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We present a study of energy–energy correlations based on 83 000 hadronic Z^0 decays. From this data we determine the strong coupling constant α_s to second order QCD:

$$\alpha_s(91.2\ \mathrm{GeV}) = 0.121 \pm 0.004(\mathrm{exp.}) \pm 0.002(\mathrm{hadr.})^{+0.009}_{-0.006}(\mathrm{scale}) \pm 0.006(\mathrm{theor.})$$

from the energy–energy correlation and

$$\alpha_s(91.2\ \mathrm{GeV}) = 0.115 \pm 0.004(\mathrm{exp.})^{+0.007}_{-0.004}(\mathrm{hadr.})^{+0.002}_{-0.000}(\mathrm{scale})^{+0.003}_{-0.005}(\mathrm{theor.})$$

from its asymmetry using a renormalization scale $\mu^2 = 0.1\ s$. The first error (exp.) is the systematic experimental uncertainty, the statistical error is negligible. The other errors are due to hadronization (hadr.), renormalization scale (scale) uncertainties, and differences between the calculated second order corrections (theor.).

1. Introduction

The energy–energy correlation (EEC) and its asymmetry (AEEC) were introduced by Basham et al. [1] as observables well suited for a determination of the strong coupling constant α_s. The EEC can be defined as a histogram of all angles between any particles i, j in hadronic events weighted with the product of their energies, and averaged over N events:

$$\mathrm{EEC}(\chi_{\mathrm{bin}}) = \frac{1}{\Delta_{\mathrm{bin}} N} \sum_{\mathrm{events}}^{N} \sum_{i,j} \frac{E_i E_j}{E_{\mathrm{vis}}^2} \delta_{\mathrm{bin}}(\chi_{\mathrm{bin}} - \chi_{ij}) . \tag{1}$$

$\delta_{\mathrm{bin}}(\chi_{\mathrm{bin}} - \chi_{ij})$ is 1 for angles χ_{ij} inside the bin around

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χ_{bin} and 0 otherwise. Δ_{bin} denotes the bin width. $E_{vis} = \sum_i E_i$ is the total energy of the event. For 2-jet events most angles are close to 0° or 180°, while events with hard gluon radiation contribute to the central region. Hence the integral of the EEC distribution in a range of ≈30° to ≈150° is a measure of the strong coupling constant. Events with hard gluon radiation contribute asymmetrically to the EEC distribution such that the asymmetry in the energy–energy correlation

$$\mathrm{AEEC}(\chi) = \mathrm{EEC}(180° - \chi) - \mathrm{EEC}(\chi)$$

is positive for $\chi > 10°$. Also the integral of the AEEC distribution in the range of ≈30° to 90° is a measure of α_s.

We report here on measurements of the energy–energy correlation and its asymmetry at the Z^0 resonance using the L3 detector at LEP. Comparing our data to the predictions of perturbative QCD in second order we derive values for $\Lambda_{\overline{MS}}^{(5)}$ and α_s at $\sqrt{s} = M_Z$. These results are compared to the α_s value which we measured from the fraction of 3-jet events [2]. In order to study the energy dependence of the strong coupling constant we compare α_s measurements from AEEC obtained by several experiments at different center of mass energies to the QCD calculations.

2. The L3 detector

The L3 detector covers 99% of 4π [3]. The detector consists of a central tracking chamber, a high resolution electromagnetic calorimeter composed of bismuth germanium oxide crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and an accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction.

For the present analysis, we used the data collected in the following ranges of polar angles:
- for the electromagnetic calorimeter, $42.4° < \theta < 137.6°$,
- for the hadron calorimeter, $5° < \theta < 175°$.

The energy–energy correlation measurements are based on calorimetric clusters. These are constructed by grouping together neighbouring calorimeter hits, which are likely to be produced by the same particle. Only clusters with a total energy above 100 MeV are used. The algorithm normally reconstructs one cluster for each particle produced near the interaction point. For a cluster energy of 2 GeV the angular resolution is approximately 0.4° for isolated electrons and photons and better than 3° for hadrons.

