Abstract 610
Parallel session 4
Plenary session 4

# Power Law Corrections to Hadronic Event-Shape Variables in $e^+e^-$ Annihilation

The ALEPH Collaboration

## Abstract

Measurements of distributions and mean values of the event-shape variables thrust and heavy jet mass in the center-of-mass energy range from 14 GeV up to 172 GeV are analyzed for possible non-perturbative corrections following a power law of the form $1/Q$. These corrections are characterized by a single parameter, which can be fitted to the data together with the strong coupling constant. Results on $\alpha_s$ are compared to those obtained with hadronization corrections from a Monte Carlo generator.

*(Paper contributed to Jerusalem Conference, August 1997)*

# 1 Introduction

The analysis of event-shape variables in the process $e^+e^- \rightarrow hadrons$ has corroborated the theory of strong interactions, Quantum Chromodynamics (QCD), and has provided accurate measurements of its strong coupling constant $\alpha_s$. The dominant uncertainties of these measurements are of theoretical nature. One important aspect is the transition from coloured partons, for which perturbative calculations can be performed, to colour-neutral hadrons, which are observed in the detector. So far this transition has been simulated on the basis of phenomenological Monte Carlo models, giving rise to a non- negligible hadronization uncertainty of $\alpha_s$.

In this paper the method above is compared to new analytical calculations of non-perturbative effects, which are described as corrections scaling with $1/Q$. The momentum transfer $Q$ is equal to the center-of-mass energy $\sqrt{s}$ in the case of $e^+e^-$ annihilation. These corrections have been calculated for mean values [1] and distributions [2] of some event-shape variables. Here the variables thrust ($T$) and heavy jet mass ($M_H$) are analyzed using Monte Carlo and $1/Q$ corrections. The aim of the present analysis is to study the new method based on power corrections and to compare results obtained for $\alpha_s$. Therefore, only one Monte Carlo generator is used here, although a detailed measurement of $\alpha_s$ should take into account different generators and a variation of the parameters used to describe the fragmentation process.

# 2 Experimental Data

Since the functional dependence of non-perturbative effects on the center-of-mass energy will be tested, experimental data are needed over a large range of $Q = \sqrt{s}$. Measurements of thrust and heavy jet mass have been done in the energy range from 12 GeV to 44 GeV at the PETRA collider by MARKJ [3], CELLO [4], PLUTO [5] and TASSO [6]. At 29 GeV there are data from the PEP collaborations MARKII [7] and HRS [8]. Data between 55 GeV and 58 GeV have been provided by AMY [9] and TOPAZ [10],[11]. Most precise data have been measured at $Q = M_Z$ by SLD [12], L3 [13], DELPHI [16], OPAL [18] and ALEPH [21]. The LEP collaborations have also performed measurements beyond the $Z$ resonance at 133 GeV [14][17][19][22], 161 GeV [15][20] and 172 GeV [23].

All measurements are corrected for detector acceptance and resolution, and in most cases statistical and systematic errors are given separately. The errors used in the $\chi^2$-calculations of the fits are the quadratic sum of statistical and experimental systematic errors. Correlations between measurements at different energies have not been taken into account. Further details on event selection and correction procedures can be found in the referenced publications.

# 3 Theoretical Predictions

The perturbative prediction to second order in $\alpha_s$ for the mean values $< 1 - T >$ and $< M_H >$ is given by [24]:

$$F^{pert}(X) = \frac{\alpha_s(\mu^2)}{2\pi} A(X) + \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^2 \left[A(X) 2\pi b_0 \ln\left(\frac{\mu^2}{s}\right) + B(X)\right] \ , \quad X =< 1-T >, < M_H > \ , \tag{1}$$

where $\mu$ is the renormalization scale and $b_0 = (33 - 2n_f)/12\pi$, with the number of active flavours set to $n_f = 5$. The coefficients $A$ and $B$ have been computed with the Monte Carlo program `EVENT2` [25]. In the case of distributions, $A$ and $B$ are coefficient functions, and the fixed order predictions can be improved by calculations which resum leading and next-to-leading logarithms (NLL) of the event-shape variable to all orders in $\alpha_s$. These calculations have to be matched

to the fixed order part. A number of matching schemes have been proposed [26], namely R matching, lnR matching and modified versions of these schemes. Recently, estimations of the third order coefficient have become available, which are based on Padé approximants [27].
Hadronization corrections to the perturbative predictions are usually obtained from Monte Carlo generators, defined as a global correction factor for mean values and as a bin-by-bin correction for distributions:

$$C(X) = F_{MC}^{hadron}(X)/F_{MC}^{parton}(X) \ , \quad F(X)^{corrected} = F(X)^{pert} \cdot C(X) \ . \tag{2}$$

The correction factors $C(X)$ have been computed with the program JETSET 7.4 [28] for 14 points in $Q$, the parameters having been tuned to the ALEPH data taken at $Q = M_Z$ [21].
Non-perturbative power corrections in the spirit of Refs. [1] and [2] are defined through the notion of an effective strong coupling $\alpha_s^{eff}$, which shows an infrared regular behaviour, thereby removing divergences in perturbation series arising from infrared renormalons. This approach introduces a universal non-perturbative parameter, $\alpha_0$, which represents the portion of the integral over $\alpha_s^{eff}$ up to some infrared matching scale, $\mu_I$:

$$\alpha_0(\mu_I) = \frac{1}{\mu_I}\int_0^{\mu_I} \alpha_s^{eff}(k)dk \ . \tag{3}$$

