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Measurement of $\alpha_s(M_{Z^0})$ with the OPAL detector at LEP*

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ABSTRACT

We present the value of $\alpha_s(M_{Z^0})$ determined from hadronic decays of the Z^0 measured with the OPAL detector at LEP. Based on the study of 13 observables, we quote $\alpha_s(M_{Z^0}) = 0.122^{+0.006}_{-0.005}$ as our final result, where the error is found to be dominated by the theoretical uncertainties. Several procedures to quote a combined result, analyses using resummed calculations, and two analyses of Z^0 line shape and hadronic τ decays using $\mathcal{O}(\alpha_s^3)$ QCD calculations, provide results which are in good agreement with the quoted final result. The good agreement among $\alpha_s(M_{Z^0})$ values determined from different observables constitutes a significant test of the consistency and validity of perturbative QCD.

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1. Introduction

Because of the large data samples at high center-of-mass energy, the e^+e^- collider LEP, at CERN, offers ideal opportunities for testing quantum chromodynamics (QCD), the theory of strong interactions, and measuring the strong coupling constant α_s. In perturbative QCD, the observables may be parametrized in powers of α_s. High center-of-mass energy, E_{cm}, implies that uncalculated higher order terms in the perturbative expansion are less important, as the principle of asymptotic freedom in QCD promises a smaller value of α_s at higher energy. QCD calculations are performed at parton level, while only the final hadrons are observed by the detector. The effects of hadronization (a process of turning partons into hadrons), being inversely proportional to E_{cm}, are generally moderate at LEP energy.

In this note, we review the already reported results[1] on the measurement of $\alpha_s(M_{Z^0})$ from an analysis of 15 different observables which are calculated from a data sample of about 127,000 hadronic Z^0 decays and 6,600 τ decays, recorded by the OPAL detector at LEP. Such a study not only checks the validity of perturbative QCD, but is also useful in predicting the outcome of and hence designing the future experiments at higher energy. Furthermore, precise and consistent knowledge of $\alpha_s(M_{Z^0})$ is a key input into the ongoing attempts[2] to use the precision LEP data for testing the proposed extensions of the Standard Model such as the Grand Unified Theories (GUTS). The multitude of different observables would also provide the unique check on the size of the uncertainty in the determination of $\alpha_s(M_{Z^0})$ due to the uncalculated higher order terms.

2. Definitions

In the following, we define the observables used for the determination of α_s:

- **Jets:** Within the framework of QCD, multihadron production in e^+e^- collisions is associated with the production of partons which subsequently materialize into collimated clusters of hadrons called jets. The most commonly used algorithm for jet counting is the JADE algorithm[3] in which the resolvable jets of particles in an event are defined by requiring that the scaled jet pair masses y_{ij} exceed a threshold value y_{cut}: $y_{ij} = M_{ij}^2/E_{vis}^2 > y_{cut}$, where M_{ij} is the jet pair mass and E_{vis} the visible energy of the event. The different approaches to combine the four momenta of the pair gives rise to different recombination schemes, namely the E_0-, P-, E-, and D- schemes.[1,4] The relative multijet production rates R_i are determined by the strong coupling constant α_s. Thus, the experimental studies of jet production rates are suitable to determine α_s.

- **C Planarity, Oblateness and Thrust:**

  C planarity,[5,6] Oblateness[7] O, and Thrust[8] T are the observables which measure the deviation of the event shape from ideal 2-jet configuration. For rather detailed MC, experimental and phenomenological study of C, O, T, and jet rates, one is referred to Ref.[9]

- **The Energy-Energy Correlations:** The energy-energy correlation, EEC, is defined[10] as an energy weighted histogram of the angle χ between all pairs of particles in a multihadronic event, summed over many events. The asymmetry of the EEC distribution,[10] $\mathrm{AEEC}(\chi) = \mathrm{EEC}(180^\circ - \chi) - \mathrm{EEC}(\chi)$, is also sensitive to α_s, and cancels out the systematic effects with symmetric dependence on χ. The natural extension of energy-energy correlations to combining the energies of triplets, instead of pairs, of particles gives rise to yet another energy correlation variable called planar triple-energy correlation, PTEC.[11]

