LEP RESULTS ON $\alpha_s(M_Z)$ FROM $R_{\rm had}$ AND EVENT SHAPE VARIABLES

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Abstract

We present here the LEP results on the measurement of the QCD coupling constant, α_s, using two complementary analyses. Firstly, from the fits within the framework of the Standard Model, we determine $\alpha_s(M_Z) = 0.127 \pm 0.006$. Secondly, from the study of global event shape variables, we obtain $\alpha_s(M_Z) = 0.123 \pm 0.006$. Both measurements agree within the errors. The latter method of determining α_s is dominated by theoretical uncertainties.

We present here very precise mesurements of the QCD coupling constant, α_s, at LEP. The L3 collaboration analyses will be discussed in some detail and will be used as an example of the LEP analyses on this subject. The paper is divided in two sections, in the first part we show the α_s determination from the R_{had} value obtained in the Standard Model fits of the Z boson parameters and in the second part, we show the α_s determination from the fit of several event shape variables to the hadronic Z-decay distributions. In each section, we focus the discussion on the the L3 analysis and finally combine the four collaboration results into a LEP average value of $\alpha_s(M_Z)$.

1 α_s determination from R_{had}

The ratio of the hadronic and the electronic partial widths of the Z boson, R_{had}, is conceptually the simplest quantity measured by the LEP experiments which in turn allows a determination of $\alpha_s(M_Z)$. The sensitivity of this observable to the strong coupling constant arises from the QCD corrections appearing in hadronic final states but not present in leptonic final states. The non-perturbative uncertainties on R_{had} are expected to be small since the theoretical calculations do not rely on specific knowledge of the hadronization mechanism.

The perturbative QCD corrections, calculated up to $O(\alpha_s^3)$ for massless quarks [1], have a relative contribution of $\sim 4\%$ for reasonable values of α_s. The smallness of this correction implies very precise measurements of the ratio R_{had} in order to achieve an accurate determination of α_s.

QED and QCD corrections to R_{had} do not exactly factorize. Nevertheless, the relation between R_{had} and α_s can be represented through a factorized effective formula as proposed in [2]. Its expression for $m_{Higgs} = 300$ GeV and $m_{top} = 180$ GeV is

$$R_{had} = 19.943 \cdot \left(1 + 1.060\frac{\alpha_s}{\pi} + 0.85\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3\right). \quad (1)$$

1.1 L3 results from R_{had}

The L3 detector has collected about $3.5 \cdot 10^6$ Z° decays during 1990-1994 LEP running period. The details of the data sample can be found in [3].

The experimental determination of R_{had} can be obtained from a fit of the Standard Model parameters to the measured cross sections and lepton asymmetries at each energy point. Assuming lepton univerality, five independent parameters can be determined. The usual choice is the Z boson mass M_Z, its width Γ_Z, the hadronic pole cross section σ^o_{had}, the lepton asymmetry A^o_{FB}, and finally the ratio R_{had}.

The main source of systematic error in the determination of R_{had} is the uncertainty in the leptonic and hadronic cross sections, whose relative contribution is $\sim 0.5\%$.

The results of the fit are shown in table 1. From the L3 preliminary result $R_{had} = 20.836 \pm 0.080(\mathrm{exp})$, after applying (1) we obtain $\alpha_s(M_Z) = 0.132 \pm 0.012(\mathrm{exp}) \pm 0.004(\mathrm{theor})$, where the contributions to the theoretical uncertainty, as discussed in ref. [2], split into three parts:

- Electroweak corrections (± 0.002) arising from the comparison of factorized and non factorized QED and QCD corrections and from the uncertainty on the hadronic contribution to the electromagnetic coupling constant, α_{em}.
- QCD corrections (± 0.002) due to the unknown higher contributions to the perturbative expansion.

- $m_{\rm top}, m_{\rm Higgs}$ dependence ($\pm 0.0005, \pm 0.002$) estimated respectively by varying the top mass within the error of the combined CDF and DØ measurements [4] $m_{\rm top} = 180 \pm 12\,\rm GeV$ and the Higgs mass between $60\,\rm GeV$ and $1000\,\rm GeV$.

Parameter	L3	LEP
$M_{\rm Z}$ (GeV)	91.1935 ± 0.0037	91.1887 ± 0.0022
$\Gamma_{\rm Z}$ (GeV)	2.5040 ± 0.0053	2.4971 ± 0.0033
$\sigma^{\rm o}_{\rm had}$ (nb)	41.410 ± 0.110	41.492 ± 0.081
$\rm A^{o}_{FB}\,(M_{\rm Z})$	0.0183 ± 0.0032	0.0172 ± 0.0013
$R_{\rm had}$	20.836 ± 0.080	20.800 ± 0.035

Table 1: Line shape and asymmetry parameters from a 5-parameter fit to L3 data and average from the results of the four LEP collaborations. $\Gamma_{\rm Z}$ values have an additional error of $0.001\,\rm GeV$ due to an uncertainty of $5\,\rm MeV$ in the LEP center-of-mass energy spread.