The matching scale separates the perturbative form of $\alpha_s$ from the effective one and should be chosen to be of the order of a few GeV, $\Lambda \ll \mu_I \ll Q$, where $\Lambda \approx 200$ MeV is the fundamental QCD scale where the strong coupling constant diverges. The power corrected expression for the mean values is thus

$$\begin{aligned} F^{corrected} &= F^{pert} + F^{power} \ , & (4)\\ F^{power} &= a\frac{\mu_I}{Q}\left[\alpha_0(\mu_I) - \alpha_s(\mu) - 2b_0\left(\ln\frac{\mu}{\mu_I} + \frac{4\pi K}{b_0} + 1\right)\alpha_s^2(\mu)\right] \ , & (5)\\ K &= \left(\frac{67}{18} - \frac{\pi^2}{6}\right)C_A - \frac{5}{9}n_f, \ a = -4\frac{C_f}{\pi} \ , \end{aligned}$$

with the colour factors $C_A = 3$, $C_F = 4/3$. The leading power correction coefficient $a$, being calculated from the perturbative cut-off behaviour of thrust, is assumed to be the same for the heavy jet mass, since these variables are identical to first order in $\alpha_s$. Power corrections to the thrust distribution can be implemented as a shift of the whole distribution:

$$F^{corrected}(X) = F^{pert}\Big(X - \Delta X\Big) \ , \ \Delta X = F^{power} \ ( \text{ Eq.(5)}) \ . \tag{6}$$

Note that in the case of heavy jet mass, the leading power correction is not expected to be represented by such a simple shift [2].

# 4 Data Analysis

## 4.1 Mean Values

The prediction based on Eq.(1) is fitted to the data by a least-squares minimization. Two parameters are determined in the case of $1/Q$ corrections (Eq.(4)). The results for $\mu = Q$ and $\mu_I = 2$ GeV in the case of $< 1 - T >$ are :

$$\alpha_s(M_Z) = 0.1196 \pm 0.0017 \ , \ \alpha_0(2 \text{ GeV}) = 0.531 \pm 0.011 \ , \ \text{(statistical errors only)} \ ,$$

with $\chi^2/N_{dof}$ =44/37. The correlation between $\alpha_s$ and $\alpha_0$ is found to be $-77\%$. This result should be compared to a fit with MC-based hadronization corrections (Eq.(2)) :

$$\alpha_s(M_Z) = 0.1306 \pm 0.0006 \ ,$$

with $\chi^2/N_{dof}$ =74/38. Examples of the fits are shown in Fig. 1. The largest contribution to the $\chi^2$ is observed in the energy range of PETRA, where the spread of the measurements is large. Fits to $< M_H >$ give similar results: the quality of the fit is slightly better with $1/Q$ corrections than with MC-based corrections. Compared to the measurement on thrust, the values found for $\alpha_0$ and $\alpha_s$ are lower (Fig. 2). The results on the mean values are summarized in Table 1.

In order to check the functional dependence of non-perturbative corrections on $Q$, a number of options have been tested. The perturbative formula Eq.(1) has been extended by additional terms of the form $C/f(Q)$. The corresponding fit results for $< 1 - T >$ are listed in Table 2. It can be summarized that the $C/Q$ Ansatz is favoured by the data, with $C$ being of the order of 1 GeV. The power of $Q$ is found to be close to one, and with the present precision of the data no indication of higher order power corrections can be seen for thrust.

Further systematic checks have been performed. The dominant systematic uncertainty on $\alpha_s$ and $\alpha_0$ is related to the choice of the renormalization scale $\log f$ , $f = \mu^2/s$. The scale has been varied around its nominal value $\log f = 0$ until the $\chi^2/N_{dof}$ is increased by one, i.e., $-0.25 \leq \log f \leq 1$. The quality of the fits deteriorated rapidly when scales $\mu \leq 0.5Q$ were applied. It turned out that also $\alpha_0$ depends on the $\mu$ scale, although being a non-perturbative quantity. Another systematic error stems from the choice of the infrared matching scale $\mu_I$, which has been varied by 1 GeV around its nominal value of 2 GeV. Here, the quality of the fit does not change much and the value of $\alpha_s$ is rather stable with respect to this variation. This should be compared to the change in $\alpha_s$ obtained when a different Monte Carlo model is used for corrections [21]. By construction (Eq.(3)), $\alpha_0$ depends directly on $\mu_I$. In the case of $< 1 - T >$ its value changes from 0.793 at $\mu_I = 1$ GeV to 0.432 at $\mu_I = 3$ GeV. Finally, the fit range has been varied, i.e., experiments below 30 GeV and experiments at energies higher than the mass of the $Z$ have been excluded from the fit. All systematic uncertainties are given in Table 3.

