JET PHYSICS AT LEP
AND
WORLD SUMMARY OF $\alpha_s$

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Recent results on jet physics and tests of QCD from hadronic final states in $e^+e^-$ annihilation at PETRA and at LEP are reviewed, with special emphasis on hadronic event shapes, charged particle production rates, properties of quark and gluon jets and determinations of $\alpha_s$. The data in the entire energy range from PETRA to LEP-2 are in broad agreement with the QCD predictions. The world summary of measurements of $\alpha_s$ is updated and a detailed discussion of various methods to determine the overall error of $\alpha_s(M_{Z^0})$ is presented. The new world average is $\alpha_s(M_{Z^0}) = 0.119 \pm 0.004$. The size of the error depends on the treatment of correlated uncertainties.

1 $e^+e^-$ Annihilation Data

Over the past few years, a large amount of $e^+e^-$ annihilation data in the c.m. energy range from $Q = \sqrt{s} = 10$ to 189 GeV was accumulated at the CESR, PETRA, PEP, Tristan, LEP and SLC accelerators. The large data samples at LEP-1, which amount to about 4 million hadronic events around the $Z^0$ resonance for each of the four LEP experiments, and the most recent data at the highest energies of LEP-2 (a few thousand events per experiment), together with reanalysed PETRA data at lower c.m. energies (about 50,000 hadronic events), provide powerful tools for precise tests of perturbative QCD.

At energies below or at the $Z^0$ resonance, respectively at PETRA and at LEP-1, the study of $e^+e^-$ annihilation events is rather “easy” and straightforward: apart from two-photon processes, the energy and quantum numbers of the hard scattering are well defined and different processes can be identified and selected with only very little backgrounds or biases. At LEP-2, i.e. at energies above the $Z^0$ pole, the situation is more complicated:

- The annihilation cross section is orders of magnitude lower than at the $Z^0$ pole; see Figure 1b.
- Initial state photon radiation reduces the available energy of the hadronic c.m. system, $\sqrt{s'}$, see Figure 1a, and causes, together with the resonant

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$^a$Presented at the IV$^{th}$ Int. Symp. on Radiative Corrections, Barcelona, Sept. 8-12, 1998.
Figure 1: Hadronic cross sections and available data in $e^+e^-$ annihilation (for details see text); $R = \sigma(e^+e^- \to q\bar{q})/\sigma(e^+e^- \to \mu^+\mu^-)$.

cross section around the $Z^0$ mass, a large “return-to-the-$Z$” effect. Radiative events can be suppressed requiring a minimum reconstructed ratio of $\sqrt{s'}/\sqrt{s}$ and other kinematic constraints.

- Other processes like $e^+e^- \to W^+W^-$ and $e^+e^- \to Z^0Z^0$ emerge above the respective energy thresholds, see the shaded area in Figure 1(c), causing a certain irreducible background for QCD studies.

In the following sections, recent QCD tests from LEP-1 ($\sqrt{s} \sim 91$ GeV; Section 2), from LEP-2 ($\sqrt{s} \sim 130$ GeV to 189 GeV; Section 3) and from a combination of PETRA and LEP data ($\sqrt{s} \sim 14$ GeV to 172 GeV; Section 4) are presented. The world summary of $\alpha_s$ is updated in Section 5.
2 QCD Tests at LEP-1

2.1 $\alpha_s$ from Event Shapes using Optimised $\mathcal{O}(\alpha_s^2)$ QCD

![Figure 2: Measurements of $\alpha_s$ from hadronic event shapes at LEP-1 using $\mathcal{O}(\alpha_s^2)$ QCD predictions with (left) and without (right) optimised renormalisation scales $\mu$.](image)

The DELPHI collaboration contributed a new measurement of $\alpha_s$ from oriented event shape distributions at LEP-1. 17 different event shape observables are measured as a function of the polar angle of the thrust axis, and $\alpha_s$ is determined from fits to $\mathcal{O}(\alpha_s^2)$ QCD calculations. As already reported earlier, good agreement between theory and data can be obtained if both $\alpha_s$ and the renormalisation scale $\mu$ are determined simultaneously; see Figure 2.

With optimised renormalisation scales and allowing for scale uncertainties between $0.5 \times \mu_{exp}$ and $2 \times \mu_{exp}$, consistent results of $\alpha_s(M_Z)$ emerge, leading to a combined average of $\alpha_s(M_Z) = 0.117 \pm 0.003$. Both the average and the error, which includes theoretical uncertainties from scale changes as given above, are smaller than those obtained from resummed $\mathcal{O}(\alpha_s^2)$ QCD fits. This
is basically due to the choice of the averaging procedure and error definition. The broad consistency between data and optimised $\mathcal{O}(\alpha_s^2)$ QCD justifies this procedure and suggests to reconsider optimised fixed order perturbation theory as an alternative to resummation which was preferred in the past.

