Measurement of α_s from the Structure of Particle Clusters Produced in Hadronic Z Decays

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Abstract

Using 106000 hadronic events obtained with the ALEPH detector at LEP at energies close to the Z resonance peak, the strong coupling constant α_s is measured by an analysis of energy-energy correlations (EEC) and the global event shape variables Thrust, C-parameter and Oblateness. It is shown that the theoretical uncertainties can be significantly reduced if the final state particles are first combined in clusters using a minimum scaled invariant mass cut, y_{cut}, before these variables are computed. The combined result from all shape variables of pre-clustered events is $\alpha_s(M_Z^2) = 0.117 \pm 0.005$ for a renormalization scale $\mu = M_Z/2$. For μ values between M_Z and the b-quark mass, the result changes by $^{+0.006}_{-0.009}$.

1. Introduction

The determination of the strong coupling constant $\alpha_s(M_Z^2)$from the structure of hadronic events at LEP energies generally requires direct comparison of data with the structure of partonic final states as calculated in second order perturbative Quantum Chromo-Dynamics (QCD). This paper shows that the theoretical uncertainties associated with this comparison can be reduced by considering variables which are not computed for the single particle momenta of the final state (as done in our earlier work [1]) but for clusters of neighbouring particles in phase space. Naively, these clusters should more closely resemble the structure of a purely partonic final state as accessible in finite order perturbation theory.

2. Analysis

2.1 Event Selection and Data Correction

The ALEPH detector, which provides both tracking information and calorimetry over almost the full solid angle, is described in detail in reference [2]. The analysis is based on 106000 hadronic events at center-of-mass energies in the range 91.0 GeV $\leq E_{CM} \leq$ 91.5 GeV. Further details may be found in [3]. The experimental distributions are constructed using only charged particle information and are corrected for detector effects as described in [1,3,4].

2.2. Definition of Clusters

Before computing event shape variables the final state particles are combined in clusters, with every particle initially representing a cluster. For each pair (i,j) of clusters a scaled mass y_{ij} is defined according to the JADE metric [3,5]. If the pair with the smallest y_{ij} fulfills $y_{ij} < y_{cut}$, the corresponding clusters are combined according to the E_0 recombination scheme [6]. The E_0 scheme was preferred over alternative schemes [6] because it was found to have consistently the smallest sensitivity to fragmentation processes.

2.3. Second Order QCD Predictions

As the basic theoretical ingredient the second order QCD matrix elements as calculated by Ellis, Ross and Terrano (ERT) [7] are used. These can be integrated to predict the distribution for a given event shape variable, X, as described for example in reference [6],

$$\frac{1}{\sigma_0}\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \frac{\alpha_s(\mu^2)}{2\pi}A(X) + \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^2 \left[A(X)\cdot 2\pi b_0 \log\left(\frac{\mu^2}{s}\right) + B(X)\right] + \mathcal{O}\left(\alpha_s^3\right) \qquad (1)$$

with $b_0 = (33 - 2n_f)/12\pi$. Here, $n_f(=5)$ denotes the number of active flavours and $\sqrt{s}$ is the center-of-mass energy. The functions A and B are specific to the particular event shape variable, contain the full information of the second order matrix elements, and, in the case of shape variables for pre-clustered events, they also depend on the value chosen for y_{cut}. The parameter μ denotes the renormalization scale used for the calculation. An example of the result is shown in Figure 1 for the functions $A(\cos\chi, y_{cut})$, $B(\cos\chi, y_{cut})$ for $\sin^2\chi \cdot \mathrm{EEC}(\cos\chi)$, where $\mathrm{EEC}(\chi)$ is the energy-energy correlation.

2.4. Choice of Renormalization Scale

Comparing equation (1) to the data one can now determine $\alpha_s(\mu^2)$ for any choice of the renormalization scale μ and then translate it into $\alpha_s(M_Z^2)$ using the two-loop