1.2 LEP combined results

The dominant uncertainty in the $\alpha_{\rm s}$ determination from the ratio $R_{\rm had}$ by a single LEP collaboration is the experimental error as seen in the previous section. A more precise measurement is then expected from the total LEP statistics. A consistent average of the preliminary results of the four collaborations has been performed [5]. The combined fit makes use of the full covariance matrix of the five parameter fits from the different LEP experiments and takes into account the common systematic errors. These common errors arise from the theoretical uncertainty in the luminosity normalization, affecting the hadronic pole cross section, $\Delta\sigma^{\rm o}_{\rm had}/\sigma^{\rm o}_{\rm had} = 0.16\%$; and from the energy calibration of LEP, which gives $\Delta M_{\rm Z} = 1.5\,\rm MeV$, $\Delta\Gamma_{\rm Z} = 1.5\,\rm MeV$ and $\Delta \rm A^{o}_{FB} = 0.0005$.

The LEP combined results on more than $11 \cdot 10^6$ Z° decays are shown in table 1. Using the preliminary result $R_{\rm had} = 20.800 \pm 0.035(\rm exp)$, we obtain:

$$\alpha_{\rm s}(M_{\rm Z}) \;=\; 0.127 \;\pm\; 0.005\,(\rm exp) \;\pm\; 0.004\,(\rm theor) \tag{2}$$

2 $\alpha_{\rm s}$ determination from event shape variables

The event shape variables are designed to be sensitive to multijet events. Their relationship to $\alpha_{\rm s}$ measurement comes from the ratio of 3-jet to 2-jet cross sections which is, to leading order, proportional to $\alpha_{\rm s}$. These variables must be insensitive to the soft and collinear divergencies associated to the gluon emission. A compilation of variables fulfilling these requirements and also widely used in LEP/SLD analyses can be found in ref. [6].

The perturbative expansion in terms of $\alpha_{\rm s}$ for an event shape variable y, that vanishes in the 2-jet limit, contains logarithmically enhanced terms of the form $\alpha_{\rm s}^n \rm L^m$, where $\rm L = -\log y$. For a given order in the perturbative expansion, we can distinguish leading logarithmic, $m > n$, next-to-leading, $m = n$, and subleading, $m < n$, terms. If the perturbative prediction exponenciates, the leading terms vanish for $m > n+1$.

Up to $O(\alpha_{\rm s}^2)$ the theoretical predictions are known for all the event shape variables from numerical integration of the exact matrix element. For some variables whose perturbative expansion exponenciates, the leading and next-to-leading logarithmic contributions have been resummed. For these variables the theoretical predictions can be improved by a matching of the fixed order and the resummed calculations. The matching scheme is not unique and leads to the so called *matching ambiguities* [7].

2.1 L3 results from event shape variables

The L3 collaboration has measured $\alpha_s(M_Z)$ from event shape variables using fixed order [8] and fixed order plus resummed theoretical predictions [9]. Since the analyses are similar, we will describe in detail the most recent one [9], based on the data recorded during 1991.

The hadronic events are selected and analyzed by two independent methods. The first method is based on the energy measured in the calorimeters, while the second method uses charged tracks measured in the central tracking chamber. 240K hadronic events have been selected with an efficiency of 98.5% and an estimated contamination less than 0.2%.

The determination of α_s is based on the following event shape variables: trust T [10], normalized heavy jet mass $\rho = \mathrm{M}_\mathrm{H}^2/\mathrm{E}_\mathrm{vis}^2$ [11], total and wide jet broadening $\mathrm{B}_{\mathrm{T,W}}$ [12], energy-energy correlation *EEC* [13], and average jet multiplicity $<\mathrm{n}_{\mathrm{jet}}>$ using the $\mathrm{k}_\perp$ algorithm [14]. The analyses of refs. [8] were based on three jet multiplicity R_3, energy-energy correlation and its asymmetry, *AEEC* .

The observables have been measured using histograms with bin widths bigger than the experimental resolution. The detector effects were corrected using JETSET PS 7.3 [15] and HERWIG 5.4 [16] Monte Carlo programs including the full detector simulation. The experimental errors were estimated by varying the energy response of the calorimeters, comparing the unfolded distributions using JETSET and HERWIG and comparing the corrected distributions obtained from calorimetric clusters and charged tracks. The uncertainties are typically of a few percent per histogram bin.

The hadronization corrections are determined using several Monte Carlo programs [15–18]. These corrections change the perturbative predictions by less than 5% over a large kinematical range. The uncertainties on their parametrization have been estimated by changing the parton shower cutoff, Q_0, and the fragmentation parameters in JETSET to within their errors [19] and comparing the prediction of the different hadronization models.

