EXPERIMENTAL STATUS OF MEASUREMENTS OF $\alpha_s$ AT LEP*

G. Dissertori,
EP Division, CERN, Geneva

March 24, 2022

Abstract
A summary is given of the current status of measurements of the strong coupling constant $\alpha_s$ performed at LEP. These include measurements from inclusive observables as well as from event shape variables. Recent results based on power law corrections are discussed.

1 Introduction
Quantum Chromodynamics (QCD) is generally accepted as the theory of strong interactions between quarks and gluons. If the quark masses are fixed, there is only one free parameter in the theory, the strong coupling constant $\alpha_s$. Thus measurements of this parameter are of paramount importance. Such measurements have been performed in a large variety of experiments, for various initial states, processes and energy scales. During recent years good consistency has been obtained between the different determinations and the theoretical prediction for the running (energy dependence) of the coupling \[1, 2\]. Here a summary of the measurements performed at LEP is given, which contribute in an important way to the achieved precision on the world average value of $\alpha_s(M_Z^2) = 0.118 \pm 0.002$ \[1\].

2 Inclusive observables
At LEP the strong coupling constant is measured in $e^+e^-$ annihilations into quarks which subsequently fragment into hadrons, or in $e^+e^- \rightarrow \tau^+\tau^-$, where one or both tau leptons decay hadronically. For inclusive observables such as the total cross section the hadronic final state is not analyzed w.r.t. its particular properties such as particle content or topology. In practice a ratio of cross sections or partial decay widths is measured, in order to take advantage of the cancellation of common systematic uncertainties, $R_{\ell(\tau)} = \Gamma(Z(\tau) \rightarrow \text{hadrons}) / \Gamma(Z(\tau) \rightarrow \text{muons}) = R_{\ell(\tau)}^{EW}(1 + \delta_{QCD} + \delta_{\text{mass}} + \delta_{\text{np}})$. The QCD correction is known up to next-to-next-to-leading order.

*to be published in the proceedings of the XIIIth meeting on physics at LEP, LEPTRE, Rome, April 2001.
(NNLO), \( \delta_{\text{QCD}} = \sum_{n=1}^{3} c_n \alpha_s^n \), with known coefficients \( c_{1...3} \). In addition there are corrections for quark mass and non-perturbative effects.

In the case of \( R_l \) the LEP combination turns out to be \( R_l = 20.768 \pm 0.024 \) [3], which translates into \( \alpha_s(M_Z^2) = 0.124 \pm 0.004 \) [4]. The error is dominated by experimental uncertainties, mainly the statistical error in the muon cross section. Mass corrections and non-perturbative effects are very small, since they are suppressed as \( m_q^2/M_Z^2 \) and \( c/M_Z^4 \). Theoretical uncertainties arise from the missing knowledge of the Higgs mass and the uncertainty on the top mass, as well as from renormalization scale and scheme variations.

For tau decays ALEPH and OPAL have measured the hadronic mass spectrum and determined its moments. For example, \( R_\tau \) corresponds to the zeroth moment. By measuring several moments, not only \( \alpha_s \) can be fitted, but at the same time also some non-perturbative parameters. A combination of the results from the two experiments yields \( \alpha_s(M_Z^2) = 0.1181 \pm 0.0007(\text{exp}) \pm 0.0030(\text{theo}) \) [2], which represents one of the most precise measurements. In contrast to \( R_l \), here the experimental error is negligible, whereas the theoretical uncertainty dominates. This uncertainty stems from different estimates of higher order corrections.

### 3 Event shape distributions

Event shape distributions are observables which are sensitive to the topology of an hadronic event, and thus give direct sensitivity to \( \alpha_s \) since gluon radiation influences the topology. For a particular set of infrared and collinear safe variables the cross section is known at NLO, and large logarithms have been resummed to all orders in \( \alpha_s \) (see [4] for a review on this topic). This set of observables comprises thrust, heavy jet mass, the differential two-jet rate computed in the Durham scheme, the C parameter, as well as the total and wide jet broadening. These distributions have been measured by all LEP collaborations and used for \( \alpha_s \) determinations, for a large set of centre-of-mass energies at LEP I and LEP II (for a review see eg. [4]). Recently, also the four-jet rate (Durham scheme) has been employed for \( \alpha_s \) measurements [5, 6], since a NLO calculation as well as the resummation of large logarithms is at hand.