### 4.2 Distributions

The same strategy as for the mean values is pursued for distributions, with the improvements on the perturbative side from NLL calculations. The same values for $\mu$ and $\mu_I$ as for the mean values have been taken and the fit range has been set to 0.65-0.95 for thrust and to 0.04-0.30 for heavy jet mass. Taking the mean of the fit results with the lnR matching and the R matching, the following numbers are obtained from the thrust distribution :

$$\alpha_s(M_Z) = 0.1194 \pm 0.0003 \ , \ \alpha_0(2 \text{ GeV}) = 0.529 \pm 0.002 \ , \ \text{(statistical errors only)} \ ,$$

with $\chi^2/N_{dof}$ =723/205 for the lnR matching and $\chi^2/N_{dof}$ =352/205 for the R matching. These results are very consistent with the results from $< 1 - T >$. Again, the comparison with fits using hadronization corrections from Monte Carlo is made :

$$\alpha_s(M_Z) = 0.1272 \pm 0.0002 \ ,$$

with $\chi^2/N_{dof}$ =315/206 for the lnR matching and $\chi^2/N_{dof}$ =347/206 for the R matching. In contrast to the analysis of the mean values, the quality of the fits with Monte Carlo corrections is generally better than for the $1/Q$ option, which can be observed from Table 4. Examples of these fits to thrust are shown in Fig. 3. Results for all perturbative predictions are summarized in Table 4.

The analysis of the heavy jet mass distribution is more difficult, because the quality of the fits is poor for both methods. Particular problems appear for low energy measurements (Fig. 4). The results with $1/Q$ corrections are :

$$\alpha_s(M_Z) = 0.1117 \pm 0.0004 \ , \ \alpha_0(2 \text{ GeV}) = 0.423 \pm 0.002 \ ,$$

with $\chi^2/N_{dof}$ =1555/180 for the lnR matching and $\chi^2/N_{dof}$ =1795/180 for the R matching. The fits with hadronization corrections are better, but still worse than the ones for thrust :

$$\alpha_s(M_Z) = 0.1219 \pm 0.0003 \; ,$$

with $\chi^2/N_{dof}$ =642/181 for the lnR matching and $\chi^2/N_{dof}$ =877/181 for the R matching. Monte Carlo studies indicate that b-quark mass effects are important at lower energies. These effects are ignored in the $1/Q$ approach, but are to some extent taken into account by the Monte Carlo models. The value of $\alpha_0$ obtained with distributions is consistent with the one from mean values, but large differences appear between the values obtained from different variables. The apparent non-universality of $\alpha_0$ might also be due to mass effects, which show up in different ways for thrust and heavy jet mass, or it could be related to missing higher order power corrections. The best $\chi^2$ for the $M_H$ distribution is obtained with fixed order calculations completed by $\mathcal{O}(\alpha_s^3)$ estimations based on Padé approximants, for both options of non-perturbative corrections. A complete summary of fit results is given in Table 4.

Systematic uncertainties have been estimated as for the mean values, except for the treatment of the scale and the matching scheme uncertainty, where the following procedure has been applied. The mean of the results on $\alpha_s$ and $\alpha_0$ obtained with R matching and lnR matching are taken as central result and half of the maximum discrepancy between the results from the different schemes are quoted as error from the scheme ambiguity. In addition, the scale has been varied in the range $-1 \leq \ln f \leq 1$ for each individual scheme, and the largest deviation from the results at $\ln f = 0$ is taken as error stemming from the scale uncertainty. Both variations characterize the impact of unknown higher orders. Note that the $1/Q$ method depends less on the matching scheme than the Monte Carlo method. The error arising from the $\mu$ scale variation is somewhat smaller than for the mean values, since the sensitivity to missing higher orders has been reduced by the inclusion of resummation. Another check has been performed by varying the fit range in thrust and heavy jet mass. The ranges have been extended (and also reduced) by 0.02 at both ends of the nominal ranges. A detailed breakdown of all systematic uncertainties is given in Table 5.

## 5 Conclusions

Analytic non-perturbative $1/Q$ corrections to event-shape variables have been tested and compared to a method based on hadronization corrections from a Monte Carlo model. A good description of the experimental data is obtained for the mean value and the distribution of thrust, with a less model-dependent Ansatz. The preliminary results on $\alpha_s(M_Z)$ and the non-perturbative parameter $\alpha_0$, using the thrust distribution, are:

$$\alpha_s(M_Z) = 0.1194 \pm 0.0003_{stat} \pm 0.0035_{syst} \; , \; \alpha_0(2\text{ GeV}) = 0.529 \pm 0.002_{stat} \pm 0.0034_{syst} \; .$$

In the case of the heavy jet mass distribution power corrections are not well represented by a shift of the distribution. The investigation of heavy jet mass and other event-shape variables has to be pursued. Calculations taking into account quark masses should be included into the theoretical prediction, in order to disentangle hadronization from mass effects.

## Acknowledgements

We wish to thank our colleagues from the CERN accelerator divisions for the successful operation of LEP. We are indebted to the engineers and technicians in all our institutions for their contribution to the good performance of ALEPH. Those of us from non-member states thank CERN for its hospitality.

# References

[1] Yu.L. Dokshitzer and B.R. Webber, Phys. Lett. **B352** (1995) 451.

[2] Yu.L. Dokshitzer and B.R. Webber, Cavendish-HEP-97/2 (1997).

[3] D.P. Barber et al., MARKJ Collaboration, Phys. Rep. **63** (1980) 337.

