DETERMINATION OF α_s IN e^+e^- COLLISIONS UP TO 183 GeV WITH THE L3 DETECTOR

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The results of three methods of determining the strong coupling constant α_s are reviewed, together covering energy scales from the τ mass to 183 GeV . Comparisons with QCD predictions of α_s energy dependence are made. The QCD expectation of a decrease in α_s with increasing energy is observed.

1 Introduction

Studies of the process $e^+e^- \rightarrow$ hadrons at LEP provide an excellent environment for tests of QCD predictions due to the well defined initial state and collimated nature of jets arising from the hard partons. Also the expected smallness of non-perturbative and hadronisation corrections allows a straightforward comparison of observables with the perturbative QCD calculations, yielding α_s measurements.

The non-abelian nature of QCD predicts that α_s should decrease with increasing energy scale. Measurements over a wide energy range allow this prediction to be tested.

2 Measurement techniques

Observables used in the α_s determinations presented here are listed together with the order of perturbative calculations available and the relevant energy scale in Table 1. The inclusive observables R_Z and R_τ have the advantage of a

Table 1: α_s measurement observables.

observable	calculation	energy scale
Event shape T,ρ,B_T,B_W	resummed $\mathcal{O}(\alpha_s{}^2)$	$\sqrt{s}$ 30-183 GeV
R_Z	$\mathcal{O}(\alpha_s{}^3)$	m_Z
R_τ	$\mathcal{O}(\alpha_s{}^3)$	m_τ

better theoretical knowledge but are relatively insensitive to α_s when compared with the event shape variables which are proportional to α_s at lowest order. Event shape variable calculations have the advantage of being applicable over a wide energy range.

3 Hadronic event selection

Hadronic events are selected based on the energy measured in the calorimeters alone, using the characteristic large visible energy and high multiplicity. The

Table 2: Hadronic data samples at various center of mass energies $\sqrt{\mathrm{s}}$, together with event shape references, integrated luminosities and important backgrounds.

	LEP1.0		LEP1.5-2.0 after '95			
$\sqrt{\mathrm{s}}$ (GeV):	$30-86$ [1]	91.2 [2]	$130-140$ [3]	161 [4]	172 [4]	183 [5]
$\int \mathcal{L}\,(\mathrm{pb}^{-1})$:	142.4	8.0	5.0	11.1	10.2	55.3
# $q\bar{q}$ events:	3.578M	248k	402	443	341	1607
$\mathrm{W}^+\mathrm{W}^-$ bgd. (%)	-	-	-	4	9	11.9
2γ & $\tau^+\tau^-$ bgd. (%)	0.2	< 0.2	< 2	3	3	3.2

event shape analyses use all the data samples summarised in Table 2 whereas the R_Z [6] and R_τ [7] analyses use only peak data.

The first column corresponds to 6 energy bins in the range 30-86 GeV obtained from the very large sample of hadronic events collected on the Z resonance by requiring a hard isolated photon to be seen in the detector. Regarding this photon to be initial-state radiation or quark bremsstrahlung which occurs well before the development of the hadronic shower, enables the system recoiling against the photon to provide access to hadron production at reduced centre-of-mass energies.[a] The effective energy $\sqrt{\mathrm{s}'}$ is related to the photon energy E_γ by

$$\sqrt{\mathrm{s}'} = \sqrt{\mathrm{s}\,(1-2\mathrm{E}_\gamma/\sqrt{\mathrm{s}}\,)}. \tag{1}$$

Thus event shape variables calculated after excluding the photon and boosting into the recoiling system allow QCD α_s fits to be performed within the 6 bins at reduced energy. The full LEP1.0 dataset yields samples of between 1000 and 3000 events in each bin with purities in the range 70-90% as detailed in [8].

For the higher energy LEP1.5-2.0 runs a large fraction of events have hard initial state radiation that reduces the center of mass energy to the Z resonance region. These events are rejected by using their characteristic large longitudinal energy imbalances, due to the loss of an ISR photon in the beampipe, as well as by rejecting events with high energy photons seen in the detector.