3. Selection of hadronic events

Events collected at a center of mass energy of $\sqrt{s} = 91.2$ GeV from the 1990 LEP running period are used for this analysis.

The primary trigger for hadronic events requires a total energy of about 15 GeV in the calorimeters. This trigger is in local OR with a trigger using the barrel scintillation counters and with a charged track trigger. The combined trigger efficiency for selected hadronic events exceeds 99.95%.

The selection of $e^+e^- \to$ hadrons events is based on the energy measured in the electromagnetic detector and in the hadron calorimeter. Events are accepted if

$$0.6 < \frac{E_{vis}}{\sqrt{s}} < 1.4 ,$$

$$\frac{|E_\parallel|}{E_{vis}} < 0.40 , \quad \frac{E_\perp}{E_{vis}} < 0.40 ,$$

$$N_{cluster} > 12 ,$$

where E_{vis} is the total energy observed in the detector, $E_\parallel$ is the energy imbalance along the beam direction, and $E_\perp$ is the transverse energy imbalance. The cut on the number of clusters rejects low multiplicity events, for example $\tau^+\tau^-$ final states.

In total 83 000 events were selected. Applying the same cuts to simulated events, we find that 97% of the hadronic decays from the Z^0 are accepted. The contamination from final states e^+e^-, $\tau^+\tau^-$ and e^+e^- + hadrons in the event sample is below 0.2% and can be neglected.

Monte Carlo events were generated by the parton shower program JETSET 7.2 [4] and passed through the L3 detector simulation [5] which includes the effects of energy loss, multiple scattering, interactions and decays in the detector materials and beam pipe.

4. Measurements of energy–energy correlations and unfolding

Fig. 1 shows the measured EEC and AEEC distributions with a bin width of 1.8° together with the predictions of the JETSET parton shower MC. The small disagreement between data and Monte Carlo in both distributions can only be removed if Λ_{LL} in the parton shower is chosen larger for the EEC distribution than for the AEEC distribution.

For the comparison of the measured distributions to the predictions of perturbative QCD we select the angular ranges

$$57.6° \leqslant \chi \leqslant 138.6° \ (\mathrm{EEC}) ,$$

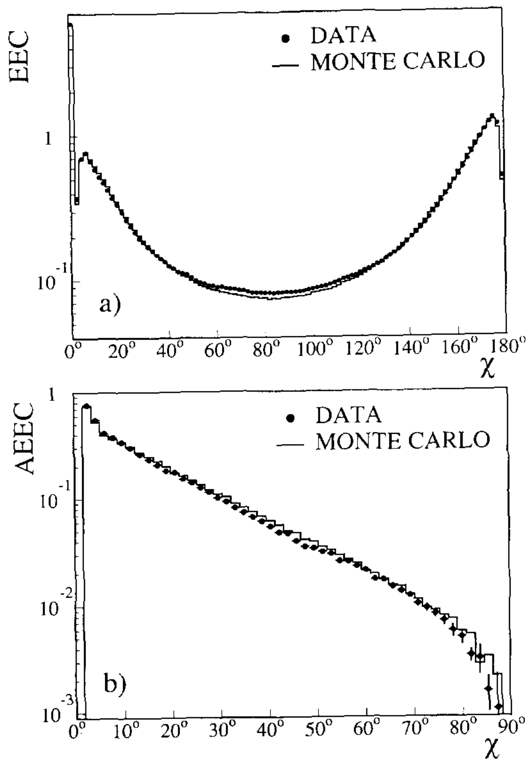

Fig. 1. Measured EEC (a) and AEEC (b) distributions with their statistical errors compared to the Monte Carlo simulation. The first bin in the EEC distribution corresponds to the case that clusters i and j are identical in eq. (1), i.e. $i=j$ and $\chi_{ij}=0$. The content of the second bin is small since the smallest resolvable angle between two clusters exceeds the bin size of 1.8°. The first bin (negative) and the last bin (very small) of the AEEC distribution are not shown.

