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Event shape and determination of α_s at LEP

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Abstract. The 4 LEP experiments have reanalysed their data on event shape variables for $e^+e^- \to$ *hadrons* to determine the strong coupling constant α_s. A consistent treatment of these measurements and a better understanding of the theoretical uncertainties by the LEP QCD Working Group yields the result $\alpha_s(M_Z) = 0.1202 \pm 0.0003$ (stat) $\pm$ 0.0009 (exp) $\pm$ 0.0009 (hadr) $\pm$ 0.0047 (theo).

PACS. 12.38.Qk Experimental tests of QCD – 13.66.Bc Hadron production in e^+e^- interactions

1 Introduction

The event shape variables for $e^+e^- \to$ *hadrons* are sensitive to the rate of hard gluon emission and hence to the value of the strong coupling constant, α_s. The 4 LEP experiments, ALEPH, DELPHI, L3 and OPAL have investigated the following six event shape variables for which improved theoretical calculations exist:

1−Thrust: $1 - \mathrm{T} = 1 - (\sum_a |\mathbf{p}_a \cdot \mathbf{n}_T| / \sum_a |\mathbf{p}_a|)_{\max}$

Heavy jet mass: $\rho_H = \left(\sum_{a \in S_\pm} p_a/\sqrt{s}\right)^2_{\max}$, where $S_\pm$ are the two hemispheres defined by a plane perpendicular to the thrust axis.

Jet broadenings: $B_\pm = \sum_{i \in S_\pm} |\mathbf{p}_i \times \mathbf{n}_T| / (2 \sum_i |\mathbf{p}_i|)$ is computed in each hemisphere. These lead to the definition of the total ($B_T = B_+ + B_-$) and the wide ($B_W = \max(B_+, B_-)$) jet broadening variables.

C Parameter: is determined from the eigenvalues of the linearised momentum tensor ($\theta^{ij} = \sum_a (p_a^i p_a^j / \mid \mathbf{p}_a \mid) / \sum_a \mid \mathbf{p}_a \mid$) as $C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$.

3-Jet parameter: y_3 is the value of the jet resolution parameter in the $k_\perp$ algorithm at which the event changes from 2-jet to 3-jet configuration.

Fixed order calculations exist up to $\mathcal{O}({\alpha_s}^2)$ for all shape variables. The cumulative cross section $R(y)$ for the event shape variable y can be written as a function of α_s in terms of two functions $A(y)$, $B(y)$ which are computed by integrating ERT [1] matrix elements using Monte Carlo programs [2,3]. This describes data well in the multi-jet region, but fails in the two jet region (small y).

For the six event shape variables mentioned above, all the leading and next-to-leading terms in $L(\equiv -\ln(x_L y))$ have been resummed [4,5,6,7,8,9,10,11,12] where x_L is a scale parameter. These terms dominate at small y whereas the sub-leading terms are important at large y.

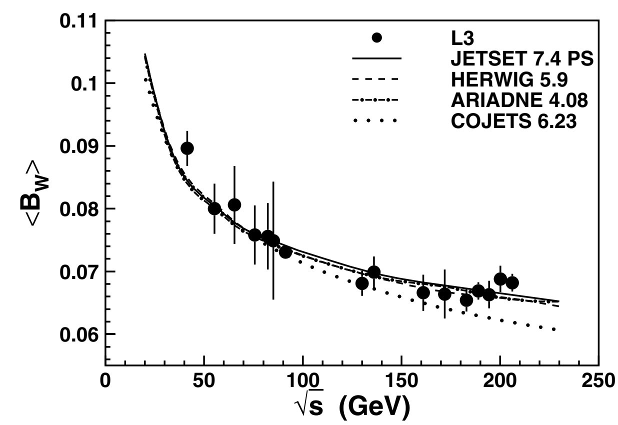

Fig. 1. Average wide jet broadening as measured by L3 compared with predictions of several parton shower models

Fixed order $\mathcal{O}({\alpha_s}^2)$ calculations are combined with resummed ones, avoiding double counting of terms, in various matching schemes. In the Log R Matching, logs of fixed order are taken, expanded in power series and matched in $\ln R(y)$. In the R Matching scheme $\mathcal{O}({\alpha_s}^2)$ terms are removed from resummed $R(y)$ and replaced by terms from the fixed order calculation.

Also kinematic constraints are imposed so that cross sections vanish beyond the kinematic limit. This is done in the modified Log R Matching scheme by replacing L in the resummed terms by $L' = (1/p)\ln[\ (1/x_L \cdot y)^p - (1/x_L \cdot y_{\max})^p + 1]$ with modification degree $p \geq 1$. In the modified R matching scheme, L is similarly modified and the matching coefficients become functions of y to enforce the kinematic constraints. All matching algorithms are exact up to $\mathcal{O}\ ({\alpha_s}^2)$.