[4] H.J. Behrend et al., CELLO Collaboration, Z. Phys. **C44** (1989) 63.

[5] Ch. Berger et al., PLUTO Collaboration, Z. Phys **C12** (1981) 297.

[6] W. Braunschweig et al., TASSO Collaboration, Z. Phys. **C47** (1990) 187; Z. Phys. **C45** (1989) 11; Z. Phys. **C22** (1984) 307.

[7] A. Petersen et al., MARKII Collaboration, Phys. Rev. **D37** (1988) 1.

[8] D. Bender et al., HRS Collaboration, Phys. Rev. **D31** (1985) 1.

[9] Y.K. Li et al., AMY Collaboration, Phys. Rev. **D41** (1990) 2675.

[10] Y. Ohnishi et al., TOPAZ Collaboration, Phys. Lett. **B313** (1993) 475.

[11] K. Nagai et al., TOPAZ Collaboration, Phys. Lett. **B278** (1992) 506.

[12] K. Abe et al., SLD Collaboration, Phys. Rev. **D51** (1995) 962.

[13] B. Adeva et al., L3 Collaboration, Z. Phys. **C55** (1992) 39.

[14] M. Acciarri et al., L3 Collaboration, Phys. Lett. **B370** (1996) 137.

[15] M. Acciarri et al., L3 Collaboration, CERN-PPE/97-42,
*submitted to Phys. Lett.*

[16] P. Abreu et al., DELPHI Collaboration, Z. Phys. **C73** (1996) 11.

[17] P. Abreu et al., DELPHI Collaboration, Z. Phys. **C73** (1997) 229.

[18] P.D. Acton et al., OPAL Collaboration, Z. Phys. **C55** (1992) 1; Z. Phys. **C59** (1993) 1.

[19] G. Alexander et al., OPAL Collaboration, Z. Phys. **C72** (1996) 191.

[20] K. Akerstaff et al., OPAL Collaboration, CERN-PPE/97-15,
*submitted to Z. Phys.*

[21] R. Barate et al., ALEPH Collaboration, CERN-PPE/96-186,
*submitted to Phys. Rep.*

[22] D. Buskulic et al., ALEPH Collaboration, Z. Phys. **C73** (1996) 195.

[23] R. Barate et al., ALEPH Collaboration, this Conference, Abstract 629.

[24] R.K. Ellis, D.A. Ross and A.E. Terrano, Nucl. Phys. **B 178** (1981) 421.

[25] S. Catani and M. Seymour, Nucl. Phys. **B485** (1997) 291.

[26] S. Catani et al., Phys. Lett. **B263** (1991) 491; Phys. Lett. **B272** (1991) 368; Nucl. Phys. **B407** (1993) 3.

[27] P.N. Burrows et al., Phys. Lett. **B392** (1997) 223.

[28] T. Sjöstrand, Comp. Phys. Comm. **39** (1986) 347; **43** (1987) 367; **82** (1994) 74.

| Variable | Fits with MC corrections | Fits with $1/Q$ corrections | |
|---|---|---|---|
| | $\alpha_s$ | $\alpha_s$ | $\alpha_0$ |
| $< 1 - T >$ | $0.1306 \pm 0.0087$ | $0.1196 \pm 0.0083$ | $0.531 \pm 0.039$ |
| $< M_H >$ | $0.1268 \pm 0.0092$ | $0.1151 \pm 0.0099$ | $0.437 \pm 0.047$ |
| $1/\sigma\ d\sigma/dT$ | $0.1272 \pm 0.0043$ | $0.1194 \pm 0.0035$ | $0.529 \pm 0.034$ |
| $1/\sigma\ d\sigma/dM_H$ | $0.1219 \pm 0.0038$ | $0.1117 \pm 0.0035$ | $0.423 \pm 0.036$ |

Table 1: Comparison of preliminary results on $\alpha_s$ from mean values and distributions of event-shape variables for two methods. The errors on $\alpha_s$ and $\alpha_0$ ($1/Q$ approach) are the quadratic sum of statistical and systematic errors. The systematic errors are dominant in all cases.

| Fit Option | $\alpha_s(M_Z)$ | Other Parameters | $\chi^2/N_{dof}$ |
|---|---|---|---|
| $\mathcal{O}(\alpha_s^2)+$ Eq.(5) | $0.1195 \pm 0.0017$ | $\alpha_0 = .531 \pm 0.011$ | 44/37 |
| $\mathcal{O}(\alpha_s^2)*$ Eq.(2) | $0.1306 \pm 0.0006$ | *none* | 74/38 |
| $\mathcal{O}(\alpha_s^2)$ | $0.1464 \pm 0.0006$ | *none* | 135/38 |
| $\mathcal{O}(\alpha_s^2) + \frac{C}{Q}$ | $0.1263 \pm 0.0021$ | $C = 0.73 \pm 0.07$ | 43/37 |
| $\mathcal{O}(\alpha_s^2) + \frac{C}{\sqrt{Q}}$ | $0.0552 \pm 0.005$ | $C = 0.43 \pm 0.02$ | 52/37 |
| $\mathcal{O}(\alpha_s^2) + \frac{C}{Q^2}$ | $0.1406 \pm 0.0010$ | $C = 6.21 \pm 0.69$ | 56/37 |
| $\mathcal{O}(\alpha_s^2) + \frac{C}{Q^P}$ | $0.1258 \pm 0.0093$ | $C = 0.74 \pm 0.22$<br>$P = 0.98 \pm 0.19$ | 44/37 |
| $\mathcal{O}(\alpha_s^2)+$<br>$\frac{C}{Q} + \frac{D}{Q^2}$ | $0.1267 \pm 0.0037$ | $C = 0.74 \pm 0.20$<br>$D = -0.04 \pm 1.7$ | 44/38 |