$$36.0° \leqslant \chi \leqslant 90.0° \ (\mathrm{AEEC}) . \quad (2)$$

For these angles the ratio of the second order QCD calculation [6] and the predictions of the parton shower MC including hadronization is constant within about 5%. Outside the chosen angular ranges the second order calculations and parton shower predictions disagree, which is probably due to higher order contributions and/or fragmentation effects. The χ interval is asymmetric for the EEC with respect to $\chi=90°$.

To be able to study the dependence of our results on the angular interval we present the distributions for an enlarged angular range (46.8°–149.4° and 25.2°–90.0°).

To compare EEC and AEEC to the QCD calculations we correct our measured EEC distribution for (a) detector effects, acceptance and resolution, (b) hadronization and decays and (c) initial and final state photon radiation. We apply bin-by-bin correction factors:

$$\mathrm{EEC}^{i}_{\mathrm{corr}} = c^{i}_{\mathrm{det}} c^{i}_{\mathrm{hadr}} c^{i}_{\mathrm{rad}} \mathrm{EEC}^{i}_{\mathrm{meas}} ,$$

where i denotes the bin number. The unfolded AEEC distribution is then calculated from the corrected EEC. We choose a bind width of 5.4° (3×1.8°) which exceeds the experimental resolution by a factor or two.

Fig. 2a shows the correction factor c_{det} for detector effects in the angular range 25.2°–154.8°. It has been calculated from

$$c^{i}_{\mathrm{det}} = \mathrm{EEC}^{i}_{\mathrm{hadr}} / \mathrm{EEC}^{i}_{\mathrm{det}} ,$$

where $\mathrm{EEC}^{i}_{\mathrm{det}}$ stands for the JETSET Monte Carlo calculations with detector simulation and $\mathrm{EEC}^{i}_{\mathrm{hadr}}$ denotes the MC predictions at the hadron level. The uncertainty in c^{i}_{det} was studied by comparing EEC and AEEC distributions for data and MC in different detector regions and by changing the energy response in different detector components in the Monte Carlo simulation by up to 10%. Larger variations are incompatible with the measured energy distributions in the calorimeters. We find a systematic uncertainty in c^{i}_{det} of 4%. The measured EEC values, corrected for detector effects, are shown in table 1 in the angular interval 25.2°–154.8°.

To study the effects of hadronization and decays we use the JETSET parton shower MC program with

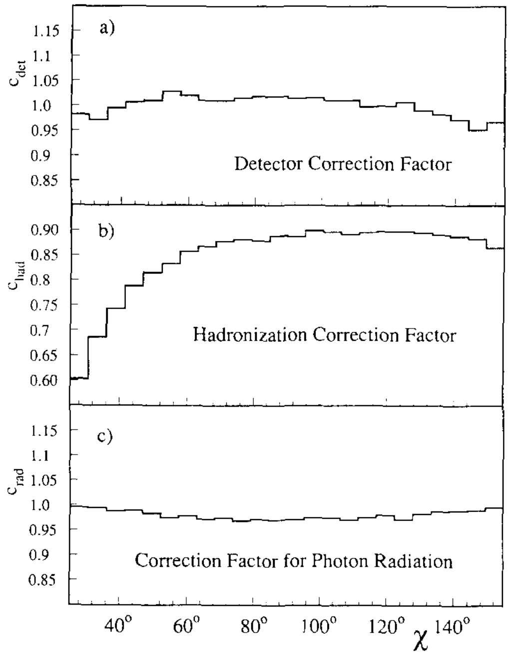

Fig. 2. Correction factors c^i_{det} for detector effects (a), c^i_{hadr} for hadronization (b), and c^i_{rad} for photon radiation (c). Systematic uncertainties are not shown.