2.2 Differences between Quark- and Gluon-Jets

![Figure 3: Charged particle multiplicities in gluon-inclusive and in light (uds) quark jets in the central rapidity ($|y| < 2$) range.](image)

Differences between quark- and gluon-jets were studied quite intensively during the past few years. The aim is to test the basic QCD prediction that hadrons coming from gluon jets should exhibit a softer energy spectrum and a wider transverse momentum distribution than those originating from quark jets, due to the larger colour charge of the gluon. In particular, the ratio $R_{qg}$ of the average multiplicities of hadrons in gluon jets and in quark jets should, for infinite jet energies and in leading order QCD, be $\approx C_A/C_F = 3/(4/3) = 9/4 = 2.25$.

Experimental procedures to separate quark- from gluon-jets are usually based on vertex tagging of primary $b$-quark decays. In short, 3-jet like events $^b$ Note that, for instance, a previous study based on 13 observables and using a different procedure to average results and determine the overall error obtained $\alpha_s(M_Z) = 0.122^{+0.006}_{-0.005}$ which, if the same procedure as used in the DELPHI analysis is applied, converts to $\alpha_s(M_Z) = 0.116 \pm 0.003$. 

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are selected in which one of the two lower energetic jets is tagged as a b-quark, while the other low energy jet is then taken to be the gluon jet. From first analyses of this type it was found that, after correction for misidentified jets, $R_{qg} = 1.27 \pm 0.07$. No QCD calculation for this particular type of analysis exists, such that a direct comparison of this result with theory is not possible.

Theoretical predictions only exist for colour singlet $q\bar{q}$ and $gg$ final states, where however the latter state is not experimentally accessible. In order to perform an analysis closer to theory, OPAL followed a new strategy in which events with a high-energetic gluon-jet recoiling against a (vertex-tagged) $q\bar{q}$ system, were selected. Such events are relatively rare, leading to about 550 selected gluon jets from OPAL’s LEP-1 data sample.

A comparison of the charged hadron multiplicity distribution of such gluon hemispheres with those of ordinary light quark event hemispheres is shown in Figure 3, where a significant difference between quark- and gluon-jets is seen.
For a central rapidity range, the hadron multiplicity ratio $R_{qg}$ is found to be $1.87 \pm 0.13$; the remaining difference to the QCD expectation of 2.25 is likely to be explained by finite jet energy effects.

DELPHI has studied the scale dependence of particle multiplicities in quark- and gluon-jets\textsuperscript{7}. Here, gluon-jets and light quark-jets are (anti-)tagged in 3-jet events, and a jet energy scale of $\kappa = E_{\text{jet}} \sin(\theta/2)$, where $\theta$ is the angle between the two lowest energetic jets, is defined. The charged hadron multiplicities for quark- and gluon-jets, as a function of $\kappa$, are displayed in Figure 4. Also shown is the ratio of multiplicities and the ratio of slopes; the latter being close to the QCD prediction of 2.25.

From these measurements DELPHI determines the ratio $C_A/C_F$ to be $2.27 \pm 0.012$ which is in good agreement with QCD, and in particular with the expected colour charge of the gluon.

3 QCD Tests at LEP-2

3.1 Hadronic Event Shapes and Running of $\alpha_s$

![Figure 5: Thrust-distributions measured by ALEPH at various c.m. energies, and common fit to analytic QCD calculations in resummed next-to-leading order perturbation theory.](image)

At each new energy point of LEP-2, all four LEP experiments have extensively studied hadronic event shape distributions and compared the new measurements with the predictions of QCD Monte Carlo models, as well as with analytic QCD calculations. In all cases, up to and including the most re-
cent data at $\sqrt{s} = 189$ GeV, good agreement of data and theory was found, and no significant deviation from the standard expectation was seen. As an example, Figure 5 shows the thrust-distributions measured by ALEPH at LEP-1 and at four energy points of LEP-2, together with a fit to resummed $O(\alpha_s^2)$ QCD calculations which is in good agreement with the data at all energies.

The L3 collaboration has summarised their measurements of $\alpha_s$ from various event shape distributions, at LEP-1, at all LEP-2 energy points, and at hadronic c.m. energies below the $Z^0$ pole, from an analysis of radiative events recorded at LEP-1. The data, which are displayed in Figure 6, are in very good agreement with the QCD prediction of a running coupling $\alpha_s(\sqrt{s})$.