In order to derive $\alpha_s(M_Z)$ from the corrected distributions, the theoretical predictions are fitted to the data within a range where the theoretical calculation is reliable and the detector corrections are small ($< 10\%$). The results are shown in table 2. The theoretical errors include the hadronization uncertainties and the scale dependence, estimated by varying the renormalization scale μ within a wide range[1)]. When comparing with fixed order plus resummed theoretical predictions, the *matching ambiguity* has been estimated by changing the matching scheme. Since scale and matching scheme dependence are related to unknown higher order terms, the biggest effect of the two has been taken as the theoretical uncertainty due to uncalculated higher order corrections. From the unweighted average of the α_s measurements obtained applying fixed order predictions we obtain $\alpha_s(M_Z) = 0.117 \pm 0.004(\mathrm{exp}) \pm 0.009(\mathrm{theor})$. The unweighted average of the measurements obtained from fits to α_s^2+ resummed calculations leads to $\alpha_s(M_Z) = 0.124 \pm 0.002(\mathrm{exp}) \pm 0.007(\mathrm{theor})$. The α_s value obtained from $<\mathrm{n}_{\mathrm{jet}}>$

[1)]For fixed order calculations, several principles have been suggested for choosing μ. The principle of minimal sensitivity [20] leads to a choice of $\mu^2/s \simeq 0.1$ for *EEC*,*AEEC* and R_3. In this case, the range of variation for μ is $0.001 \lesssim \mu^2/s \leq 1$. For fixed order plus resummed predictions there is no valid argument for the use of scales much different from the physical ones. In this case the value $\mu^2 = 1$ has been chosen and the scale has been varied between $0.5\cdot\sqrt{s}$ and $2\cdot\sqrt{s}$.

theory	variable	$\alpha_s(M_Z)$	$\Delta(\alpha_s)$(exp)	$\Delta(\alpha_s)$(theor)
α_s^2	*EEC*	0.121	0.004	0.010
α_s^2	*AEEC*	0.115	0.004	0.007
α_s^2	R_3	0.115	0.005	0.011
α_s^2+LL+NLL	$1-T$	0.123	0.003	0.008
α_s^2+LL+NLL	ρ	0.123	0.001	0.005
α_s^2+LL+NLL	B_T	0.126	0.002	0.008
α_s^2+LL+NLL	B_W	0.117	0.002	0.006
α_s^2+LL+NLL	*EEC*	0.133	0.001	0.006
α_s^2+LL+NLL	$<n_{jet}>$	0.132	0.002	0.005

Table 2: L3 measurements of α_s both for the second order QCD predictions and improved resummed predictions.

has not been included in the last average because some terms are missing in the theoretical calculations for this variable. Since the theoretical uncertainties dominate the error in these measurements, the improved predictions have significantly brought down the total error.

2.2 LEP combined results

Similar analyses have been performed by the ALEPH [21], DELPHI [22] and OPAL [23] collaborations. The reader is referred to the quoted publications for details. The single experiment averages are shown in table 3, where the errors are dominated by theoretical uncertainties in all the cases. Since these uncertainties are common to all the experiments, a conservative estimation of the LEP combined result is an unweighted average of the α_s measurements for the central value and the average error for the final uncertainty as quoted in table 3. This estimation leads to similar results as obtained with more elaborated methods [24]. On the basis of a better theoretical prediction, we choose as LEP combined result the value

$$\alpha_s(M_Z) = 0.123 \pm 0.006 \tag{3}$$

corresponding to the fit to the LEP data of the fixed order plus resummed QCD predictions.

	$O(\alpha_s^2)$	$O(\alpha_s^2)$+Res.
ALEPH	0.117 ± 0.010	0.125 ± 0.005
DELPHI	0.113 ± 0.007	0.123 ± 0.006
L3	0.117 ± 0.010	0.124 ± 0.007
OPAL	0.122 ± 0.006	0.120 ± 0.006
LEP	0.117 ± 0.008	0.123 ± 0.006

Table 3: α_s measurements of the four LEP experiments obtained by combining the results of several event shape variables using both fixed order or improved QCD predictions. The LEP average is also included.

Conclusions

The large statistics accumulated by the four LEP experiments allows accurate measurements of the QCD coupling constant α_s. From the line shape fits we have derived the LEP average value $\alpha_s(M_Z) = 0.127 \pm 0.006$, where the experimental errors are comparable to the theoretical ones due to the inclusion of 1994 data. Also from global event shape distributions we have obtained $\alpha_s(M_Z) = 0.123 \pm 0.006$, where the error is dominated by theoretical uncertainties. A significant reduction of the total error in determining α_s will require improved theoretical calculations of $R_{\rm had}$ and event shape variables.

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