To take into account hadronisation effects, the perturbative level calculation is convoluted with a probability function which relates the parton level distribution to the hadron level distribution. This has been done using several Parton Shower Monte Carlo programs.

This approach (a) can explain the small y (high statistics) region; (b) gives good fits at a reasonable scale ($Q \approx \sqrt{s}$); (c) has fewer uncalculated terms (and hence reduces the uncertainty due to them). So α_s is expected to be measured with good precision. All 4 LEP experiments [13, 14,15,16] have measured these event shape variables at different beam energies. Using radiative events at LEP I, event shape distributions are also measured [17] at reduced centre-of-mass energies. Thus α_s is determined over a large energy region by the same method. Extraction of α_s by the 4 experiments has been discussed in the LEP QCD working group report which provides a unified approach to the 4 sets of measurements.

2 Measurement of event shape distributions

Hadronic events in e^+e^- interactions are characterised by (a) large visible energy; (b) high multiplicity; (c) small transverse energy imbalance. These characteristics are used to select hadronic events with high efficiency and small background. Typically each experiment has collected ~ 600 pb^{-1} of integrated luminosities at LEP2 energies. There are large backgrounds at high energies due to initial state radiation (radiative return to Z) and four fermion processes (mainly W-pair production). This required active rejection of these types of events.

OPAL [17] has looked at the radiative events in their LEP I data. 11.3 K hadronic events are selected with standard cuts and with at least one high energy isolated photon candidate. The hadronic subsystem of reduced centre-of-mass energy: $\sqrt{s'} = \sqrt{s\,(1 - 2E_\gamma/\sqrt{s})}$ is divided into 7 $\sqrt{s'}$ bins. The largest background, due to neutral hadrons, is suppressed using a likelihood function which utilises shower shape variables and isolation criteria. The final sample consists of 3.8 K events with background between 0.6% and 6.6%.

The event shape variables are measured from charged and neutral particles. The contributions due to known backgrounds (2-photon, 4-fermion, initial state radiation) are subtracted from these distributions which are then corrected for detector resolution and acceptance. The corrections are rather small and lead to small systematic uncertainties. Figure 1 shows the average wide jet broadening, as a function of centre-of-mass energy, compared with predictions from various parton shower Monte Carlo programs [18,19,20,21]. As can be seen from the figure, the energy evolution of this variable is well explained by Parton Shower models.

3 Determination of α_s

Several groups have re-analysed their data in view of:

- use of EVENT2 program [3] (rather than EVENT [2]) in determining the fixed order terms (having a better statistical precision);

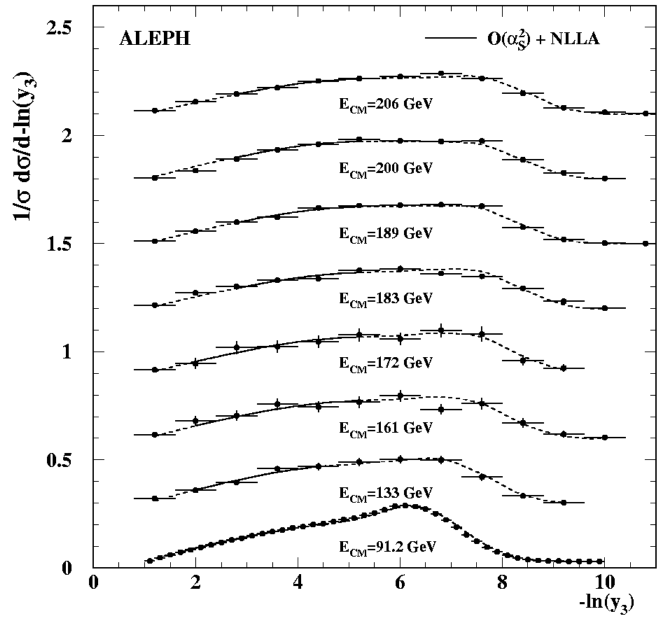

Fig. 2. y_3 distributions at different centre-of-mass energies as measured by ALEPH compared with the QCD fits

- use of more recent theoretical calculations for jet broadening variables [10] (correct treatment of multiple gluon emission contribution) and for y_3 [11,12] (completing the missing log terms due to multiple emission);
- use of a more complete set of variables at all energies;
- use of modified Log R matching scheme in determining the central value of α_s;
- use of Pythia [18], Herwig [19] and Ariadne [20] in estimating the hadronisation correction.

