

## DETERMINATION OF THE STRONG COUPLING CONSTANT AT LEP

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Multi-hadronic events produced in  $e^+e^-$  collisions provide an excellent laboratory to study QCD, the theory of strong interactions, and in particular to determine the strong coupling parameter  $\alpha_s$  and demonstrate its predicted behavior as a function of the energy scale. Determinations of  $\alpha_s$  at LEP will be reviewed with emphasis on event shape variables and jet rates in 3-jet and 4-jet events.

### 1. $\alpha_s$ from 3-jet observables

The grouping of particles into a number of collimated jets is one of the most striking features of hadronic final states produced in  $e^+e^-$  collisions, and is easily reconcilable with the model of energetic and hence boosted partons undergoing parton branchings and hadronisation processes as prescribed by QCD. To quantify this structure two types of observables are commonly used: event shapes and jet rates.

To calculate jet rates clustering algorithms are used to group the particles of the hadronic final state into a number of jets, based on a resolution criterion which determines when the clustering should stop. The rate of events with a given number of jets is directly related to the coupling strengths involved. Event shapes on the other hand are constructed by calculating a single number for each event which classifies its topology. The left picture of Fig. 1 shows the Thrust,  $T$ , as an example for an event shape observable. The Thrust of an event is defined as the normalised sum of absolute momentum components of all observed particles projected along the axis that maximizes this sum. A well aligned, or "pencil-like", 2-jet event with few branchings will result in a value of  $T$  close to unity, while a more spherical event with many branchings will tend to have smaller values of  $T$ .

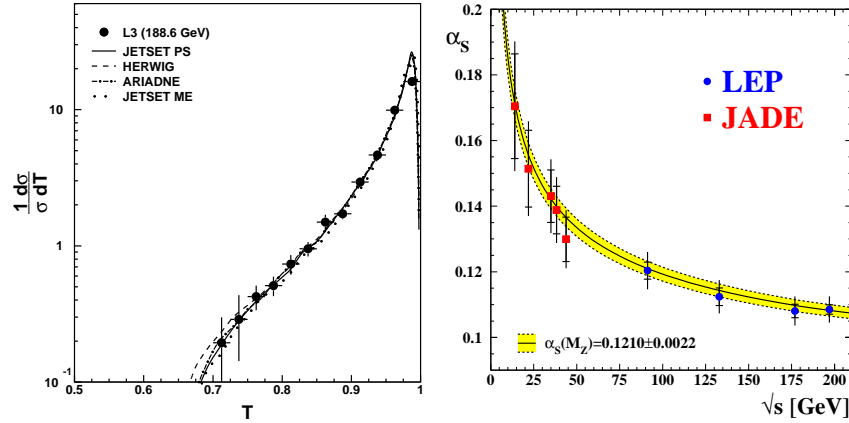


Figure 1. The left picture shows an example of an event shape distribution - the Thrust,  $T$ , as measured by L3<sup>1</sup>. The picture<sup>2</sup> on the right summarises the combined values of  $\alpha_s$  based on the analysis of 3-jet observables by the LEP collaborations or using JADE data.

The experimental procedure to determine the value of  $\alpha_s$  starts with selecting multi-hadronic events, while rejecting events with initial state radiation and  $WW$  and  $ZZ$  events. The measured distributions are then corrected for detector effects, background and efficiency, and theoretical predictions are fitted to determine  $\alpha_s$ . The best available theoretical predictions involve calculations in next-to-leading order (NLO) perturbative QCD matched to next-to-leading-log (NLLA) resummed calculations.

The LEP experiments<sup>2</sup> have chosen six event shapes for which NLO+NLLA calculations are available in addition to jet rates to produce a combined value of  $\alpha_s$ :  $(1 - T)$ , the heavy jet mass  $M_H$ , the jet-broadening observables  $B_T$  and  $B_W$ , the  $C$ -parameter, and the value of the resolution parameter of the Durham jet algorithm that marks the transition of a 2-jet event into a 3-jet event,  $y_{23}$ . The value of  $\alpha_s$  determined at four LEP centre-of-mass energies (CME) is shown in the right picture of Fig. 1.

The yellow band in the right picture of Fig. 1 represents the value of  $\alpha_s$  as determined from an NNLO analysis of inclusive observables, like the properties of the  $Z$  line shape or the ratio of the longitudinal and total cross section. There is an excellent agreement between these two methods, and also with values determined from JADE data at lower energies. The overall combined value from event shapes and 3-jet rates at LEP quoted at the  $Z$  mass is  $\alpha_s(m_Z) = 0.1201 \pm 0.0053$ , where the systematic error is dominated by the theoretical uncertainty.