- **Jet masses:** The particles are divided into two groups by a plane orthogonal to the thrust axis, and their invariant masses, M_H for heavier group and M_L for lighter group, are computed.The variables suggested[12] for the determination of α_s are $M_H^{(T)} = M_H$ and $M_D^T = \sqrt{M_H^2 - M_L^2}$. An alternative way is to divide the particles into all possible two groups, and choose the one which minimizes $M_H^2 - M_L^2$. This gives rise to two more variables $M_H^{(M)}$ and $M_D^{(M)}$. The M_D variables may be expected to be less sensitive to higher order effects since some cancellation between the two halves of the event will occur.

3. Determination of $\alpha_s(M_{Z^0})$

The differential cross-section for an observable X to $\mathcal{O}(\alpha_s^2)$ may be written in the form:

$$\frac{1}{\sigma_0}\frac{d\sigma}{dX} = \frac{\alpha_s(\mu)}{2\pi}A(X) + \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 [A(X)2\pi b_0 \ln(\mu^2/E_{cm}^2) + B(X)]; \tag{1}$$

where σ_0 is the leading order cross-section for e^+e^- annihilation into hadrons. Values for the coefficients A and B have been derived for a number of variables in Ref.,[13] by integrating the $\mathcal{O}(\alpha_s^2)$ matrix elements of Ref..[14] To $\mathcal{O}(\alpha_s^2)$, the strong coupling constant may be written (following the convention of Ref.[15]):

$$\alpha_s(\mu) = \frac{1}{b_0 \ln(\mu^2/\Lambda_{\overline{MS}}^2)}\left[1 - \frac{b_1 \ln(\ln(\mu^2/\Lambda_{\overline{MS}}^2))}{b_0^2 \ln(\mu^2/\Lambda_{\overline{MS}}^2)}\right]; \tag{2}$$

where

$$b_0 = (33 - 2n_f)/12\pi \quad , \quad b_1 = (153 - 19n_f)/24\pi^2 \tag{3}$$

and n_f is the number of active quark flavors, taken to be 5. The QCD parameter $\Lambda_{\overline{MS}}$ refers to the $\overline{MS}$ renormalization scheme.

$\Lambda_{\overline{MS}}$ is determined by fitting equation 1 to the measured experimental distributions corrected for the detector and hadronization effects. We determine and quote the systematic uncertainties, both experimental and theoretical, in the following way. In the absence of a commonly accepted way to handle the renormalization scale $\mu = x_\mu E_{cm}$, we adopt the following approach: $\Lambda_{\overline{MS}}$ is determined for x_μ=1, and both x_μ and $\Lambda_{\overline{MS}}$ are determined in a two parameter fit. We then determine α_s, using equation 2 with $\mu = M_{Z^0}$, from these two extreme $\Lambda_{\overline{MS}}$ values and quote the arithmetic mean as the final value of $\alpha_s(M_{Z^0})$. The symmetric difference between the mean and the two extreme values is taken to be the error on the determination of α_s due to the renormalization scale ambiguity, $\Delta\alpha_s(scale)$. In addition to the statistical error $\Delta\alpha_s$(stat), the systematic experimental error, $\Delta\alpha_s$(exp), is determined by comparing the results of three separate analyses: one which uses the charged track information only, one which uses the electromagnetic calorimeter information only, and one which uses both. The experimental distributions, before comparing to $\mathcal{O}(\alpha_s^2)$ QCD, were corrected for hadronization using the JETSET[16] Monte Carlo (MC). The error on α_s due to the uncertainty in the hadronization corrections, $\Delta\alpha_s(had)$, was estimated by comparing the results from the data corrected by JETSET and HERWIG[17] MC, or by varying the JETSET hadronization parameters within reasonable limits. The virtual cutoff mass Q_0 for a parton, where the parton stops showering, is an arbitrary parameter in the hadronization process. We repeated our analysis for Q_0 values ranging from 1 GeV to 6 GeV and the resulting variation in the final results was taken as the error due to the parton virtuality, $\Delta\alpha_s(Q_0)$. The central values of α_s were determined at $Q_0 =$

