Measurements of α_s with the DELPHI detector at LEP

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The data collected with DELPHI during the LEP1 period is used to perform a simultaneous fit to the strong coupling constant α_s in 2^{nd} order perturbation theory and to the renormalisation scale x_μ . The results are compared to α_s fits in 2^{nd} order perturbation theory with fixed scale x_μ and to other theoretically motivated scale setting methods.

To determine the energy dependence of α_s , event shape distributions and their mean values are measured for $\sqrt{s} = 48$ GeV to 189 GeV. The strong coupling α_s is extracted in $\mathcal{O}(\alpha_s^2)$, Next to Leading Log Approximation (NLLA) and in a combined scheme using hadronisation corrections—evaluated with fragmentation model generators, and an analytical power ansatz.

1. Introduction

From 1994 to 1998 LEP operated at different centre-of-mass energies between 91 GeV and 189 GeV. DELPHI and its performance have been described in detail in [?]. Due to the ~ 1000 times larger resonant cross section over the $1/E$ dependent point particle cross section, DELPHI collected several million hadronic events at the Z^0 mass, which can serve for a precise determination of $\alpha_s(M_Z^2)$. With the high energy data from LEP2, the running of α_s can be studied in further detail.

2. Precise measurement of α_s from LEP1 data

From the ~ 1.5 million hadronic events measured with the DELPHI detector in 1994, event shape distributions are calculated. Event shape distributions depend on the event orientation given by the direction of the Thrust vector $\vec{T}$. All event shape distributions are calculated in eight angular bins $0 \leq \cos\vartheta_T \leq 0.96$ and compared to various Monte Carlo calculations. All observed event shape distributions are in very good agreement with Monte Carlo model predictions.

Second order coefficients for the angular dependent event shapes are calculated using the EVENT2 program for the integration of $\mathcal{O}(\alpha_s^2)$ matrix elements.

2.1. Dependence on the renormalisation scale μ

Since the renormalisation scale μ is an internal parameter of renormalisation theory and should not affect exact infinite order calculations, a simultaneous fit to α_s and renormalisation scale x_μ is performed, the outcoming scale being the "experimental optimised scale x_μ^{exp} ". Using the experimental optimised scale x_μ^{exp} results in α_s are consistent with each other for all of the 18 event shape distributions studied. Experimentally speaking additional systematic error evaluation due to scale ambiguities is not needed. Nevertheless, in this analysis additional systematic errors are estimated by varying the scale around the experimental optimised scale: $0.5 \cdot x_\mu^{exp} \leq x_\mu \leq 2 \cdot x_\mu^{exp}$. Results in α_s for fixed and experimental optimised scales are shown in Fig. ??.

2.1.1. Scale setting methods from theory

The $\alpha_s(M_Z^2)$ measurement using experimentally optimised scales is compared to $\alpha_s(M_Z^2)$ measurements using renormalisation scales predicted by three different theoretical motivated scale setting methods: The principle of minimal sensitivity (PMS) [?], the method of effective charges (ECH) [?] and the method of Brodsky, Lepage and MacKenzie (BLM) [?]. Fig. ?? shows the correlation between experimentally optimised scales and theoretical motivated scale set-

Figure 1. a) Results of the QCD fits applying a fixed renormalisation scale $x_\mu = 1$ for 18 event shape distributions. The error bars indicated by the solid lines give the experimental and the hadronisation uncertainty. The error bars indicated by the dotted lines include the uncertainty due to the variation of the renormalisation scale. Also shown is the correlated weighted average.

b) Same as in a) but for the experimental optimised scale $x_\mu^{\text{exp.}}$.

ting methods. Results in α_s are consistent with each other and with "experimental optimised" results.

2.2. Result

The final result in $\alpha_s(M_Z^2)$ is taken from the Cone Energy Fraction (JCEF)[?], the observable with the smallest theoretical and experimental uncertainties.

After correcting the measured value for heavy quark mass effects, the final result is

$$\begin{aligned} \alpha_s(M_Z^2) = 0.1180 & \pm 0.0006(\text{exp.}) \\ & \pm 0.0013(\text{hadr.}) \\ & \pm 0.0008(\text{scale}) \\ & \pm 0.0007(\text{mass}) \end{aligned}$$

3. Measurement of the running of α_s

The analysis is based on data taken with DELPHI at six different centre-of-mass energies between 91 GeV and 189 GeV. From hadronic events event shape distributions their means and moments are calculated. α_s is determined by fitting an α_s dependent QCD prediction to the measured event shape distributions at various centre-of-mass energies.