string fragmentation. For b and c quarks we use the Peterson fragmentation function [7] with the parameters $\epsilon_c=0.07$ and $\epsilon_b=0.015$ [8]. The value of (i) the parton shower scale Λ_{LL}, (ii) the fragmentation parameter σ_q, which controls the transverse momentum of the hadrons, and (iii) the parameter b influencing the longitudinal momentum spectrum, were determined from a fit to our data. All other JETSET parameters were kept at their default values. First we have unfolded [9] the three measured distributions

(a) differential 3-jet fraction df_3/dy [10,2],

(b) minor (narrow side) [11] and

(c) fourth Fox–Wolfram moment [12]

for detector effects. Then we have fitted the three parameters Λ_{LL}, σ_q and b for various values of the parton shower termination parameter Q_0^2 [4]. The fitted parameter values are shown in table 2 with their systematic errors, which are due to uncertainties in the unfolding. For the determination of c^i_{det} and in fig. 1 the parameter set for $Q_0^2=1$ GeV^2 (JETSET default) has been used. Table 2 shows also the average number of partons produced as a function of Q_0^2.

Table 1
Measured EEC distribution corrected for detector effects. The relative statistical errors are below or equal to 0.6% for each bin. The overall systematic error due to uncertainties in the detector correction is 4%.

χ	EEC(χ)
25.2°–30.6°	0.196
30.6°–36.0°	0.157
36.0°–41.4°	0.134
41.4°–46.8°	0.117
46.8°–52.2°	0.107
52.2°–57.6°	0.098
57.6°–63.0°	0.092
63.0°–68.4°	0.088
68.4°–73.8°	0.085
73.8°–79.2°	0.083
79.2°–84.6°	0.083
84.6°–90.0°	0.083
90.0°–95.4°	0.083
95.4°–100.8°	0.086
100.8°–106.2°	0.090
106.2°–111.6°	0.096
111.6°–117.0°	0.102
117.0°–122.4°	0.111
122.4°–127.8°	0.123
127.8°–133.2°	0.138
133.2°–138.6°	0.159
138.6°–144.0°	0.190
144.0°–149.4°	0.233
149.4°–154.8°	0.303

Since we want to compare our data to the second order QCD calculations with a maximum of four partons we calculate the hadronization correction for the case $Q_0^2=16$ GeV^2, for which on average four partons are produced:

$$c^i_{hadr}=EEC^i_{part}/EEC^i_{hadr}\,.$$

EEC^i_{part} is the Monte Carlo predictions for partons and EEC^i_{hadr} denotes the EEC calculated for hadrons after fragmentation and decays. Fig. 2b shows the result. To estimate the uncertainty we recalculate the hadronization correction for $Q_0^2=1$ GeV^2 and $Q_0^2=32$ GeV^2.

Finally we apply a correction for initial and final state radiation:

$$c^i_{rad}=EEC^i_{no\ rad}/EEC^i_{rad}\,.$$

Here EEC^i_{rad} and $EEC^i_{no\ rad}$ are the parton shower calculations with and without initial and final state photon radiation, respectively. The correction factor

Table 2
Fitted JETSET parameters Λ_{LL}, σ_q and b for three values of the parton shower termination parameter Q_0^2. The systematic errors are due to uncertainties in the unfolding. The average number of partons is also shown.

Q_0^2 [GeV^2]	Partons	Λ_{LL} [GeV]	σ_q [GeV]	b [GeV^{-2}]
1	9.0	0.30±0.03	0.40±0.05	0.75±0.05
16	4.0	0.31±0.03	0.50±0.05	0.60±0.10
32	3.5	0.28±0.03	0.50±0.05	0.40±0.05

is shown in fig. 2c. It is close to one and its uncertainty is negligible.