Variable	$\alpha_s(M_{Z^0})$	$\Delta\alpha_s$(stat)	Systematic uncertainties				$\Delta\alpha_s$(tot)
			$\Delta\alpha_s$(exp)	$\Delta\alpha_s$(scale)	$\Delta\alpha_s(Q_0)$	$\Delta\alpha_s$(had)	
C	0.128	±0.001	±0.001	±0.016	±0.001	±0.001	±0.016
O	0.122	±0.001	±0.002	±0.001	$+0.046$	±0.008	$^{+0.047}_{-0.008}$
T	0.129	±0.001	±0.003	±0.016	-0.006	±0.002	±0.017
$M_H^{(T)}$	0.129	±0.001	±0.001	±0.008	$+0.002$	±0.006	±0.010
$M_D^{(T)}$	0.120	±0.001	$^{+0.000}_{-0.004}$	±0.003	$+0.009$	±0.008	$^{+0.013}_{-0.009}$
$M_H^{(M)}$	0.128	±0.001	$^{+0.000}_{-0.002}$	±0.008	±0.001	±0.007	±0.010
$M_D^{(M)}$	0.119	±0.001	±0.001	±0.002	$+0.011$	±0.006	$^{+0.012}_{-0.007}$
$D_2(y)$ E0	0.120	±0.001	±0.002	±0.008	$+0.002$	±0.001	$^{+0.009}_{-0.008}$
$D_2(y)$ D	0.125	±0.001	±0.004	±0.006	$+0.004$	±0.001	$^{+0.008}_{-0.007}$
$D_2(y)$ p	0.122	±0.001	±0.001	±0.003	$+0.008$	±0.001	$^{+0.009}_{-0.004}$
$D_2(y)$ E	0.128	±0.001	±0.003	±0.016	±0.001	±0.003	±0.016
Σ_{AEEC}	0.118	±0.001	±0.003	-0.004	$+0.009$	±0.002	$^{+0.009}_{-0.005}$
PTEC	0.112	±0.001	$\pm0.009^*$	±0.002	$+0.004$	±0.001	$\pm$ 0.010

Table 1: Values of $\alpha_s(M_{Z^0})$ obtained from fitting $\mathcal{O}(\alpha_s^2)$ QCD to the OPAL data.

1 GeV. All these errors, added in quadrature, yield the overall error, $\Delta\alpha_s$(tot). The values of $\alpha_s(M_{Z^0})$ determined from various observables, together with errors from different sources, are presented in Table 1.

The so called resummed calculations, including the full $\mathcal{O}(\alpha_s^2)$ terms together with the leading and next-to-leading log terms for all higher orders, have recently been made available for thrust[18] and jet masses.[19] Fig. 1 demonstrates that the resummed calculations, including next-to-leading logarithmic approximation (NLLA), provide a better description of the data at large T and low mass values. We have also found that the scale dependence of the fitted values of $\Lambda_{\overline{MS}}$, determined from the fits of resummed calculations to the data, is significantly reduced.

