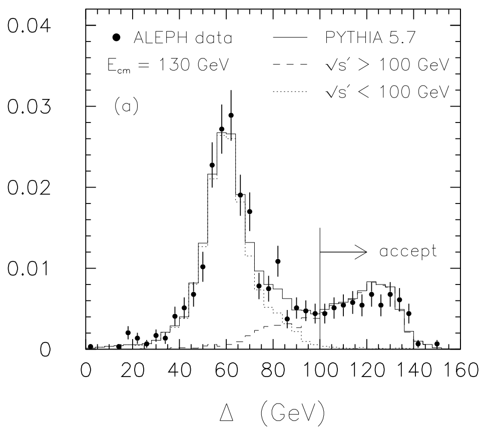

Figure 1: Distribution used by ALEPH at 133 GeV to separate hard ISR.

To fulfill these requirements, selections are then based on a large visible and small missing energy. Each experiment defined variables sensitive to such kinematic configurations. Figure 1 shows the variable used by ALEPH [1] to separate the 'return to the Z' events from the genuine ones:

$$\Delta = M_{vis} - |\Sigma p_z| \quad (1)$$

It corresponds to the difference between the visible mass M_{vis} and the absolute value of the sum of the momenta along the beam direction $|\Sigma p_z|$. One can see the double peak structure corresponding to the two classes of events. The num-

Table 1: Luminosity, number of selected events and remaining ISR fraction for each experiment at LEP1.5

	ALEPH [1]	DELPHI [4]	L3 [2]	OPAL [3]
lumi.(pb^{-1})	5.7	5.9	5.0	5.1
events selected	299	321	402	291
ISR content $\leq$	2.7% 30 GeV	16% 20GeV	20% 15GeV	14% 5GeV

ber of selected events and remaining ISR together with the luminosity recorded by the 4 experiments are given in Table 1. After applying all the selection cuts the efficiency of keeping high energy events is evaluated to be around 70 to 80%.

2.1 Event shape distributions

The jet structure of hadronic events can be analysed using global event shape variables. Definitions of some of them can be obtained from references [1,2,3].

At LEP 1.5 the procedure to obtain a distribution of a given variable is the following: after subtracting the background events 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. These correction factors are around 1 and have a maximum spread of 20%. The effect of initial and final state photon radiation is corrected bin by bin using Monte Carlo distributions at particle level with and without radiation. These correction factors multiplied by the previous ones are typicaly between 0.5 and 1.5 for most of the variables. This unfolding procedure is sufficiently accurate considering the limited statistics of the data sample available. 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 2 shows the thrust distribution T as measured by ALEPH compared to PYTHIA, HERWIG and ARIADNE Monte Carlo. Except a slight excess of events in the low thrust region corresponding to the excess of 4 jet events already reported by the ALEPH collaboration [5] the agreement is satisfactory. It

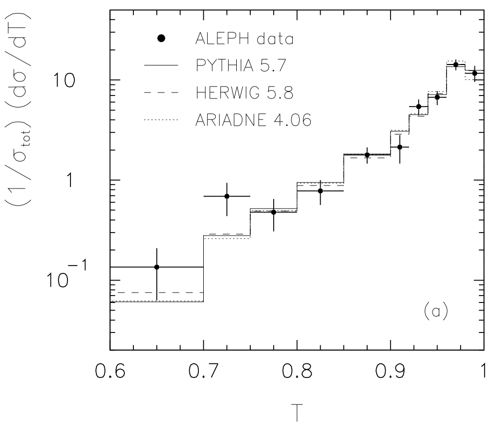

Figure 2: Thrust distribution measured by ALEPH at 133 GeV.

Table 2: Mean thrust value and mean charged multiplicity at E_{cm} between 130 and 136 GeV

	$< T >$	$< n_{ch} >$
ALEPH	0.933 $\pm$ 0.007	24.13 $\pm$ 0.55
DELPHI	0.938 $\pm$ 0.003 (stat)	23.84 $\pm$ 0.73
L3 (130)	0.948 $\pm$ 0.008	24.9 $\pm$ 0.9
L3 (136)	0.943 $\pm$ 0.009	24.2 $\pm$ 1.0
OPAL	0.935 $\pm$ 0.004	23.40 $\pm$ 0.65

should be noticed that none of the other collaborations see this disagreement in their thrust distribution.