The unfolded EEC and AEEC distributions with their statistical errors are shown in fig. 3.

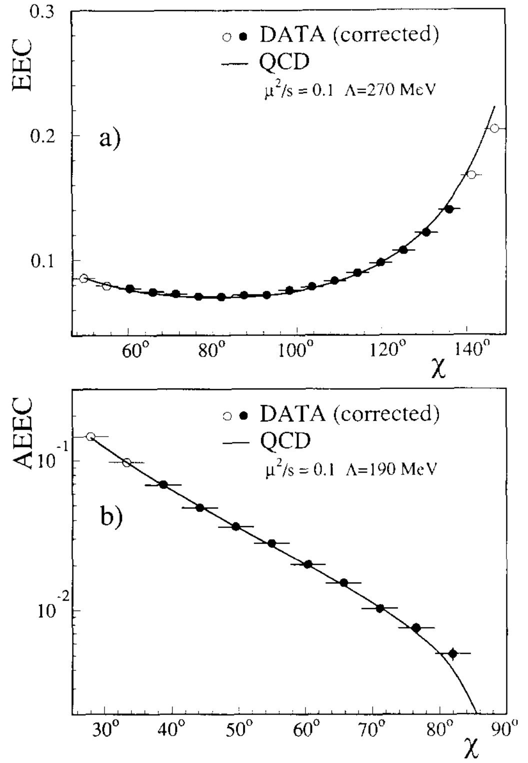

Fig. 3. Comparison of corrected EEC (a) and AEEC (b) distributions with their statistical errors to the second order QCD prediction for $f=0.1$ and the measured values $\Lambda=270$ MeV (a) and $\Lambda=190$ MeV (b). The Λ values have been obtained from a comparison, between data and QCD, of the integrals over the angles as defined in (2), indicated by the black points. The data points shown as open circles have not been used to determine Λ. The value for the last bin in the AEEC distribution which is very small and has a large uncertainty is not shown.

5. Comparison to perturbative QCD

QCD (calculated to second order) predicts the EEC and AEEC distributions as a function of the strong coupling constant α_s, the center of mass energy squared $s(\approx M_Z^2)$, and the renormalization scale $f=\mu^2/s$ [6]:

$$\mathrm{EEC}(\chi)=F(\chi)\alpha_s\{1+[b_0\ln f+R(\chi)]\alpha_s\}\,,$$

and similarly for AEEC. In these calculations 2-, 3- and 4-parton final states are included. There is no invariant mass cut applied. The coupling constant α_s is given by [13]

$$\alpha_s(\Lambda,\mu^2)=\frac{1}{b_0\ln(\mu^2/\Lambda^2)}-\frac{b_1}{b_0^3}\frac{\ln\ln(\mu^2/\Lambda^2)}{[\ln(\mu^2/\Lambda^2)]^2}\,,$$

where

$$b_0=\frac{33-2n_f}{12\pi}\,,\quad b_1=\frac{153-19n_f}{24\pi^2}\,,\quad n_f=5\,.$$

$\Lambda\equiv\Lambda_{\overline{MS}}^{(5)}$ denotes the QCD scale parameter for five active flavours.

The first order term F can be written in analytical form [1]. The second order correction R has been calculated by four different groups [14–16,6], some of those using different methods for cancelling singularities. The four results differ from each other. For the integral over the angular ranges defined in (2) the second order correction R varies by about ±25% for EEC and AEEC. These discrepancies are not understood. For the determination of α_s we use the calculations in ref. [6] and take into account the differences as a theoretical error. R is about 3 for EEC and 1 for AEEC.