After this selection the dominant backgrounds are from non-resonant 2γ collisions, $e^+e^- \rightarrow e^+e^-$ + hadrons, and $e^+e^- \rightarrow \mathrm{W}^+\mathrm{W}^- \rightarrow \mathrm{q\bar{q}q\bar{q}}$. Above the W pair threshold at 161 GeV additional rejection of hadronic W decays is applied using the 4-jet nature of these events.

[a] Comparisons of distributions from JETSET run at reduced energies with "radiatively reduced" JETSET confirm this interpretation.

4 Event shape distributions

Hadronic final states are characterised by the event shape variables "y" (thrust, T, scaled heavy jet mass, ρ, total, B_{T} and wide, B_{W}, jet broadening); which are computed from reconstructed calorimetric clusters which are considered to be massless particles.

In order to compare the observed distributions with the analytical predictions remaining backgrounds are subtracted, the distributions are corrected bin by bin for acceptance and resolution effects and corrections are applied for the effects of initial and final state radiation. The radiation correction factors are obtained by comparison of the PYTHIA generator distributions with and without radiation. Systematic errors in the distributions arise mainly from uncertainties in detector calibration and in background estimation.

The resummed $\mathcal{O}(\alpha_{\mathrm{s}}{}^2)$ calculations available for the event shape variables "y" apply to partons and do not include heavy quark mass effects. The effects of hadronisation and decays are incorporated using Monte Carlo programs with standard L3 parameters tuned using LEP1 data [9].

The QCD fits to the event shape distributions for the 172 GeV sample are shown in Figure 1a; the corresponding results and uncertainties are presented in Table 3. The experimental systematic uncertainties are estimated by

Table 3: $\alpha_{\mathrm{s}}(172\ \mathrm{GeV})$ results from the fits to event shape distributions.

	$(1-T)$	ρ	B_{T}	B_{W}
Fit range	0.00-0.30	0.00-0.20	0.00-0.25	0.00-0.20
$\alpha_{\mathrm{s}}(172\ \mathrm{GeV})$	0.108	0.104	0.106	0.099
χ^2/d.o.f.	0.28	0.89	1.12	1.08
Statistical	±0.005	±0.005	±0.004	±0.004
Systematic	±0.003	±0.003	±0.003	±0.003
Overall experimental	±0.006	±0.006	±0.005	±0.005
Fragmentation model	±0.003	±0.002	±0.003	±0.001
Model parameters	±0.002	±0.002	±0.001	±0.001
Hadronisation total	±0.003	±0.002	±0.003	±0.001
QCD scale uncertainty	±0.004	±0.003	±0.005	±0.005
Matching scheme	±0.002	±0.003	±0.005	±0.005
Error due to higher orders	±0.004	±0.003	±0.005	±0.005
Overall theoretical	±0.005	±0.004	±0.006	±0.005

varying the energy calibration and background content. Uncertainties due to uncalculated higher orders dominate those from hadronisation; two methods of evaluating each of these are used and the higher of the two is taken as the error estimate. The higher orders uncertainty is estimated by using different renormalisation scales $0.5\sqrt{s} \leq \mu \leq 2.0\sqrt{s}$ and by varying the resummation