2.2 Energy dependences of the Mean Values

An important test of the QCD models is to check the predicted energy evolution of the shape distributions using the same Monte Carlo parameter values. This energy evolution comes mainly from the logarithmic dependence of α_s and from the hadronization process leading to a dependence proportional to 1/E. The mean values of thrust and charged multiplicity given in table 2 are shown in figures 3 and 4, together with measurements at the Z resonance as well as those at low energy e^+e^- machines.

Also shown are the energy dependences of

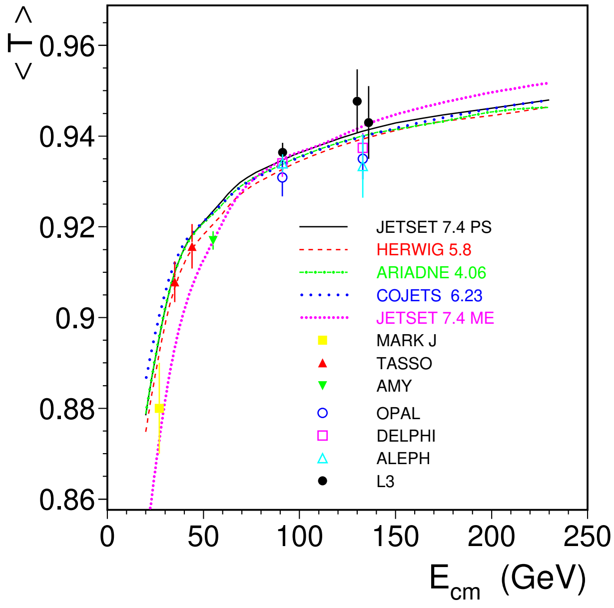

Figure 3: Mean thrust value as a function of the CM energy.

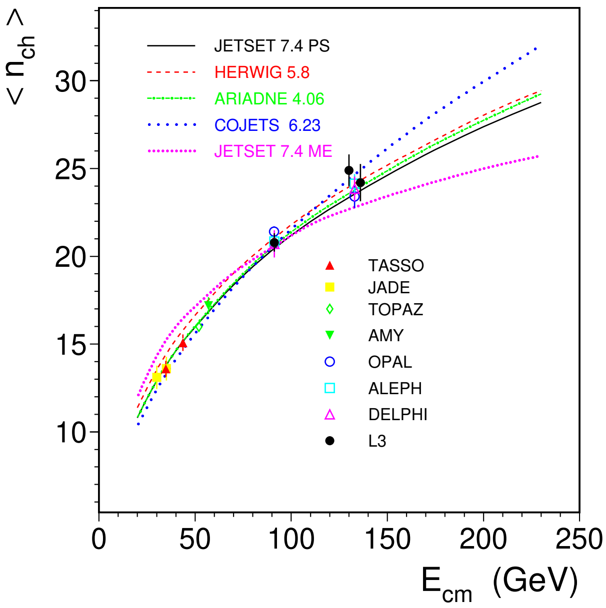

Figure 4: Mean charged multiplicity as a function of the CM energy.

these quantities as predicted by JETSET 7.4 PS, HERWIG 5.6, ARIADNE 4.06, COJETS 6.23 and JETSET 7.4 ME 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. They generally are in satisfactory agreement with the data. The JETSET 7.4 ME model however fails to describe the energy dependence of $< n_{ch} >$ over a wide energy range. This is understood as a consequence of low parton multiplicity before fragmentation compared to the other models incorporating multiple gluon emission.