To interpret the measured energy–energy correlations in the framework of QCD the renormalization scale f needs to be fixed. Various principles have been suggested for choosing f [17–19,15]. One of them, the principle of minimal sensitivity [18], postulates a scale f_0 for which the derivative of an observable such as EEC with respect to f vanishes. This would be fulfilled automatically if calculated to all orders. The size of f_0 depends on the size of R. We conservatively allow a variation of f in the range $\frac{1}{4}f_0 - 1$ to estimate the scale uncertainty in α_s. This yields

$$0.001 \leqslant f \leqslant 1\,(\mathrm{EEC})\,, \quad 0.03 \leqslant f \leqslant 1\,(\mathrm{AEEC})\,. \qquad (3)$$

We choose as central value in both cases $f=0.1$.

The integrals of the corrected EEC and AEEC distributions are

$$\int_{56.6^\circ}^{138.6^\circ} \mathrm{EEC}(\chi)\,\mathrm{d}\chi = 0.123 \pm 0.0002\,(\mathrm{stat.}) \pm 0.005\,(\mathrm{exp.}) \pm 0.002\,(\mathrm{hadr.})\,,$$

$$\int_{36.0^\circ}^{90.0^\circ} \mathrm{AEEC}(\chi)\,\mathrm{d}\chi = 0.0225 \pm 0.0002\,(\mathrm{stat.}) \pm 0.0009\,(\mathrm{exp.})^{+0.0016}_{-0.0009}\,(\mathrm{hadr.})\,.$$

The statistical errors (stat.) are negligible. The experimental systematic errors (exp.) correspond to the uncertainty in the detector correction factor c^i_{det}. The hadronization uncertainty (hadr.) is estimated by recalculating the hadronization correction for the different sets of Monte Carlo parameters given in table 2.

For a renormalization scale $f=0.1$ we derive for the QCD scale parameter using the second order calculations in ref. [6]:

$$\Lambda(\mathrm{EEC}) = 270 \pm 60\,(\mathrm{exp.}) \pm 30\,(\mathrm{hadr.})\,{}^{+160}_{-70}\,(\mathrm{scale})\,{}^{+100}_{-80}\,(\mathrm{theor.})\ \mathrm{MeV}$$

$$\Lambda(\mathrm{AEEC}) = 190^{+50}_{-40}\,(\mathrm{exp.})\,{}^{+90}_{-40}\,(\mathrm{hadr.})\,{}^{+30}_{-0}\,(\mathrm{scale})\,{}^{+30}_{-50}\,(\mathrm{theor.})\ \mathrm{MeV}\,.$$

The corresponding α_s values at $\sqrt{s}=91.2$ GeV are

$$\alpha_s(\mathrm{EEC}) = 0.121 \pm 0.004\,(\mathrm{exp.}) \pm 0.002\,(\mathrm{hadr.})\,{}^{+0.009}_{-0.006}\,(\mathrm{scale}) \pm 0.006\,(\mathrm{theor.}) \qquad (4)$$

$$\alpha_s(\mathrm{AEEC}) = 0.115 \pm 0.004\,(\mathrm{exp.})\,{}^{+0.007}_{-0.004}\,(\mathrm{hadr.})\,{}^{+0.002}_{-0.000}\,(\mathrm{scale})\,{}^{+0.003}_{-0.005}\,(\mathrm{theor.})\,. \qquad (5)$$

The scale uncertainty (scale) is calculated by varying f in the range given in (3). It is small for AEEC due to the smallness of the second order correction. The theoretical error (theory) is estimated by repeating the α_s calculation using the different second order calculations (at a scale $f=0.1$) for R. For a renormalization scale $f=1$ we obtain for the central values of the strong coupling constant at $\sqrt{s}=91.2$ GeV $\alpha_s(\mathrm{EEC})=0.130$ and $\alpha_s(\mathrm{AEEC})=0.117$.

Fig. 3 compares the EEC and AEEC distributions calculated in second order QCD to our measurements.

If α_s is derived from a fit to the distributions in fig. 3 the result differs by less than 1% from the numbers obtained by comparing the integrals. A variation in the angular ranges (2) by up to $\pm 10.8^\circ$ (open circles in fig. 3) yields a change in the strong coupling constant by less than 2% for EEC and less than 1% for AEEC.