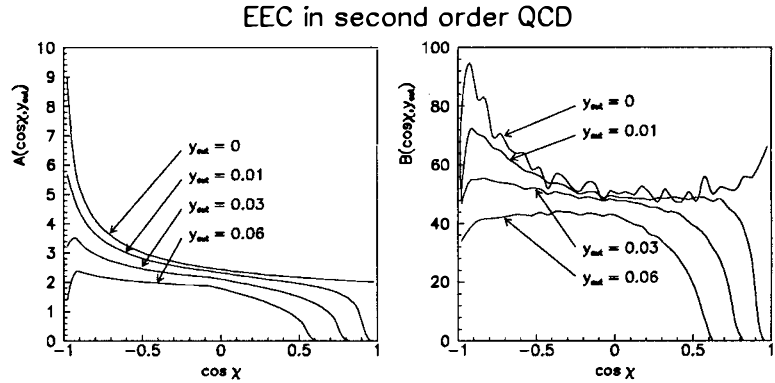

Figure 1: *Second order QCD prediction for the functions A, B of the EEC after pre-clustering(see text). The fluctuations are due to the finite statistics of the Monte Carlo integration.*

expression for the running coupling constant [6]. The choice of μ enters the result to third order, reflecting our ignorance of higher order corrections. Since α_s is relatively large this third order effect still has a significant impact on the numerical results and constitutes a source of theoretical uncertainty. Theoretical prescriptions to reduce the sensitivity to the scale by choosing appropriate and typically very small values for μ [8] cannot guarantee that third order terms become small. Therefore, we prefer to determine the value $\alpha_s(M_Z^2)$ using $\mu = M_Z$ and to give an explicit parameterization of the shifts induced if the scale is varied. The impact of higher order contributions is estimated by means of parton shower Monte Carlo models based on the leading-logarithm approximation. In addition the renormalization scale is allowed to vary between M_Z (which is taken to be 91.2 GeV) and the b-quark mass.

2.5. Correction for Fragmentation and Systematic Errors

The methods used to extract $\alpha_s(M_Z^2)$ from distributions of event shape variables and to estimate the theoretical uncertainties are described in detail in references [1] and [3]. The fit results for $\alpha_s(M_Z^2)$ are corrected for the effects of higher order perturbative effects and for the effects of hadronization (both together in the following being referred to as effects of *fragmentation*) using the Lund second order matrix element (ME) model (JETSET 7.2) [9]. The correction was performed using a transition probability matrix (from parton to hadronic states) or a simple ratio (in the case of the EEC).

In all cases the magnitude of the correction enters the theoretical error estimate. One should therefore try to find variables where the corrections are very small, i.e. typically less than 10%.

For the study of systematic errors inherent in the correction based on the ME model the transition from the parton level to the hadron level was studied in addition for the Lund ME model and for the Parton Shower model [10]. In the case of the Parton Shower model, two calculations were done, differing in the minimum virtuality of the partons. In one case, the virtuality was set so that the average number of partons was the same as in the ME model. In the second case, the average number of partons was four. The theoretical error is defined to be the maximum deviation of the corrected value of $\alpha_s(M_Z^2)$ from the results using any of these alternative response matrices.

In order to separate the effects of perturbative higher order effects from the non-perturbative final hadronization process, the transition of the final shower states into hadrons was also studied in the LUND and HERWIG [11] PS models which are both based on the leading-logarithm approximation but employ very different hadronization schemes.

3. Determination of $\alpha_s(M_Z^2)$ from Energy-Energy Correlation of Clusters

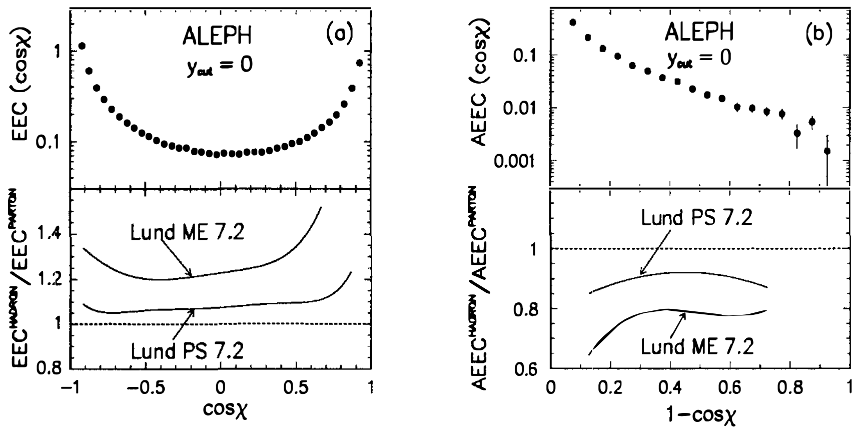

Figure 2: *Measured EEC (a) and AEEC (b) distributions together with the ratio of distributions on hadron and parton level, as derived from the Lund ME model and the Lund PS model.*