2.3 Other Charged Particle Inclusive distributions

Charged particle momentum distributions offer a good test of QCD assuming the Local Hadron Parton Duality (LPHD) hypothesis. In this context the low energy particles produced in e^+e^- collisions are remnants of soft gluon radiation and their distributions (shapes and variations with energy) may be predicted in the context of the Leading Logarithmic Approximation (LLA). Figure 5 shows the scaled momenta $x_p = p/E_{beam}$ and the $\xi_p = \ln(1/x_p)$ distributions obtained by OPAL at 133 GeV. The x_p distribution is compared with

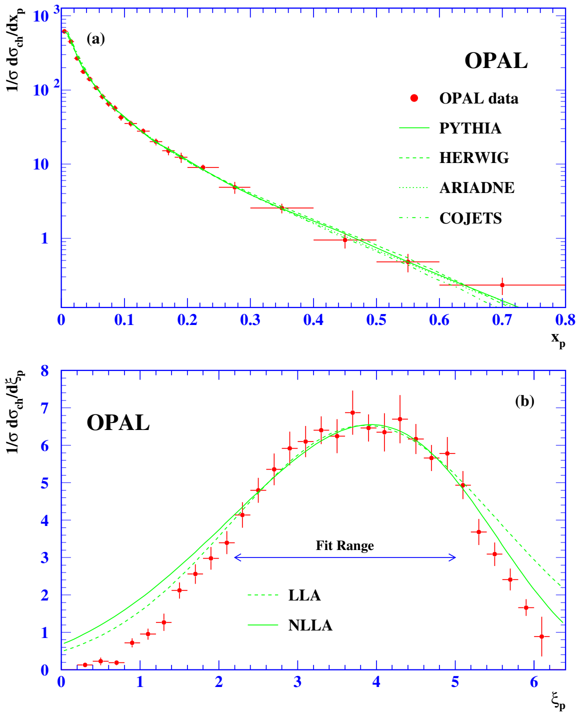

Figure 5: x_p and ξ_p distributions from OPAL .

Table 3: Peak position of the ξ_p distribution at 133 GeV

ALEPH	$3.834 \pm 0.038 \pm 0.029$
DELPHI	3.83 ± 0.05
OPAL	$3.94 \pm 0.05 \pm 0.11$

several Monte Carlo Models showing a reasonable agreement. Most of these models are based on LLA methods. The x_p distribution emphasises the higher momentum region while the ξ_p one emphasises the low momentum region where the LLA is expected to be valid.

QCD NLLA (Next to LLA) calculation predicts the ξ_p distribution to have a hump-backed shape due to destructive inteference in coherent emission reducing the number of soft gluons. This shape can be approximated by a skewed gaussian function around the peak of the distribution according to next to leading order calculations. Figure 5b shows fits of LLA and NLLA functions to the ξ_p distribution. Adding higher order terms to LLA prediction seems to improve the description of the data in the region of many soft gluon emission.

Table 3 summarises the peak values of the ξ_p distribution obtained at LEP1.5 by ALEPH, DELPHI and OPAL. These values are consistent with the expected increase with energy given by LLA calculations.

3 α_s determination at 133 GeV

Measurements of the strong coupling constant α_s at 133 GeV have been performed by ALEPH, L3 and OPAL using a similar approach. The technique is based on fits of combined $O(\alpha_s^2)$+NLLA QCD calculations to a certain number of corrected event shape distributions for which the theoretical descriptions are the most complete [8]. QCD predictions in fixed second order perturbation theory cannot take into account the effect of multiple gluon emission. For variables like thrust, heavy jet mass, etc. this leads to a singular behavior of the distributions in kinematic regions where multigluon emission becomes dominant. This is a direct consequence of the collinear and infrared divergence of the gluon emission cross section. It is possible to isolate the singular terms in every order of the perturbation series and to sum them up in the form of an exponential. These calculations have been carried out for some variables (denoted generically by y) to next-to-leading log terms. On the other hand, in the fixed order calculations [6,7], all the contributions (including the subleading terms) are summed to second order. In order to describe the data over a wide kinematic range, it is desirable to combine the two sets of calculations by a suitable matching scheme.

The hadronization corrections have been applied to the theoretical distributions using the JETSET model for L3 and OPAL and ARIADNE model for ALEPH.