Table 2: Fit results on $\alpha_s$ and additional non-perturbative parameters using the mean value of thrust. Different functional forms of hadronization corrections have been parameterized here, assuming a simple functional dependence on $Q$. The errors are statistical only.

| | thrust | | | heavy jet mass | | |
|---|---|---|---|---|---|---|
| Source | Fits with MC corr. | Fits with $1/Q$ corr. | | Fits with MC corr. | Fits with $1/Q$ corr. | |
| | $\Delta\alpha_s$ | $\Delta\alpha_s$ | $\Delta\alpha_0$ | $\Delta\alpha_s$ | $\Delta\alpha_s$ | $\Delta\alpha_0$ |
| $\mu$ Scale | $\pm 0.0085$ | $\pm 0.0077$ | $\pm 0.036$ | $\pm 0.0092$ | $\pm 0.0095$ | $\pm 0.046$ |
| $Q$ Range | $\pm 0.0018$ | $\pm 0.0004$ | $\pm 0.008$ | $\pm 0.0006$ | $\pm 0.0007$ | $\pm 0.005$ |
| $\mu_I$ Scale | | $\pm 0.0024$ | | | $\pm 0.0024$ | |
| total syst. | $\pm 0.0087$ | $\pm 0.0081$ | $\pm 0.037$ | $\pm 0.0092$ | $\pm 0.0098$ | $\pm 0.046$ |

Table 3: Systematic errors for the measurements of $\alpha_s$ and $\alpha_0$ using the mean values of thrust and heavy jet mass.

| | thrust | | heavy jet mass | |
|---|---|---|---|---|
| Fit Option | Fits with MC corr. | Fits with $1/Q$ corr. | Fits with MC corr. | Fits with $1/Q$ corr. |
| $\mathcal{O}(\alpha_s^2)$ | $\alpha_s = 0.1382 \pm 0.0003$<br>$\chi^2/N_{dof} = 1306/206$ | $\alpha_s = 0.1426 \pm 0.0005$<br>$\alpha_0 = 0.375 \pm 0.004$<br>$\chi^2/N_{dof} = 1630/205$ | $\alpha_s = 0.1371 \pm 0.0004$<br>$\chi^2/N_{dof} = 401/181$ | $\alpha_s = 0.1349 \pm 0.0005$<br>$\alpha_0 = 0.364 \pm 0.004$<br>$\chi^2/N_{dof} = 1235/180$ |
| $\mathcal{O}(\alpha_s^3)$ | $\alpha_s = 0.1198 \pm 0.0002$<br>$\chi^2/N_{dof} = 1356/206$ | $\alpha_s = 0.1212 \pm 0.0002$<br>$\alpha_0 = 0.360 \pm 0.002$<br>$\chi^2/N_{dof} = 1708/205$ | $\alpha_s = 0.1284 \pm 0.0004$<br>$\chi^2/N_{dof} = 330/181$ | $\alpha_s = 0.1280 \pm 0.0005$<br>$\alpha_0 = 0.326 \pm 0.004$<br>$\chi^2/N_{dof} = 1144/180$ |
| $lnR$ | $\alpha_s = 0.1246 \pm 0.0002$<br>$\chi^2/N_{dof} = 315/206$ | $\alpha_s = 0.1181 \pm 0.0003$<br>$\alpha_0 = 0.508 \pm 0.003$<br>$\chi^2/N_{dof} = 723/205$ | $\alpha_s = 0.1209 \pm 0.0003$<br>$\chi^2/N_{dof} = 642/181$ | $\alpha_s = 0.1110 \pm 0.0003$<br>$\alpha_0 = 0.422 \pm 0.001$<br>$\chi^2/N_{dof} = 1555/180$ |
| $lnRmod$ | $\alpha_s = 0.1263 \pm 0.0002$<br>$\chi^2/N_{dof} = 731/206$ | $\alpha_s = 0.1192 \pm 0.0003$<br>$\alpha_0 = 0.510 \pm 0.003$<br>$\chi^2/N_{dof} = 1059/205$ | $\alpha_s = 0.1224 \pm 0.0003$<br>$\chi^2/N_{dof} = 2401/181$ | $\alpha_s = 0.1126 \pm 0.0004$<br>$\alpha_0 = 0.426 \pm 0.001$<br>$\chi^2/N_{dof} = 1226/180$ |
| $R$ | $\alpha_s = 0.1298 \pm 0.0002$<br>$\chi^2/N_{dof} = 347/206$ | $\alpha_s = 0.1207 \pm 0.0002$<br>$\alpha_0 = 0.550 \pm 0.001$<br>$\chi^2/N_{dof} = 352/205$ | $\alpha_s = 0.1228 \pm 0.0003$<br>$\chi^2/N_{dof} = 877/181$ | $\alpha_s = 0.1124 \pm 0.0004$<br>$\alpha_0 = 0.422 \pm 0.002$<br>$\chi^2/N_{dof} = 1795/180$ |
| $Rmod$ | $\alpha_s = 0.1265 \pm 0.0002$<br>$\chi^2/N_{dof} = 312/206$ | $\alpha_s = 0.1195 \pm 0.0003$<br>$\alpha_0 = 0.516 \pm 0.003$<br>$\chi^2/N_{dof} = 568/205$ | $\alpha_s = 0.1197 \pm 0.0003$<br>$\chi^2/N_{dof} = 740/181$ | $\alpha_s = 0.1149 \pm 0.0004$<br>$\alpha_0 = 0.351 \pm 0.005$<br>$\chi^2/N_{dof} = 1993/180$ |