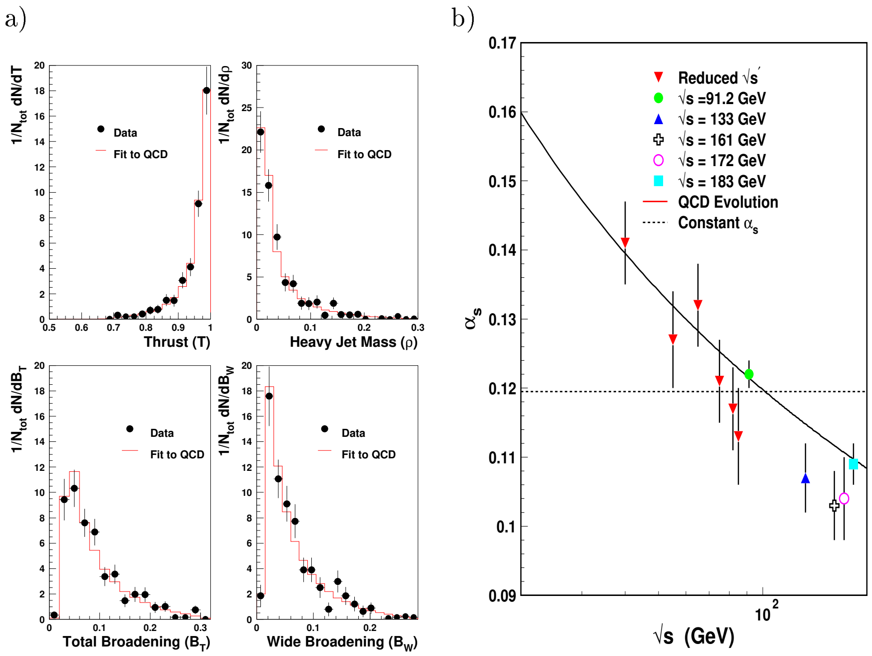

Figure 1: a) Measured distributions of thrust, T, scaled heavy jet mass, ρ, total, B_{T} and wide, B_{W}, jet broadening in comparison with QCD predictions at 172 GeV , b) α_{s} measurements as a function of the center of mass energy $\sqrt{s}$ compared to a QCD evolution fit to the event shape results.

matching scheme used while the hadronisation uncertainty is estimated by changing the JETSET model parameters by one standard deviation and using different models.

Combining the results from the four distributions by taking an unweighted average and combining the theoretical uncertainties by taking the linear average yields the result:

$$\alpha_{\mathrm{s}}\,(172\,\mathrm{GeV}\,) = 0.104 \pm 0.006 \pm 0.005$$

where the first error is experimental and the second is theoretical. This result together with those from the samples at other energies are presented in Table 4 and Figure 1b, where the errors are experimental only as the theoretical errors are highly correlated between all the points.

5 R_Z

The perturbative coefficients for the ratio of hadronic to leptonic widths of the Z, R_Z, are known to $\mathcal{O}({\alpha_s}^3)$:

$$R_Z = \frac{\Gamma_{\rm had}}{\Gamma_{\rm lep}} \approx R_0 \left[1 + 1.06 \left(\frac{\alpha_s}{\pi}\right) + 0.9 \left(\frac{\alpha_s}{\pi}\right)^2 - 15 \left(\frac{\alpha_s}{\pi}\right)^3 + \ldots\right] \qquad (2)$$

but the QCD correction to R_Z is small ($\approx 4\%$) resulting in limited sensitivity to α_s and the R_0 term has some weak dependence on the top quark mass, m_t and the Higgs boson mass, m_h, arising from electroweak radiative corrections.

Standard Model fits [6], using ZFITTER 4.9, to the preliminary L3 results from LEP 1: $m_Z, \Gamma_Z, \sigma^0_{had}, R_l, A^{0,l}_{FB}, P_\tau, A^{0,b}_{FB}$, and R_b, are performed using a fixed $m_h = 300\,\mathrm{GeV}$ to yield:

$$\begin{aligned} m_t &= 189^{+14}_{-15} \pm 16 \text{ GeV} \\ \alpha_s(m_Z) &= 0.126 \pm 0.007 \pm 0.002(m_h)\,, \end{aligned}$$

where the 2nd error on α_s indicates the variation due to moving m_h from 60 to 1000 GeV.