Data with centre-of-mass energies above M_Z are taken from the LEP2 run. At LEP2 energies analyses have to deal with new background channels: With increasing energy the probability for radiating off a photon from the initial electron or positron increases. The effective hadronic centre-of-mass energy of an event is reconstructed by an algorithm called SPRIME+ [?], based on a fit imposing four-momentum conservation to

Figure 2. Correlation between experimentally optimised renormalisation scales and the scales predicted by ECH, PMS and the BLM method.

measured jet four-momenta. A cut on the reconstructed centre-of-mass energy $\sqrt{s}_{\text{rec}} \geq 90\% E_{\text{cm}}$ is applied to discard radiative return events.

At 161 GeV the threshold for the pair production of WW and at 183 GeV the threshold for ZZ events are passed. By applying a cut on the small jetbroadening B_{min} events from WW and ZZ pair production are suppressed.

Data with centre-of-mass energies below M_Z are selected from LEP1 runs by tagging events with prompt photon radiation, reducing the effective centre-of-mass energy of the remaining hadronic system. The detected FSR photons are required to be hard and isolated to really being prompt photons. From the selected events the tagged photon is removed, the rest of the event is boosted into the centre-of-mass frame of the hadronic system. To receive proper statistics, the events are summed up into three intervals of E_{cm} .

The statistics of hadronic events collected at energies above and below M_Z , though small compared to the statistics gathered near the Z resonance, is sufficient for the measurement of event shape distributions and for a determination of the strong coupling α_s .

The data taken around 91.2 GeV, in 1993–95 were reanalysed using cuts, binnings and fit ranges coherent with the high energy data analysis.

3.1. Determination of α_s

3.1.1. α_s from event shape means

The analytical power ansatz for non-perturbative corrections to event shape means $\langle f \rangle$ by Dokshitzer and Webber [?, ?] including the Milan factor established by Dokshitzer et. al. [?, ?] is used to determine α_s from mean event shapes.

α_s is calculated for $\langle 1 - T \rangle$ and $\langle M_h^2 / E_{\text{vis}}^2 \rangle$ individually and then combined with an unweighted average.

The results are plotted as function of E_{cm} together with the QCD expectation in Figure ??.

The α_s values follow the QCD expectation. The slope of the logarithmic energy dependence of α_s^{-1} to first order is $2b_0$, independent of α_s and E_{cm} . It is obtained by fitting a straight line to the data in the α_s^{-1} vs. $\log E_{\text{cm}}$ plane. The result agrees with the QCD expectation of a running α_s (Tab. ??).

3.1.2. α_s from event shape distributions

From event shape distributions, α_s is determined by fitting an α_s dependent QCD prediction folded with a hadronisation correction to the data. As QCD predictions $\mathcal{O}(\alpha_s^2)$, pure NLLA, and the combined $\mathcal{O}(\alpha_s^2)$ +NLLA in $\ln R$ -scheme are employed [?, ?, ?].

In Sec. ?? it has been shown that fixing the renormalisation scale to $\mu^2 = E_{\text{cm}}^2$ results in a marginal description of the data. Therefore, the experimentally optimised scales $x_\mu = \mu^2 / E_{\text{cm}}^2$ are determined from the LEP1 data and are used for the $\mathcal{O}(\alpha_s^2)$ fits to the high energy data for both ob-

Theory	$d\alpha_s^{-1}/d\log(E_{\text{cm}})$
$\mathcal{O}(\alpha_s^2) + \text{power ansatz}$	$1.01 \pm 0.23 \pm 0.18$
$\mathcal{O}(\alpha_s^2)$	$1.23 \pm 0.29 \pm 0.20$
NLLA	$1.42 \pm 0.31 \pm 0.33$
$\mathcal{O}(\alpha_s^2) + \text{NLLA } (\ln R)$	$1.31 \pm 0.21 \pm 0.17$
QCD exp.	1.27
QCD+Gluinos exp.	0.90

Table 1

Results of straight line fit to the logarithmic energy dependence of α_s^{-1} , and theoretical expectations calculated in 2nd order.

servables individually. In contrast for the NLLA and the combined NLLA+ $\mathcal{O}(\alpha_s^2)$ fits, μ is set equal to E_{cm} , so that these results can be compared to other experiments more directly.

The α_s values evaluated from the distributions are plotted in Fig. ???. The results agree well with those measured from the event shape means. As for the α_s results from mean event shapes, the data follow the QCD expectation. The slope obtained from fitting a straight line to the logarithmic energy dependence of α_s^{-1} is in good agreement with the QCD expectation (Tab. ??).