Table 4: Fit results for $\alpha_s$ and $\alpha_0$ ($1/Q$ approach) using the distributions of thrust and heavy jet mass. Different perturbative predictions are compared, and two methods describing the hadronization process are confronted to each other. All results are given at $\mu = Q$ and $\mu_I = 2$ GeV.

|  | thrust |  |  | heavy jet mass |  |  |
|---|---|---|---|---|---|---|
| Source | Fits with MC corr. | Fits with $1/Q$ corr. |  | Fits with MC corr. | Fits with $1/Q$ corr. |  |
|  | $\Delta\alpha_s$ | $\Delta\alpha_s$ | $\Delta\alpha_0$ | $\Delta\alpha_s$ | $\Delta\alpha_s$ | $\Delta\alpha_0$ |
| Matching Scheme | ±0.0026 | ±0.0013 | ±0.021 | ±0.0010 | ±0.0006 | ±0.001 |
| $\mu$ Scale | ±0.0031 | ±0.0026 | ±0.014 | ±0.0036 | ±0.0032 | ±0.031 |
| Fit Range | ±0.0013 | ±0.0011 | ±0.016 | ±0.0004 | ±0.0006 | ±0.012 |
| $Q$ Range | ±0.0003 | ±0.0008 | ±0.017 | ±0.0001 | ±0.0006 | ±0.014 |
| $\mu_I$ Scale |  | ±0.0013 |  |  | ±0.0011 |  |
| total syst. | ±0.0043 | ±0.0035 | ±0.034 | ±0.0038 | ±0.0036 | ±0.036 |

Table 5: Systematic uncertainties on the measurements of $\alpha_s$ and $\alpha_0$ from event-shape distributions.

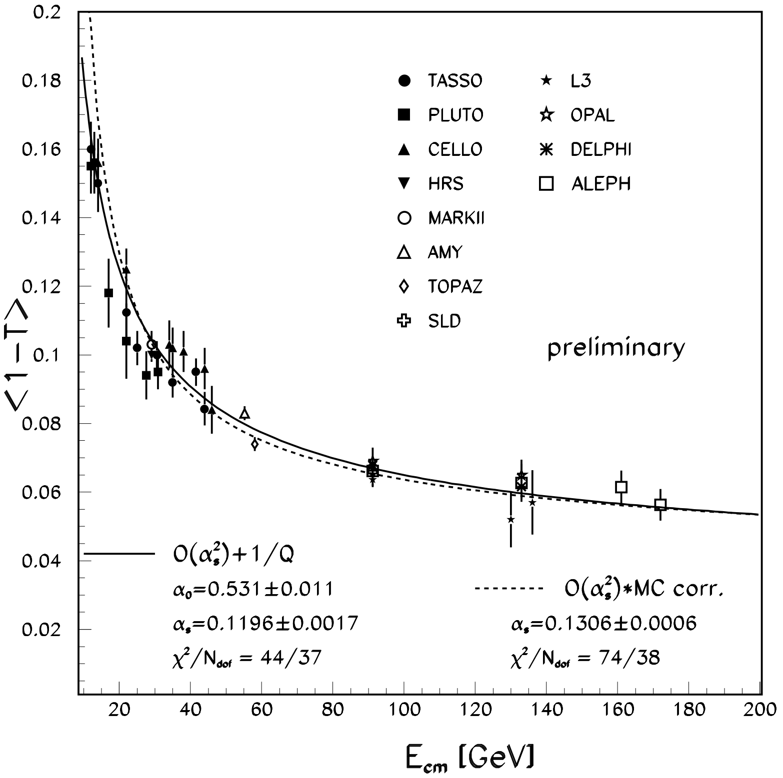

Figure 1: Fits to $< 1 - T >$. Full line: $\mathcal{O}(\alpha_s^2)$ with $1/Q$ corrections according to Eq.(4), dashed line: $\mathcal{O}(\alpha_s^2)$ with hadronization corrections from JETSET (Eq.(2)).