An alternative approach [10] with less model dependence uses the preliminary value of R_Z alone,

$$R_Z = 20.788 \pm 0.066$$

to yield the compatible result:

$$\alpha_s(m_Z) = 0.126 \pm 0.010 \pm 0.002(m_h) \pm 0.003(th.)\,.$$

6 R_τ

The ratio of hadronic to leptonic widths of the τ lepton R_τ can also be used to measure α_s at the very low energy scale of the tau mass $m_\tau \approx 1.78\,\mathrm{GeV}$. Analogously to R_Z:

$$R_\tau \equiv \frac{\Gamma(\tau \to \text{ hadrons}\,\nu_\tau)}{\Gamma(\tau \to \; e\,\nu_e\,\nu_\tau)} = \frac{1 - B^\tau_e - B^\tau_\mu}{B^\tau_e} = R^0_\tau \left[1 + \delta^\tau_{QCD}\right], \qquad (3)$$

where δ^τ_{QCD} follows the same form as in the R_Z perturbative expansion and the relation to the measured branching ratios is shown. It is also possible to obtain R_τ from lifetime measurements [7] using the Standard Model relation $\tau_\tau = B^\tau_e\,\tau_\mu\,(m_\mu/m_\tau)^5$ and $B^\tau_\mu = 0.973\,B^\tau_e$ from phase space considerations.

Combining results from the two methods gives, $R_\tau = 3.61 \pm 0.13$, yielding values at the measurement scale and evolved to m_{Z}:

$$\alpha_{\mathrm{s}}(m_\tau) = 0.35 \pm 0.06(expt.) \pm 0.03(th.).$$
$$\alpha_{\mathrm{s}}(m_{\mathrm{Z}}) = 0.121 \pm 0.006(expt.) \pm 0.003(th.).$$

The theoretical error includes a surprisingly small contribution from non-perturbative corrections given the very low energy scale; controversy remains over this issue[11]. Hadronic final states of the τ are typically π, ρ or a_1, whereas the final state assumed in the calculation consists of two free quarks and up to three gluons, lending doubt to a perturbative treatment.

7 Conclusion

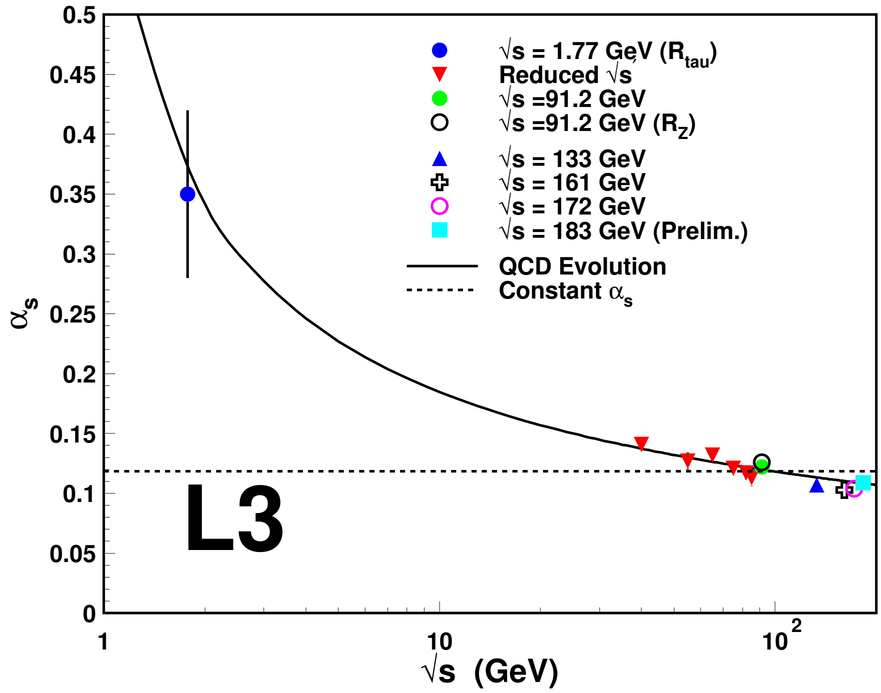

Figure 2: α_{s} results from all the methods compared to the QCD evolution fit to the event shape results

The results from all three methods at the various energy scales are shown in Figure 2 together with a fit to the QCD evolution function for the event shape results only, which yields:

$$\alpha_s(m_Z) = 0.1215 \pm 0.0016(expt.) \pm 0.0066(th.)\,,$$

with $\chi^2 = 16.6$ for 10 degrees of freedom. A fit to constant α_s gives a χ^2 of 46.1, corresponding to a confidence level of 0.14×10^{-5}. In Table 4 the results are listed together with values evolved to m_Z.