Figure 2 shows the measured y_3 distribution at different centre-of-mass energies fitted to the predictions of perturbative QCD after hadronisation corrections. As can be seen from the figure, the theoretical predictions fit the data well. All the experiments use $p = 1$, $x_L = 1$ and renormalisation scale $x_\mu = 1$ in quoting the central value of α_s.

The errors on α_s can be classified as (a) statistical; (b) experimental systematics (estimated by varying selection cuts, methods for background estimation, detector corrections, etc.); (c) hadronisation (estimated by changing the parton shower models Pythia/ Herwig/ Ariadne); (d) theoretical (estimated by varying renormalisation scale, matching scheme, kinematic constraint, scale parameter x_L and modification degree).

Each experiment measures α_s at each energy point from several event shape variables. They are combined into one measurement at each energy by taking a weighted or unweighted average.

The refits show the central values of α_s from the $1 - T$ and ρ_H distributions do not alter significantly. α_s measurements from the broadening distributions move systematically to higher values and those from C and y_3 distributions move to lower values - but always within the statistical uncertainties of the measurements. The combined α_s

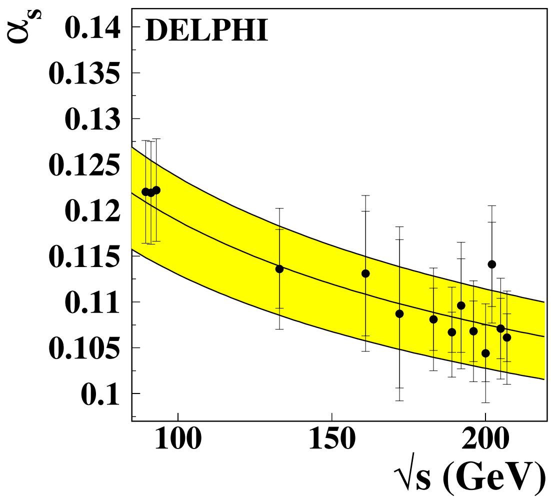

Fig. 3. α_s determined by DELPHI from event shape distributions as a function of centre-of-mass energy

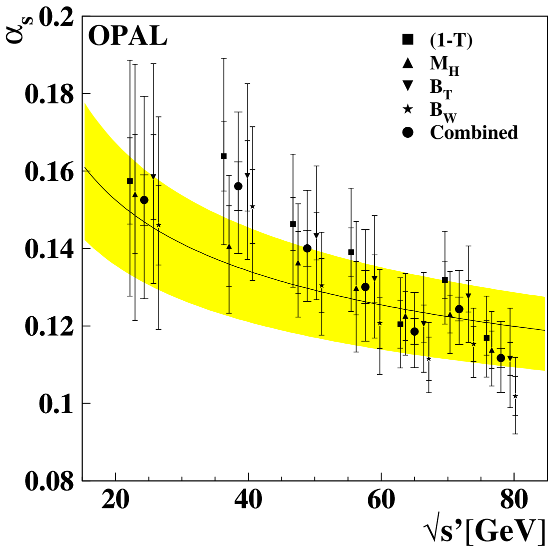

Fig. 4. α_s determined by OPAL from event shape distributions as a function of reduced centre-of-mass energy

values are not significantly changed after the refit procedures.

Figures 3 and 4 show the α_s measurements from the DELPHI and OPAL experiments as a function of (reduced) centre-of-mass energy. The measurements agree well with the energy evolution as predicted by QCD. All the four experiments have combined the measurements at different energies into a single measurement at $Q = M_Z$ with a proper treatment of correlated uncertainties.

4 Summary

The 4 LEP experiments have reanalysed their data on event shape variables for $e^+e^- \to$ hadrons. The α_s values as obtained by the four experiments are summarised in Table 1.

Table 1. α_s measurements from the 4 LEP experiments. The two errors refer to overall experimental and theoretical uncertainties

Experiment	$\alpha_s(M_Z)$
ALEPH	0.1214±0.0014±0.0046
DELPHI	0.1205±0.0021±0.0050
L3	0.1227±0.0012±0.0058
OPAL (Rad.)	$0.1176 \pm 0.0012\ ^{+\,0.0093}_{-\,0.0085}$

A consistent treatment of these measurements and a better understanding of the theoretical uncertainties have been worked out by the LEP QCD Working Group [22] giving $\alpha_s(M_Z) = 0.1202 \pm 0.0003$ (stat) $\pm\ 0.0009$ (exp) $\pm\ 0.0009$ (hadr) $\pm\ 0.0047$ (theo).

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