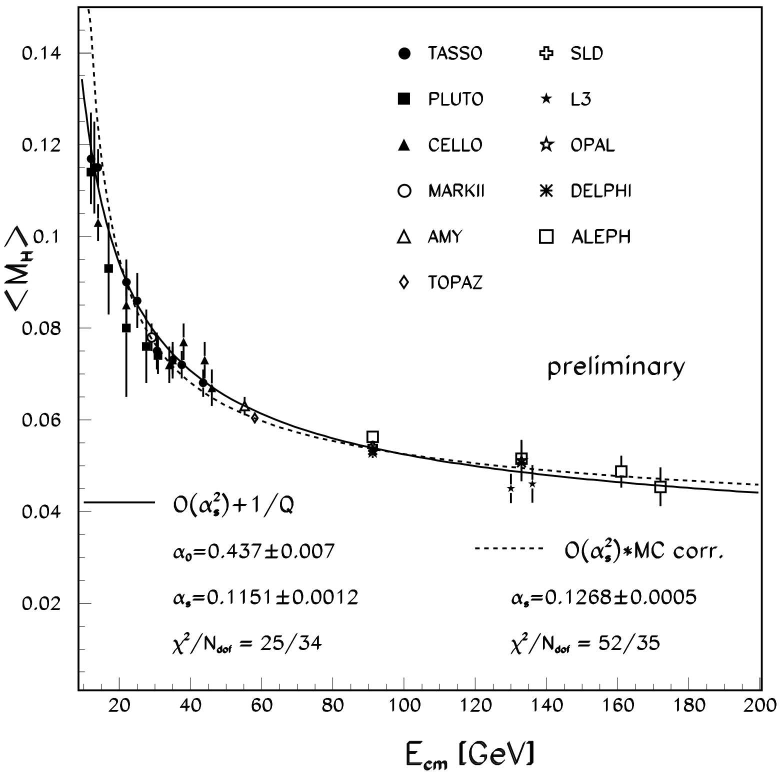

Figure 2: Fits to $< M_H >$. Full line: $\mathcal{O}(\alpha_s^2)$ with $1/Q$ corrections according to Eq.(4), dashed line: $\mathcal{O}(\alpha_s^2)$ with hadronization corrections from JETSET (Eq.(2)).