The experimental result for the EEC and AEEC distributions are shown in figure 2 together with the prediction of the hadron and parton level distributions from model calculations. In the Lund PS model these ratios deviate from 1 by at least $5 - 10\%$, indicating a moderate sensitivity of the EEC and AEEC distributions to hadronization effects. The ratios derived from the Lund ME model, however, deviate from 1 by more than 20%, suggesting that higher order perturbative corrections are very important even at LEP energies. Therefore one expects relatively large theoretical uncertainties for α_s if derived from these distributions.

The systematic distortions of the EEC distribution vanish to a large extent if one considers pre-clustered events (CEEC variable). This is shown in figure 3 where the measured CEEC distribution is displayed together with the ratio of hadron and parton level distributions from model calculations for two values of y_{cut}. The CEEC distribution changes in shape with varying y_{cut}. This is quantitatively predicted by the second order QCD calculation which is shown in figure 3 after correction using the Lund ME model.

Although the residual fragmentation effects for the CEEC are small they are slightly asymmetric in $\cos\chi$. The range $-0.5 < \cos\chi < 0$ has consistently small and constant distortions and is therefore chosen to fit $\alpha_s(M_Z^2)$. The change of the results when moving to a symmetric range $-0.25 < \cos\chi < 0.25$ has been included in the theoretical error. The results from fits of the second order QCD prediction to the data are presented in figure 4 as function of y_{cut} before correction for residual fragmentation effects (figure 4(a)), and after correction with theoretical uncertainties for a fixed scale $\mu = M_Z/2$

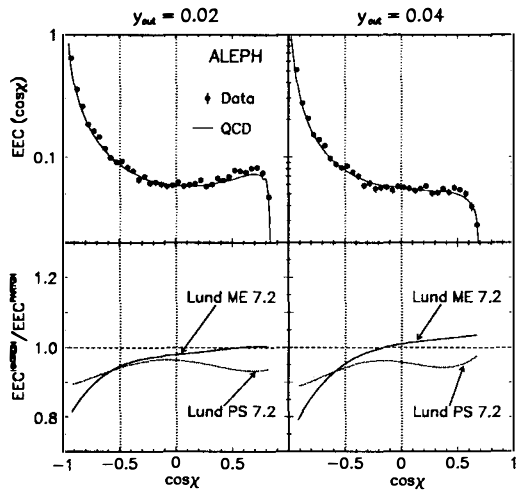

Figure 3: *Measured CEEC distribution together with the ratio of CEEC distributions on hadron and parton level from model calculations for two values of y_{cut}. Also shown are second order QCD predictions for $\alpha_s(M_Z^2) = 0.118$ and $\mu = M_Z/2$ after correction for fragmentation effects.*

included in the errors.

Finally $y_{cut} = 0.02$ was chosen. Comparison of the uncorrected value of α_s to the value after correction for hadronization and higher order effects and to the value after correction for hadronization alone [3] gives:

$$\alpha_s(M_Z^2)\,|_{\rm CEEC} = 0.118 \pm 0.002 \pm 0.001 \pm 0.005 \;\text{ for }\; \mu = \frac{M_Z}{2}\;,$$

the errors denoting the statistical error, the experimental systematic error, and the theoretical uncertainties defined in section 2.5. Varying μ between M_Z and the b-quark mass changes the result in addition by $^{+0.006}_{-0.010}$. The dependence of the uncorrected result on the choice of $f = \mu^2/M_Z^2$ was found to be $\alpha_s(M_Z^2, f) - \alpha_s(M_Z^2, f = 0.25) = 0.00371\ln(4f) + 0.00034\ln^2(4f)$ for $f \geq 0.002$.

The analysis was repeated using the covariant E recombination scheme [6] together with the JADE metric. In the E0 scheme, the Lund ME correction is 3% and in the E scheme it is 6%, but the corrected result for α_s agrees within 1%.

4. Influence of Clustering on Global Event Shape Variables

In this section the variables thrust, T, oblateness, O, and the C-parameter, as defined in reference [6], are reconsidered in the context of pre-clustered events.