For this kind of observables the dominant uncertainties on \( \alpha_s \) are of theoretical origin. Firstly the purely perturbative predictions have to be corrected for hadronization effects, which are larger than for inclusive observables. These corrections are taken from Monte Carlo programs based on various phenomenological models, leading therefore to ambiguities. Secondly, there are uncertainties stemming from the estimates of missing higher order terms. As an example, in a recent preliminary analysis by ALEPH [6] of the data at 206 GeV centre-of-mass energy the following uncertainties on \( \alpha_s \) are quoted when combining the results from the six event shapes mentioned above: 0.0022(stat), 0.0017(exp), 0.0007(had), 0.0016(match), 0.0038(scale). “Match” stands for an ambiguity in the combination of fixed order and resummation calculations, and “scale” for variations of the renormalization scale. The statistical error can be substantially reduced by combining with the results from the Z resonance and from other experiments. Therefore these findings clearly indicate that a considerable improvement can only be obtained if the theoretical uncertainties are reduced. This might be possible with the advent of NNLO calculations for three-jet observables.
A somewhat different approach to the problem of missing higher orders has been attempted by DELPHI [2]. Using only the NLO prediction for a large set of event shape variables, and setting the renormalization scale equal to the centre-of-mass energy, a large scatter in the $\alpha_s$ values from different observables is found. However, this scatter is considerably reduced if both $\alpha_s$ and the renormalization scale are fitted at the same time. The price to pay is a large scatter in renormalization scales, from 5 to 240 GeV. These extreme values might not be natural from a theoretical point of view. In any case, a clear indication for large missing higher orders is obtained, which depend strongly on the observable.

4 Power law corrections

During recent years there has been a lot of activity on the phenomenology of power law corrections to event shape variables. For an overview the interested reader is referred to [9]. Instead of obtaining the non-perturbative corrections from Monte Carlo models it turns out that additive terms in the case of moments or shifts in the case of event shape distributions of the type $1/Q$ are capable of giving a good description of the data. Using this power law behaviour, $\alpha_s$ can be determined together with a non-perturbative parameter $\alpha_0$ which is expected to be universal. A recent analysis of a large set of data from a wide range of energies [10] indicates that indeed universality is obtained at the 20% level for the mean values of event shapes. However, in the case of distributions still some larger fluctuations are observed. Several effects might be at the origin of this. It might be that hemisphere variables such as heavy jet mass and jet broadenings need a more careful analysis than event variables such as thrust. An approach in this direction could be the introduction of a non-perturbative shape function (see [11] for a recent review). In addition, further understanding is needed for the effects of hadron masses and resonance decays [12]. In any case, a high precision measurement of $\alpha_s$ based on power law corrections will need further theoretical as well as experimental investigations.

5 Summary

A large set of measurements of $\alpha_s$ is available from LEP. These determinations contribute in an important way to the world average value and are nicely consistent with the predicted running of the strong coupling, as shown in fig. 1. The results from event shape variables have shown that further theoretical work is needed in order to improve the precision, such as the completion of NNLO calculations for three-jet quantities and a better understanding of power law corrections. Since these developments might not be finished within a few years from now, it is of great importance to preserve the LEP data well, in order to facilitate a possible re-analysis in the future.

6 Acknowledgements

I would like to thank S. Kluth and S. Tafat for providing me with useful information on power law corrections.
Event Shapes

Figure 1: Summary of the measurements of $\alpha_s$ performed at LEP.

References

[1] D.E. Groom et al., Eur. Phys. J. C 15 (2000), 1.
[2] S. Bethke, J. Phys. G 26 (2000) R27; hep-ex/0004021.
[3] The LEP Electroweak Working Group, CERN preprint CERN-EP/2000-016.
[4] M. Grazzini, these proceedings.
[5] ALEPH collaboration, conf. note ALEPH 2000-045, CONF 2000-028, 2000.
[6] OPAL collaboration, G. Abbiendi et al., CERN preprint CERN-EP/2001-001.
[7] ALEPH collaboration, conf. note ALEPH 2001-007, CONF 2001-004, 2001.
[8] DELPHI collaboration, P. Abreu et al., Eur. Phys. J. C 14 (2000) 557.
[9] A. Banfi, these proceedings.
[10] S. Kluth, arXiv:hep-ex/0104016, 2001.
[11] S. Tafat, talk at the 36th Rencontres de Moriond on QCD and Hadronic Interactions, Les Arcs, France, 17-24 Mar 2001.
[12] G.P. Salam and D. Wicke, arXiv:hep-ph/0102313, 2001.