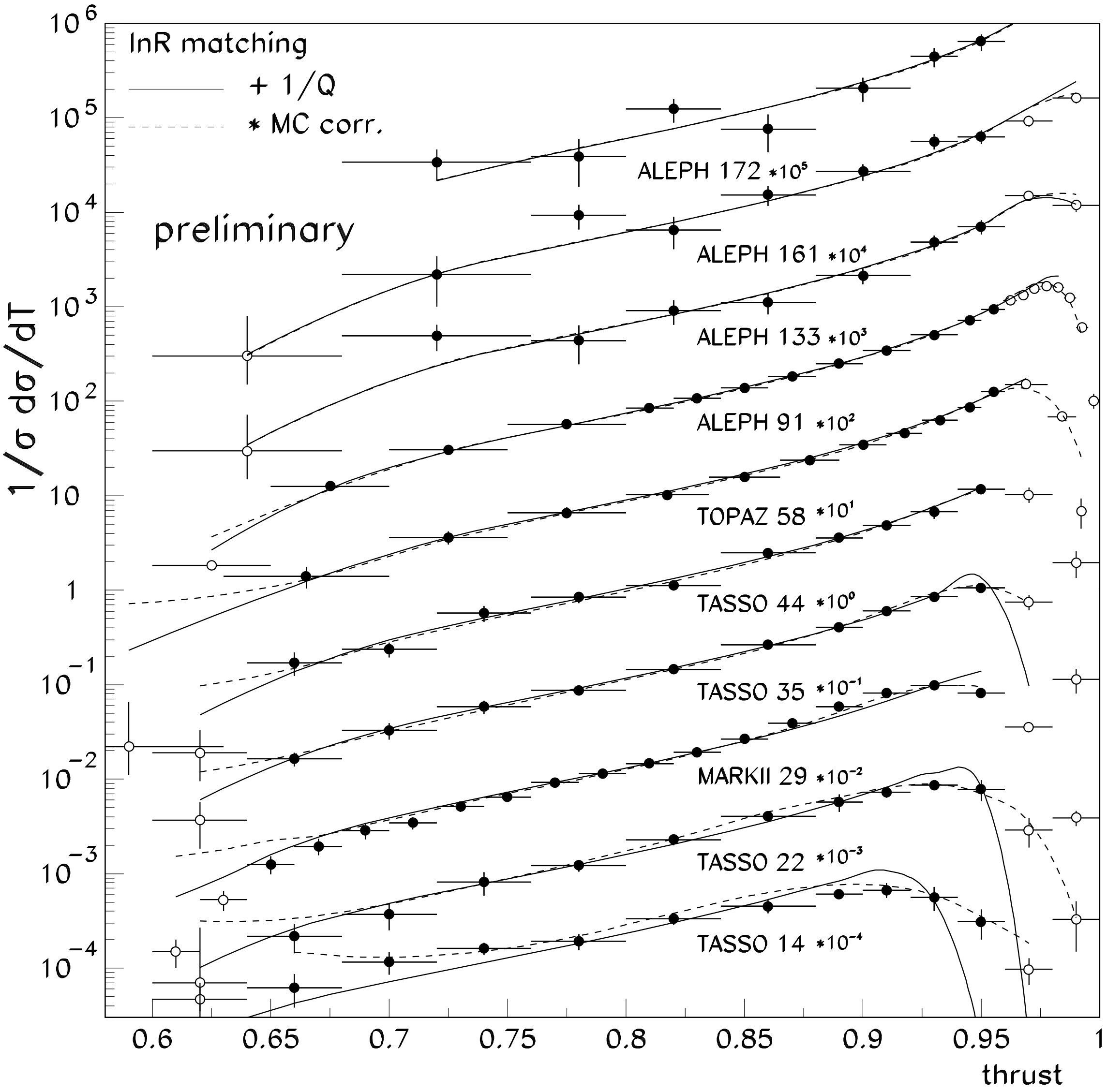

Figure 3: Fits to thrust distributions measured at different $Q$. The full line shows the result of a fit based on $\mathcal{O}(\alpha_s^2) + NLL$ with $1/Q$ corrections, the dashed line a corresponding fit with hadronization corrections from Monte Carlo simulations. Fits are performed over the thrust range of 0.65 - 0.95, which is indicated by full dots.

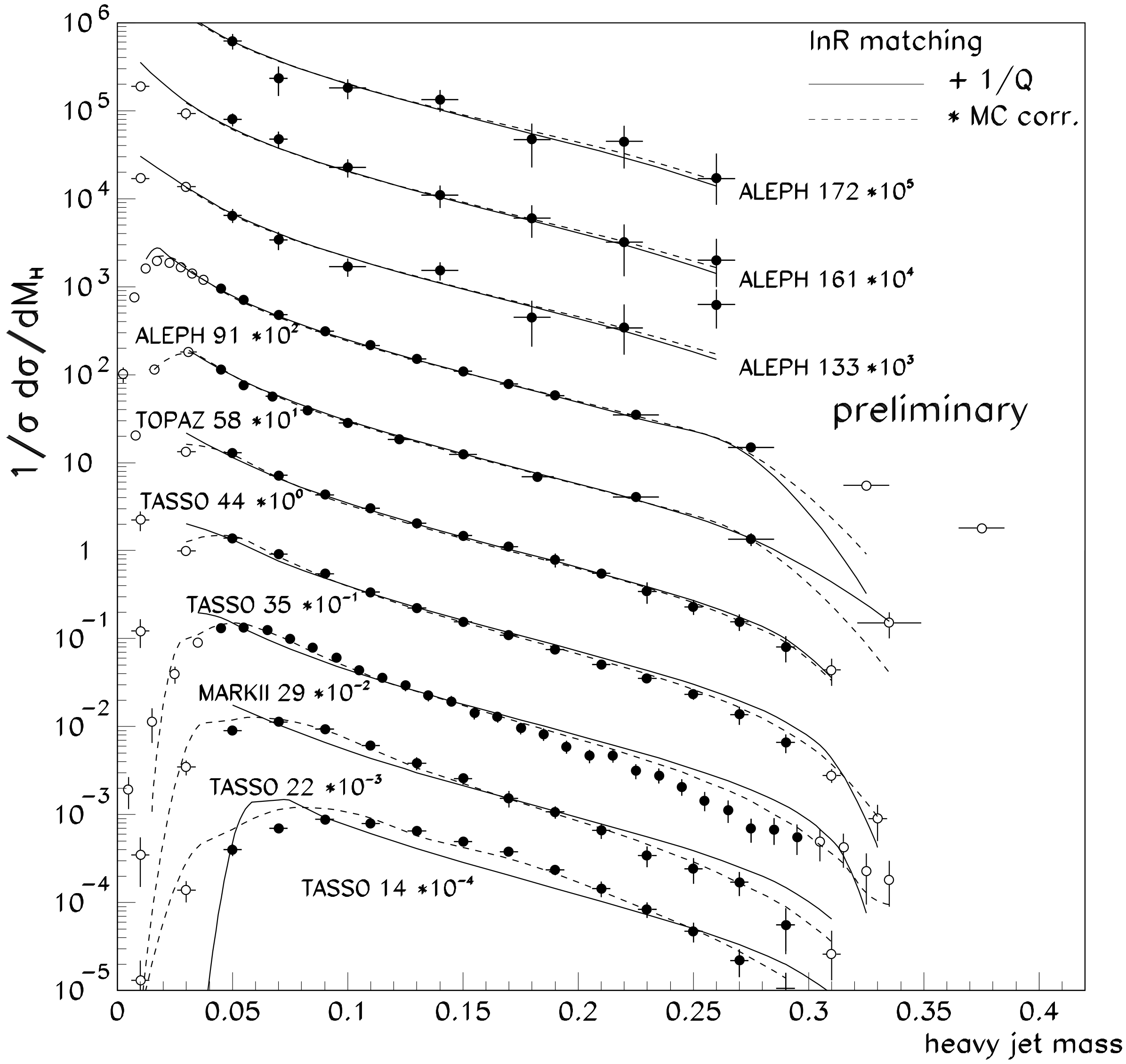

Figure 4: Fits to heavy jet mass distributions measured at different $Q$. The full line shows the result of a fit based on $\mathcal{O}(\alpha_s^2) + NLL$ with $1/Q$ corrections, the dashed line a corresponding fit with hadronization corrections from Monte Carlo simulations. Fits are performed over the heavy jet mass range of 0.04 - 0.30, which is indicated by full dots.