These results support the QCD prediction of the energy evolution of α_s. A revision of the preliminary 183 GeV results [5] has led to a closer agreement with expectations than was reported at the Institute.

The comparable size of theoretical and experimental errors for the higher energy event shape analyses motivate combinations of the results of the LEP experiments which are expected to be done during 1998. Similarly final combinations of the statistically dominated α_s determinations from LEP1 electroweak results are expected this year.

Table 4: Measured α_s values from the 3 methods determined at various centre of mass energies $\sqrt{s}$. with experimental and theoretical errors and values evolved to m_Z with experimental errors.

$\sqrt{s}$ (GeV)	α_s ($\sqrt{s}$)	Evolved α_s (m_Z)
Event shape fits		
41.2	$0.140 \pm 0.006 \pm 0.011$	0.122 ± 0.005
55.3	$0.126 \pm 0.007 \pm 0.010$	0.117 ± 0.006
65.4	$0.134 \pm 0.006 \pm 0.009$	0.127 ± 0.005
75.7	$0.121 \pm 0.006 \pm 0.009$	0.118 ± 0.006
82.3	$0.120 \pm 0.006 \pm 0.009$	0.118 ± 0.006
85.1	$0.116 \pm 0.007 \pm 0.008$	0.115 ± 0.007
91.2	$0.122 \pm 0.002 \pm 0.007$	0.122 ± 0.002
133.0	$0.107 \pm 0.005 \pm 0.006$	0.113 ± 0.006
161.0	$0.103 \pm 0.005 \pm 0.005$	0.111 ± 0.006
172.0	$0.104 \pm 0.006 \pm 0.005$	0.114 ± 0.007
183.0	$0.109 \pm 0.002 \pm 0.005$	0.121 ± 0.003
R_Z		
91.2	$0.126 \pm 0.007 \pm 0.002$	-
R_τ		
1.7769	$0.35 \pm 0.06 \pm 0.03$	0.121 ± 0.006

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References

1. L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 411** (1997) 339-353.
2. L3 Collab., O. Adriani *et al.*, Phys. Lett. **B 284** (1992) 471-481.
3. L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 371** (1996) 137-148.
4. L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 404** (1997) 390-402.
5. Sunanda Banerjee, Swagato Banerjee, D. Duchesneau, Revised L3 Internal Note 2228, 27 March 1998, *New QCD Results at* $\sqrt{s} = 183$ *GeV* .
6. The L3 Lineshape Group, L3 Internal Note 1980 (1996), *Preliminary L3 results on Electroweak Parameters using 1990-95 data.*
7. L3 Collab., O. Adriani *et al.*, Phys. Rep. **236** (1993) 128-129. L3 Collab., B. Adeva *et al.*, Phys. Lett. **B 265** (1991) 451-461.
8. D. Duchesneau, these proceedings, *QCD studies in* e^+e^- *collisions up to 183 GeV.*
9. L3 Collab., B. Adeva *et al.*, Z. Phys. **C 55** (1992) 39. Sunanda Banerjee and Swagato Banerjee, L3 Internal Note 1978 (1996), *Tuning of QCD model parameters using LEP data of hadronic Z decays.*
10. J. Mnich, private communication. L3 Collab., O. Adriani *et al.*, Phys. Rep. **236** (1993) 128.
11. G. Altarelli, P. Nason, G. Ridolfi, Z. Phys. **C 68** (1995) 257. T.N. Truong, Preprint Ecole Polytechnique, EP CPTH A 266-1093.