The variables used by L3 are the thrust, scaled heavy jet mass (ρ), total (B_T) and wide jet (B_W) broadening. OPAL used the same four, adding the differential 2-jet rate (D_2). ALEPH used only the variable -ln(y_3) corresponding to the y_{cut} value for which the event goes from a 3-jet to a 2-jet configuration with the Durham scheme. This variable should have the smallest hadronization uncertainties. Table 4 summarizes the average α_s value obtained by the different experiments together with the variable used.

DELPHI is using a method independent of fragmentation model corrections to determine α_s from the energy dependence of the mean thrust and heavy jet mass.

The mean value of an event shape variable f can be written in the form:

$$\langle f \rangle = \frac{1}{\sigma_{tot}} \int f \frac{d\sigma}{df} df = \langle f_{pert} \rangle + \langle f_{pow} \rangle \qquad (2)$$

where $\langle f_{pert} \rangle$ is the $O(\alpha_s^2)$ expression for the event shape distribution and $\langle f_{pow} \rangle$ is a power correction term taking into account the hadronization effect. The prescription used is the one given in reference [9]. The resulting α_s value is given on the 4th line of Table 4.

The DELPHI value appearing on the last line of Table 4 comes from a fit of the QCD prediction for the mean charged multiplicity to the data from various center-of-mass energies including the 133 GeV measurement [10]. The prediction for charged multiplicity as a function of α_s including the resummation of leading (LLA) and next-to-leading (NLLA) corrections is given by:

$$\begin{aligned} n_{ch}(\sqrt{s}) &= a \cdot \alpha_s(\sqrt{s})^b \cdot e^{c/\sqrt{(\alpha_s(\sqrt{s})}} \\ &\quad \cdot \left(1 + d \cdot \sqrt{(\alpha_s(\sqrt{s})}\right) \end{aligned} \qquad (3)$$

Table 4: α_s from the various LEP experiments at LEP 1.5

	$\alpha_s(133\ GeV)$	fit variable
ALEPH	$0.119 \pm 0.004 \pm 0.007$	$-lny_3$
L3	$0.107 \pm 0.005 \pm 0.006$	T,ρ,B_w, B_t
OPAL	$0.110 \pm 0.005 \pm 0.009$	T,ρ,B_w, B_t, D_2
DELPHI	$0.119 \pm 0.007 \pm 0.005$	$< 1 - T >, < M_h^2/s >$ evolution
DELPHI	$0.105 \pm 0.003 \pm 0.008$	$< N_{ch} >$ evolution

4 Testing QCD below the Z resonance

Testing energy evolution of variables sensitive to QCD is of great interest but remains difficult when comparing results of different experiments at different energy due to various systematical and theoretical uncertainties. 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. L3 presented such an analysis at this conference based on final state photon events [11].

The study of isolated high energy photons in hadronic Z decays at LEP offers an important probe of the short distance structure of QCD. 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. The effective center of mass energy is related to the photon energy via the relation

$$\sqrt{s'} = \sqrt{s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)} \qquad (4)$$

4.1 Event Shape Variables

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 to 86 GeV. After correcting the distributions for detector effect and resolution together with initial and final state radiation they have been compared with predictions from ARIADNE, HERWIG and JETSET for the six energy ranges. Events are generated using a parameter set tuned with the L3 data at the Z peak. The initial and final state radiation has been switched off. As can be seen in the figures of reference [11], the data are in good agreement with QCD model predictions.

The event shape variables of the hadronic system have thus been examined for different reduced CM energy regions. The data agree with the energy evolution of the QCD models, JETSET 7.4 PS, HERWIG 5.8, ARIADNE 4.06.

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, at the six reduced CM energy points, we have determined the strong coupling constants. Table 5 summarises the α_s values obtained with L3 from 30 to 133 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 can be subtracted to allow a more accurate check of the energy evolution.

The energy dependence of the measured α_s shown in Figure 6 is in agreement with the QCD prediction.

DELPHI measured with a similar technique the mean charged multiplicity as a function of the energy using also the hadronic events with hard photons [12]. Figure 7 shows the energy dependence compared to the fit of next to leading log QCD prediction (solid line) given by equation 3.

Table 5: α_s values at various CM energies from event shape measured by L3.The experimental error includes both the statistical and systematic errors while the theoretical error takes into account the hadronization and higher order correction uncertainties.