The fits of $\alpha_s(M_Z^2)$ were performed in intervals contained in those chosen in reference [1]. In addition it was required that the ranges are well inside the kinematic boundaries imposed on the event shape distribution due to pre-clustering up to $y_{cut} = 0.06$. The results of the fits are displayed in figure 4(c,d).

The smallest value of y_{cut} at which all three variables start to give stable values for $\alpha_s(M_Z^2)$ is 0.03. The results are shown in table 1 and are not only consistent with

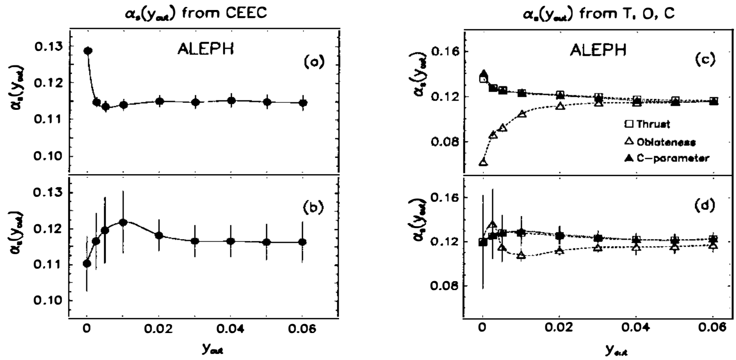

Figure 4: *Results for $\alpha_s(M_Z^2)$ as function of y_{cut} from QCD fits to event shape distributions before correction for fragmentation effects (a,c), and after correction with estimated theoretical uncertainties for a fixed scale $\mu = M_Z/2$ included in the errors (b,d).*

Distribution	$\alpha_s(M_Z^2)$, $f = 0.25$	c_1	c_2	f_{min}
CEEC	$0.118 \pm 0.002 \pm 0.005$	0.00371	0.00034	0.002
T	$0.123 \pm 0.004 \pm 0.006$	0.00449	0.00035	0.001
C	$0.124 \pm 0.004 \pm 0.006$	0.00427	0.00037	0.001
O	$0.115 \pm 0.004 \pm 0.005$	0.00375	0.00035	0.001

Table 1: Results for $\alpha_s(M_Z^2)$ with combined experimental errors and errors due to model corrections together with coefficients of a parameterization for the change $\alpha_s(f) - \alpha_s(f = 0.25) = c_1 \cdot \ln(4f) + c_2 \cdot \ln^2(4f)$. The last column gives a lower limit for the scale parameter f where the parameterization is still within the statistical error of the fitted value.

each other but also very close to earlier measurements using y_3 [1,12,13] and EEC or AEEC [14]. The fragmentation effects for all pre-clustered variables are small and the theoretical uncertainties are dominated by the scale dependences.

5. Combination of the Results

In order to derive a final result from the numbers in table 1, the correlations between the statistical and between the theoretical errors of the various measurements were determined [3]. The combined result for $\mu = M_Z/2$ is

$$\alpha_s(M_Z^2) = 0.117 \pm 0.005,$$

where the error contains both experimental and theoretical errors. The combined scale dependence is then $\alpha_s(M_Z^2, f) - \alpha_s(M_Z^2, f = 0.25) = 0.00356 \ln(4f) + 0.00035 \ln^2(4f)$ which leads to a variation of ${}^{+0.006}_{-0.009}$ for scales ranging from the b-quark mass up to M_Z.

6. Conclusions

The strong coupling constant has been measured from an analysis of the structure of pre-clustered events. Energy-energy correlation, Thrust, C-parameter and Oblateness all yield consistent values for $\alpha_s(M_Z^2)$ with moderate theoretical errors. The combined result of all four variables is $\alpha_s(M_Z^2) = 0.117 \pm 0.005$ for $\mu = M_Z/2$, where renormalization scales varying between the b-quark mass and M_Z lead to changes of ${}^{+0.006}_{-0.009}$. The combined value is almost identical to that obtained from CEEC alone, indicating that the results from the different event-shape variables have strongly correlated theoretical uncertainties. The final value is also in good agreement with our earlier measurement from y_3, $\alpha_s(M_Z^2) = 0.121 \pm 0.002(stat.) \pm 0.003(syst.) \pm 0.007(theory)^{+0.007}_{-0.012}(scale)$ [1].

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