3.1.3. α_s from the four-jet rate

Event shape observables of the four-jet type are uncorrelated to event shapes derived from 3-jet final states and thus can give an statistically independent access to the measurement of α_s . Furthermore the sensitivity of an observable on the colour charge is influenced by the fact that in perturbation theory the three gluon coupling appears at tree level first for four jet final states.

For the measurement of α_s from the four-jet rate R_4 the program DEBRECEN1.0 was used to calculate the B - and C -coefficients in Eq. ?? in next-to-leading order QCD.

$$R_4 = B \cdot \alpha_s^2 + C \cdot \alpha_s^3 + \dots \quad (1)$$

The NLO predictions are reliable for $y_{\text{cut}} \geq 10^{-2.7}$. Fig. ?? gives results for the DURHAM algorithm with $y_{\text{cut}} = 10^{-2.6}$, in good agreement

to the energy evolution of world average of α_s [?]. The running of α_s comes out to be

$$\frac{d\alpha_s^{-1}}{d\log(E_{\text{cm}})} = 1.16 \pm 0.43 \quad (2)$$

in good agreement with the results from three-jet observables.

Figure 4. Energy dependence of α_s as obtained from the four-jet rate R_4 , clustered with DURHAM at $y_{\text{cut}} = 10^{-2.6}$. The errors shown are statistical only. The band shows the QCD expectation when extrapolating the world average [?] to other energies.

REFERENCES

1. DELPHI Coll., P. Abreu and others. Performance of the DELPHI detector. *Nucl. Instr. Meth. A* **378**(1996) 57.
2. P. M. Stevenson. Optimized perturbation theory. *Phys. Rev. D* **23**(1981) 2916.
3. G. Grunberg. Renormalization scheme independent qcd and qcd: The method of effective charges. *Phys. Rev. D* **29**(1984) 2315.

Figure 3. Energy dependence of α_s as obtained from mean event shapes (left) compared to α_s obtained from distributions in $\mathcal{O}(\alpha_s^2)$, NLLA, $\ln R$. The errors shown are statistical only. The bands show the QCD expectation based on an extended α_s measurement with Z data [?, ?]

4. Stanley J. Brodsky, G. Peter Lepage, and Paul B. Mackenzie. On the elimination of scale ambiguities in perturbative quantum chromodynamics. *Phys. Rev.* **D28**(1983) 228.
5. Y. Ohnishi and H. Masuda. The jet cone energy fraction in e^+e^- annihilation. () . SLAC-PUB-6560.
6. P. Abreu, A. De Angelis, G. Della Ricca, D. Fassouliotis, A. Grefrath, N. Kjaer, R. Henriques, M. Mulders, M. Pimenta, and L. Vitale. The estimation of the effective centre of mass energy in $q\bar{q}\gamma$ events from DELPHI. CERN-OPEN 98-026, hep-ex/9809008, accepted by Nucl. Instr. Meth. A.
7. Y. L. Dokshitzer and B. R. Webber. Calculation of power corrections to hadronic event shapes. *Phys. Lett.* **B352**(1995) 451.
8. B. R. Webber. Hadronic final states. Talk given at workshop on DIS and QCD in Paris, hep-ph/9510283, Apr 1995.
9. Yu. L. Dokshitzer, A. Lucenti, G. Marchesini, and G. P. Salam. Universality of $1/q$ corrections to jet-shape observables rescued. *Nucl. Phys* **B511**(1997) 396.
10. Yu. L. Dokshitzer, A. Lucenti, G. Marchesini, and G. P. Salam. On the universality of the Milan factor for $1/Q$ power corrections to jet shapes. hep-ph/9802381, 1998.
11. Savas Dimopoulos and John Ellis. Challenges for extended technicolor theories. *Nucl. Phys.* **B182**(1982) 505.
12. S. Catani, G. Turnock, B. R. Webber, and L. Trentadue. Thrust distribution in e^+e^- annihilation. *Phys. Lett.* **B263**(1991) 491.
13. S. Catani, G. Turnock, and B. R. Webber. Heavy jet mass distribution in e^+e^- annihilation. *Phys. Lett.* **B272**(1991) 368.
14. S. Hahn J. Drees and G. Rodrigo. Consistent measurements of α_s from precise oriented event shape distributions. Contributed paper HEP'99 1-224, Tampere, 1998.
15. DELPHI Coll., P. Abreu and others. Consistent measurements of α_s from precise oriented event shape distributions. PPE Paper233/Draft2, 1999.
16. C. Caso et al. Review of particle physics. particle data group. *Eur. Phys. J.* **C3**(1998) 1.