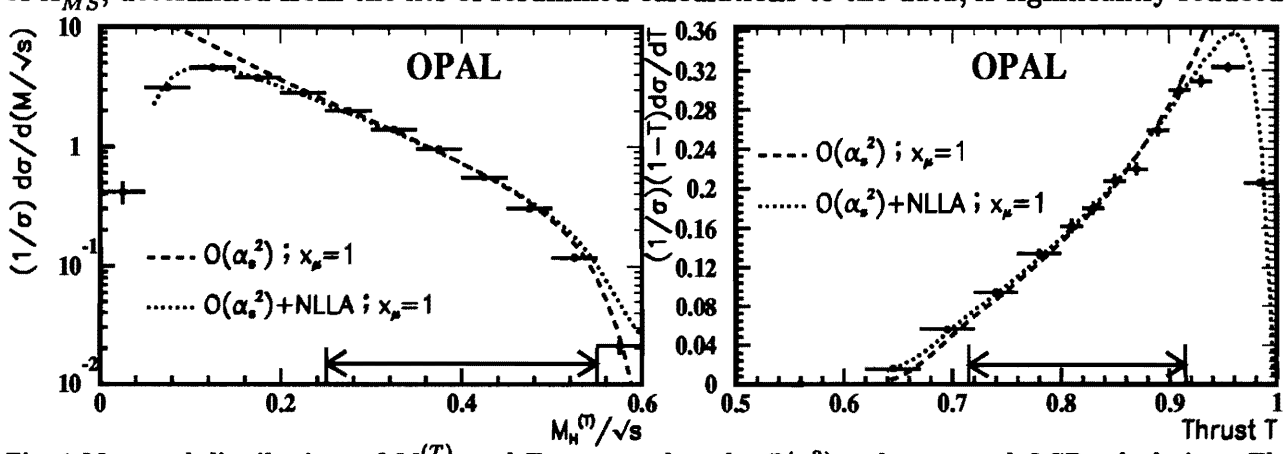

Fig. 1 Measured distributions of $M_H^{(T)}$ and T, compared to the $\mathcal{O}(\alpha_s^2)$ and resummed QCD calculations. The arrows show the ranges over which the fits were performed.

4. Summary of Results

The results on $\alpha_s(M_{Z^0})$ from different observables, with experimental uncertainties only, are displayed in Fig. 2. The difference between the $\alpha_s(M_{Z^0})$ values can be explained by including the theoretical uncertainties, as shown in Fig. 3. An average value of $\alpha_s(M_{Z^0})$ is obtained from

the individual values listed in Table 1, using the equation $\overline{\alpha_s} = \sum_i w_i \alpha_s^{(i)} / \sum_i w_i$; where the weight $w_i = (\frac{x_i + y_i}{2})^{-2}$, and $(^{+x_i}_{-y_i})$ are $\Delta\alpha_s(\mathrm{tot})$ listed in the last column of Table 1. The error on $\overline{\alpha_s}$ was estimated as explained below. For example, $\overline{\alpha_s}$ was computed first from the set of $\alpha_s^{(i)}$ values corresponding to $x_\mu = 1$ and then from the set of $\alpha_s^{(i)}$ values corresponding to the best fit value of x_μ; and the difference between the two was taken as the scale error. The same procedure was repeated for all the other sources of uncertainty, and the different errors thus obtained were added in quadrature to give the overall error on $\overline{\alpha_s}$. This procedure takes into account the correlation between different systematic uncertainties. The final results of $\alpha_s(M_{Z^0})$ are displayed in Fig. 3, where the top shaded band corresponds to $\overline{\alpha_s} = 0.122^{+0.006}_{-0.005}$, determined as explained above. The dependence of $\alpha_s(M_{Z^0})$ and χ^2 per degree of freedom of the fits on the renormalization scale factor x_μ is presented in Fig. 4.

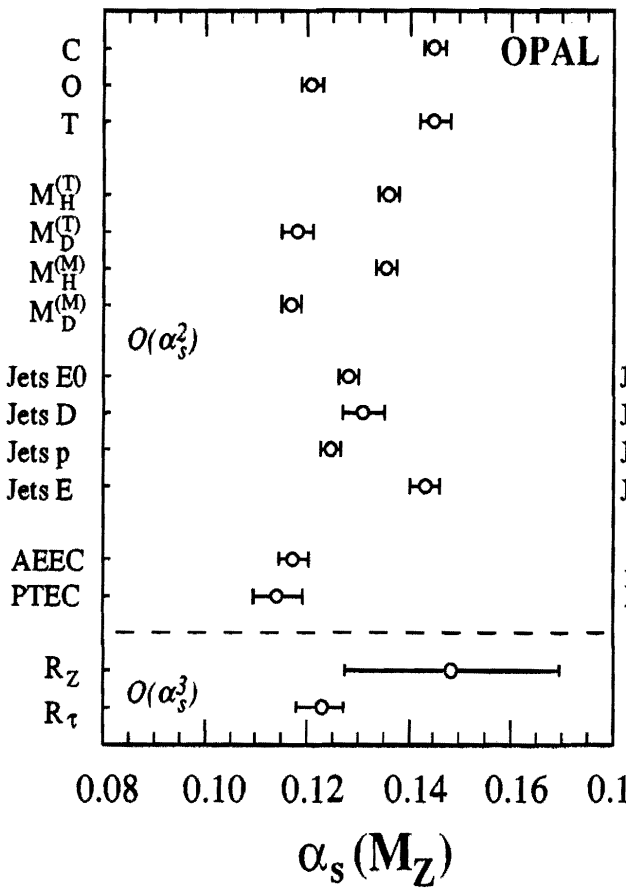

Fig. 2 Values of $\alpha_s(M_{Z^0})$ at $\mu = E_{cm}$, with statistical and experimental systematic errors only.