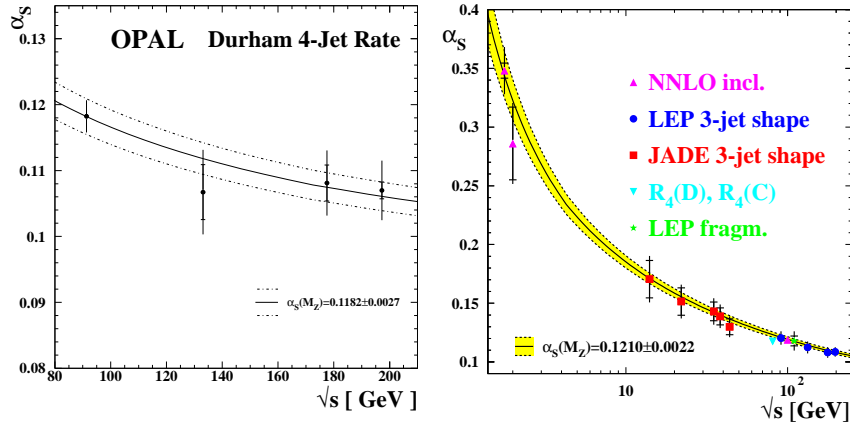


Figure 2. The picture on the left shows the values of  $\alpha_s$  obtained by OPAL<sup>5</sup> from fits to the 4-jet rate in four intervals of the centre-of-mass energy ( $\sqrt{s}$ ) at LEP2. The picture<sup>2</sup> on the right is a summary of  $\alpha_s$  values determined at different values of  $\sqrt{s}$ . The yellow band represents the value of  $\alpha_s$  determined from inclusive variables at NNLO.

## 2. $\alpha_s$ from 4-jet observables

Recently measurements have emerged from three of the four LEP experiments using the 4-jet rate to determine  $\alpha_s$ . The 4-jet rate is a promising observable, as its sensitivity to the value of  $\alpha_s$  is double that of a 3-jet observable. On the other hand this means an additional order of  $\alpha_s$  is needed in theoretical calculations to reach NLO for this process, that is  $O(\alpha_s^3)$ . Such calculations are now available and have been matched with existing NLLA calculations to produce the theoretical predictions needed to perform the fits to the data.

ALEPH<sup>3</sup> has fitted  $O(\alpha_s^3)$ +NLLA calculations corrected for hadronisation and detector effects to data at the  $Z$  peak, yielding a value of  $\alpha_s(m_Z) = 0.1170 \pm 0.0022$ . The uncertainty is dominated by theory. DELPHI<sup>4</sup> has fitted an  $O(\alpha_s^3)$  calculation corrected for hadronisation to data at the  $Z$  peak corrected for detector effects. Here no matching to an NLLA calculation is attempted, but the renormalisation scale,  $x_\mu$ , is optimised experimentally to reduce the influence of the theoretical uncertainty. DELPHI determines  $\alpha_s(m_Z) = 0.1175 \pm 0.003$ , with the uncertainty dominated by the hadronisation model, and not the variation of the renormalisation scale, commonly used to assess the theoretical uncertainty. It should be mentioned that an increased variation of  $x_\mu$  here leads to a drastic increase of the theoretical uncertainty. OPAL<sup>5</sup> fits  $O(\alpha_s^3)$ +NLLA calcu-

lations corrected for hadronisation effects to data corrected for detector effects from 91 GeV to 209 GeV CME. Values of  $\alpha_s$  are presented at four CME points in the left picture of Fig. 2. Also shown is the central value and uncertainty at the  $Z$  mass resulting from a combination of the four CME points:  $\alpha_s(m_Z) = 0.1182 \pm 0.0026$ , where the uncertainty is dominated by theory.

A combination of all three results based on 4-jet rates as been undertaken<sup>2</sup> and yields a value of  $\alpha_s(m_Z) = 0.1175 \pm 0.0029$ .

### 3. Summary

The value of the strong coupling  $\alpha_s$  has been determined at LEP based on theoretically and experimentally well behaved observables of event shapes and jet rates.  $\alpha_s$  determinations from 3-jet observables yield reliable and precise results based on NLO+NLLA calculations. The uncertainty is usually dominated by theory, and it is hoped that theoretical developments will allow a reduction of the uncertainty from now 5% to 2% in the near future. The first determinations of  $\alpha_s$  from 4-jet rates based on NLO+NLLA calculations are available and reach a precision comparable to the most precise determinations today. Due to the small number of measurements available so far the cross-checking of results is however not yet as rigorous as achieved for the 3-jet observables. A summary of  $\alpha_s$  determinations is shown in the right picture of Fig. 2.

A very consistent picture has developed across the various methods of determining  $\alpha_s$  in  $e^+e^-$  collisions. The wide spread of measurements in CME and the small uncertainties achieved for the individual values allow a clear demonstration of the asymptotic freedom of QCD.

### References

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