$\sqrt{s}$ (GeV)	α_s ($\sqrt{s}$)	$\Delta\alpha_s$ (exp.)	$\Delta\alpha_s$ (theo.)
30 – 50	0.139	± 0.010	± 0.009
50 – 60	0.139	± 0.011	± 0.007
60 – 70	0.132	± 0.008	± 0.006
70 – 80	0.116	± 0.008	± 0.006
80 – 84	0.118	± 0.010	± 0.007
84 – 86	0.111	± 0.009	± 0.005
91 GeV	0.122	± 0.002	± 0.007
133 GeV	0.107	± 0.005	± 0.006

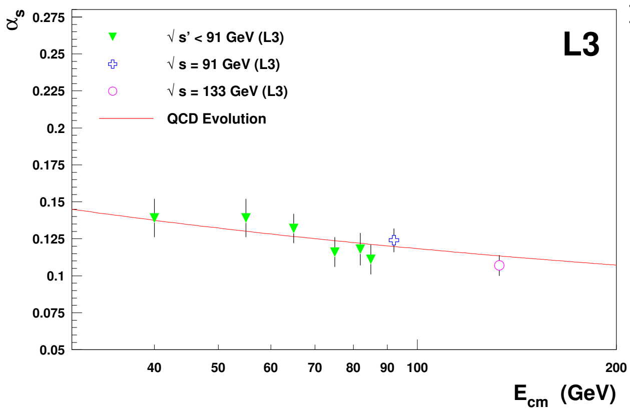

Figure 6: α_s values measured by L3 over a wide energy range.

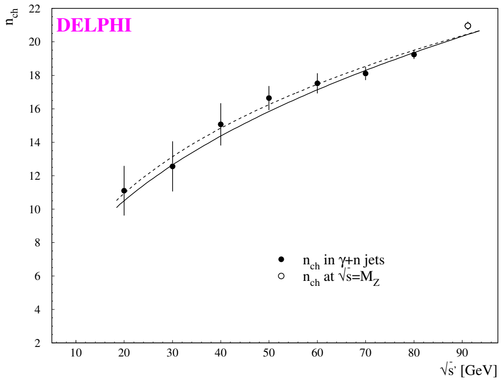

Figure 7: Charged multiplicity as a function of the effective CM energy measured by DELPHI

5 Future

At the time of the conference there were very new results from LEP2 at 161 GeV based only on $3pb^{-1}$ of luminosity per experiment that was presented. Detailed analyses of QCD at 161 GeV are performed now and should be finalised soon.

Acknowledgments

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References

1. ALEPH Collaboration, D. Buskulic et al., *CERN-PPE/* **96-43**, (1996).
2. L3 Collaboration, M.Acciarri, *Phys. Lett.* B **371**, 137-148 (1996).
3. OPAL Collaboration, G. Alexander et al., *CERN-PPE/* **96-47**, (1996).
4. DELPHI Collaboration, P. Abreu et al., contribution PA02-003 to this conference.
5. ALEPH Collaboration, D. Buskulic et al., *CERN-PPE/* **96-52**, (1996).
6. R.K. Ellis, D.A. Ross and A.E. Terrano, Nucl. Phys. **B178** (1981) 421.
7. Z. Kunszt and P. Nason in "Z Physics at LEP 1", CERN Report 89-08, Vol.I., p. 373.
8. S. Catani *et al.*, Phys. Lett. **B295** (1992) 269; S. Catani *et al.*, Nucl. Phys. **B407** (1993) 3; G. Dissertori and M. Schmelling, Phys. Lett. **B361** (1995) 167.
9. Yu.L.Dokshitzer,B.R.Webber,*Phys. Lett.* B **352**, 451-455 (1995).
10. DELPHI Collaboration, P. Abreu et al., *Phys. Lett.* B **372**, 172-180 (1996).
11. S.Banerjee, D.Duchesneau,S.Sarkar, L3 note 1958, (1996), contribution PA04-021 to this conference.
12. DELPHI Collaboration, P. Abreu et al., *Z. Phys.* C **70**, 179-196 (1996).