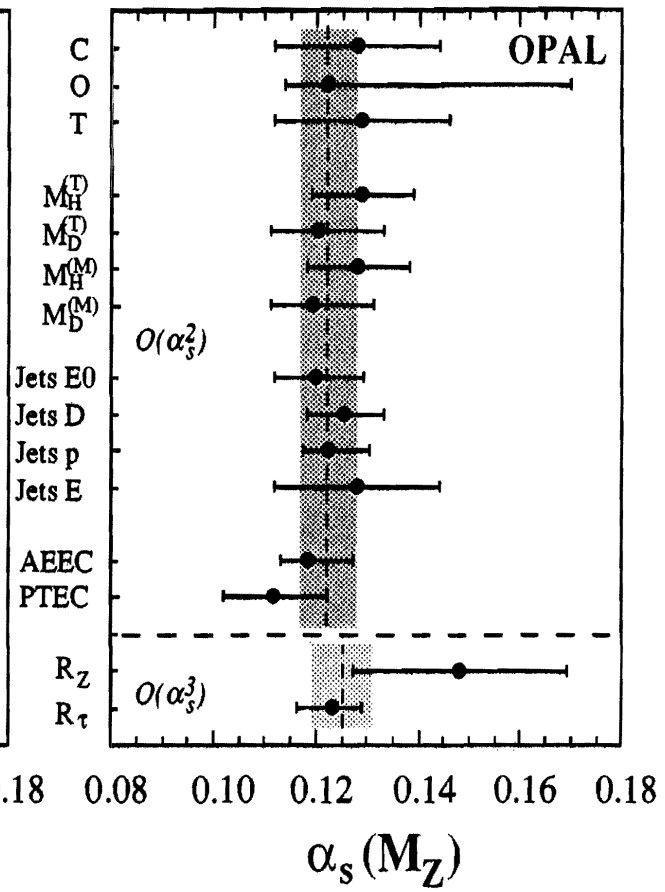

Fig. 3 The final results of $\alpha_s(M_{Z^0})$; all theoretical and experimental errors included.

The following independent checks were made on our method to determine the quoted value of $\alpha_s(M_{Z^0})$ from $\mathcal{O}(\alpha_s^2)$ QCD. We performed combined fits to subsets of the measured distributions, requiring that all observables are described by one common value of $\Lambda_{\overline{MS}}$ but allowing each observable to adjust to an individual renormalization scale. Following this procedure, we obtained $\alpha_s(M_{Z^0}) = 0.118^{+0.007}_{-0.003}$. We repeated our analysis, using resummed calculations, and obtained $\alpha_s(M_{Z^0}) = 0.122^{+0.003}_{-0.006}$. Two other observables, τ lepton branching ratios and the hadronic Z^0 line shape for which the QCD corrections are known[20,21] to $\mathcal{O}(\alpha_s^3)$, yielded $\alpha_s(M_{Z^0}) = 0.123^{+0.006}_{-0.007}$ and $\alpha_s(M_{Z^0}) = 0.148 \pm 0.021$ respectively, resulting in a weighted average of $\alpha_s(M_{Z^0}) = 0.125 \pm 0.006$ presented as the bottom shaded band in Fig. 3. The value of α_s from τ decays was originally determined to be $\alpha_s(M_\tau) = 0.389^{+0.073}_{-0.075}$, and was then extrapolated

from M_τ to M_{Z^0}. The uncertainties due to the extrapolation procedure and the renormalization scale ambiguity are included in the quoted error on $\alpha_s(M_{Z^0})$ from τ decays. These results from alternative methods are in good agreement with our quoted result of $\alpha_s(M_{Z^0}) = 0.122^{+0.006}_{-0.005}$.