To study theoretical uncertainties further, we have repeated the α_s determination using the ERT [20] matrix element generator implemented in the JETSET program with an invariant mass cutoff $y_{\mathrm{min}}=0.01$ and a scale $f=0.1$. We have used fragmentation parameters determined from a comparison of measured event shape distributions to those generated with the matrix element generator and string fragmentation. We obtain α_s values from both the EEC and the AEEC which agree with the results in (4) and (5) within the estimated hadronization error.

The α_s values derived from EEC and AEEC agree with each other and also with the strong coupling constant determined from the 3-jet fraction, $\alpha_s = 0.115 \pm 0.005\,(\mathrm{exp.})\,{}^{+0.012}_{-0.010}\,(\mathrm{theor.})$ [2]. The values of α_s determined by the OPAL [21] and DELPHI [22] collaborations for energy–energy correlations at the Z^0 resonance are in agreement with our numbers.

6. Energy dependence of α_s derived from AEEC

Several groups have used various methods to determine the strong coupling constant α_s in second order from the asymmetry of energy–energy-correlations in e^+e^- annihilation [21–23]. Fig. 4 shows only results obtained using the string fragmentation model for hadronization corrections and a renormalization scale $f=1$. Measurements based on the FKSS [24] or GKS [25] matrix element calculations, which were

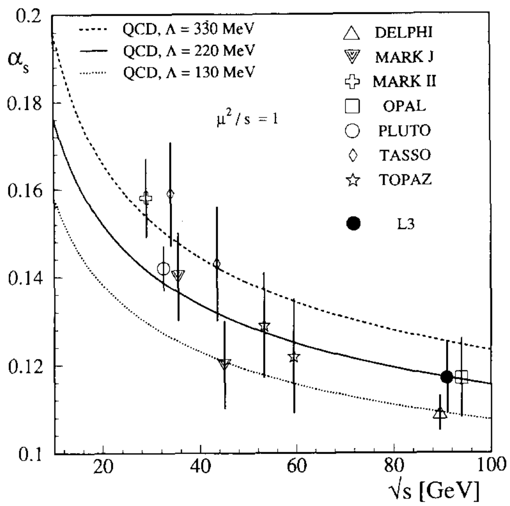

Fig. 4. Energy dependence of α_s measured from AEEC in e^+e^- annihilation at different center of mass energies in comparison with second order QCD. The energy dependence of α_s is reproduced by the QCD predictions, which have been calculated using our measured value of $\Lambda = (220^{+110}_{-90})$ MeV (for $f=1$), rather than from a fit to all data points. For a better readability of this graph different points at the same center of mass energy were slightly shifted horizontally.

found to be incomplete [26], are not shown. Statistical and systematic errors are combined quadratically.

The energy dependence of α_s is reproduced by QCD for our measured value of $\Lambda = (220^{+110}_{-90})$MeV (for $f=1$).

7. Summary

From the energy–energy correlation and its asymmetry measured for 83 000 hadronic Z^0 decays we determine the strong coupling constant α_s to second order QCD at $\sqrt{s} = 91.2$ GeV. We derive

$$\alpha_s = 0.121 \pm 0.004(\text{exp.}) \pm 0.002(\text{hadr.})$$
$$^{+0.009}_{-0.006}(\text{scale}) \pm 0.006(\text{theor.})$$

from the energy–energy correlation and

$$\alpha_s = 0.115 \pm 0.004(\text{exp.})^{+0.007}_{-0.004}(\text{hadr.})$$
$$^{+0.002}_{-0.000}(\text{scale})^{+0.003}_{-0.005}(\text{theor.})$$

from its asymmetry. The running of α_s as predicted by QCD is confirmed by a comparison of α_s values measured from the asymmetry of the energy–energy correlations at different center of mass energies.

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