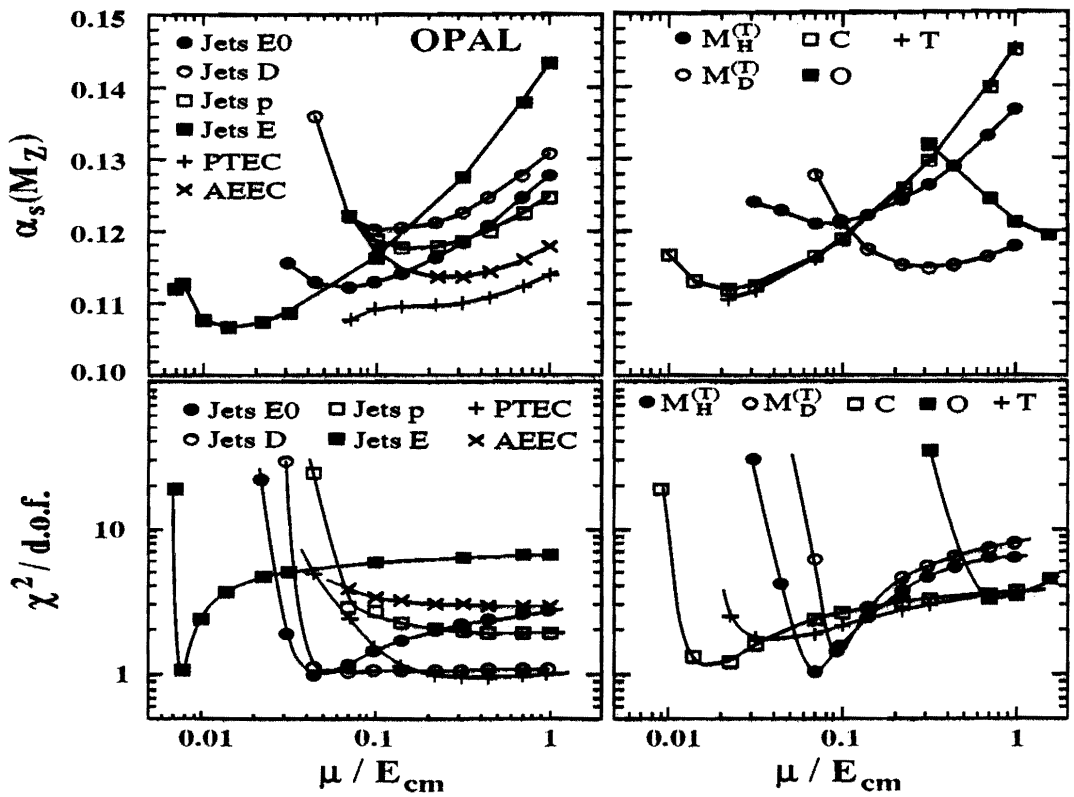

Fig. 4 $\alpha_s(M_{Z^0})$ and χ^2/d.o.f., as a function of the scale factor $x_\mu = \mu/E_{cm}$.

5. Conclusions

We have determined, from the analysis of 13 different observables in the hadronic Z^0 decays, the value of the strong coupling constant $\alpha_s(M_{Z^0}) = 0.122^{+0.006}_{-0.005}$; where the errors include the experimental and theoretical uncertainties. In order to check the validity and consistency of our procedure to obtain the quoted average result, we determined $\alpha_s(M_{Z^0})$ from a combined fit of all the observables. In addition, the values of $\alpha_s(M_{Z^0})$ were also determined using the resummed calculations as well as from two analyses of observables calculated in complete $\mathcal{O}(\alpha_s^3)$ QCD. The results from these alternative methods were found to be in good agreement with the quoted number. The quoted result is in good agreement with the theoretical prediction[22] of $\alpha_s(M_{Z^0}) = 0.11 \pm 0.01$ based on the extrapolation of the experimental results at lower energy. This is also in good agreement with the predictions from other lower energy measurements[23,24] and with the previous results from LEP and SLC.[25,26] The good agreement of $\alpha_s(M_{Z^0})$ values, determined from different observables, with each other and with the theoretical predictions based on the lower energy experiments constitute a significant test of the consistency and validity of perturbative QCD.

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