3.2 Energy Dependence of Charged Particle Production

The energy dependence of particle production was, similarly as hadronic event shapes, continuously monitored by all LEP experiments. The variation of such observables with energy is found to be in good agreement with QCD predictions, and also with the “standard” QCD plus hadronisation models. The energy dependence of the average charged hadron multiplicity and of the peak position $\xi^*$ of the $\xi = \ln(1/x)$ distribution ($x = p/E_{\text{beam}}$) are shown in Figure 7.
4 Power Corrections and Energy Dependence of Event Shapes

The energy dependence of mean values of event shape observables can be parametrised by the $O(\alpha_s^2)$ perturbative QCD prediction plus a term including the improved two-loop calculations (the “Milan factor”) of power-suppressed $1/Q$ non-perturbative contributions, the so-called “power corrections”. The latter contains the moment $\alpha_0$ of an effective coupling below an infrared scale $\mu_I$, which is expected to be universal for all applicable event shape observables.

A compilation of available data on the mean value of (1-thrust) and of the C-parameter is shown in Figure 8, which is taken from a recent re-analysis of JADE data at PETRA energies. Perturbative QCD plus power corrections is found to give a very good description of the data, with $\alpha_s(M_{Z^0}) = 0.118 \pm 0.002 \pm 0.004$ as determined from these data. However, universality of $\alpha_0$ is only found to be satisfied at a level of 30%.

For differential event shape distributions, the power corrections are simply a shift of the perturbative ($O(\alpha_s^2)$) spectra, and these were also studied in a wide c.m. energy range, including the most recent PETRA and LEP data for a total of four event shape observables. A fit to these data, with $\alpha_s(M_{Z^0})$ and $\alpha_0$ as free parameters for each observable, leads to the results displayed in Figure 9. Agreement in both $\alpha_s(M_{Z^0})$ and $\alpha_0$ is obtained, to a good level of accuracy, for two of the observables. However, the jet broadening parameters $B_w$ and $B_t$ deviate significantly in both $\alpha_s(M_{Z^0})$ and $\alpha_0$. 
Most recently, the reason for these deviations was identified and traced to the theoretical predictions\cite{4}; a cure of this problem should soon be available.

5 World Summary of $\alpha_s$

Significant determinations of the strong coupling strength, $\alpha_s$, remain to be a demanding and interesting topic in experimental as well as theoretical study projects in high energy physics. In the following subsections, previous summaries of $\alpha_s$ measurements\cite{15,16} will be updated and a new world average $\alpha_s(M_{Z^0})$ will be determined. Instead of a complete reference to all available measurements, only the newest results are briefly introduced, and more emphasis is spent on a detailed discussion of the overall uncertainty of $\alpha_s(M_{Z^0})$, $\Delta\alpha_s$.

5.1 Updates and New Results

The results of all significant determinations of $\alpha_s$, i.e. of all those which are based on QCD calculations which are complete - at least - to next-to-leading order perturbation theory, are summarised in Table 2. The following entries were added or updated since summer 1997\cite{16} (underlined in Table 2):

- The most recent determination of $\alpha_s$ from the GLS sum rules, based on new data from $\nu - N$ scattering\cite{17} is included, replacing the previous

Figure 8: Energy dependence of mean values of (1-Thrust) and of the C-parameter.
result from Chyla and Kataev $^{18}$

- New measurements of $\alpha_s$ from high statistics studies of vector and axial-vector spectral functions of hadronic $\tau$-decays are available from ALEPH $^{19}$ and OPAL $^{20}$. As the most complete and precise studies of $\tau$ decays to date, these results are combined and taken to replace earlier results $^{21}$.

- H1 has contributed new determinations of $\alpha_s$ from $(2+1)$-jet event rates at HERA $^{22}$, replacing a previous measurement $^{23}$. A combination of these new results with a former one from ZEUS $^{24}$ is updated in Table 2.

- A new determination of $\alpha_s$ from $\Upsilon$-decays $^{25}$ replaces earlier results $^{26}$.

- A recent determination of $\alpha_s$ from the total $e^+e^-$ hadronic cross section measured by CLEO at $E_{cm} = 10.52$ GeV $^{27}$ is added.

- Determinations of $\alpha_s$ from JADE data, at $E_{cm} = 35$ and 44 GeV, were updated $^{28}$ by the inclusion of another observable, the C-parameter.

- $\alpha_s$ from the most recent LEP result on $R_l = \frac{\Gamma(Z^0\rightarrow\text{hadrons})}{\Gamma(Z^0\rightarrow\text{leptons})}$ was updated $^{29}$ (these results are still preliminary).

- LEP results on $\alpha_s$ from event shapes measured at $E_{cm} = 183$ and 189 GeV $^{30}$ are combined and added to the list (some of these results are still preliminary).
Further interesting and recent developments are a QCD analysis of neutrino deep inelastic scattering data for $x F_3$, in next-next-to-leading order of perturbation theory (NNLO) \[11\], resulting in $\alpha_s(M_Z) = 0.118 \pm 0.006$, and a reanalysis of muon deep inelastic scattering data \[11\], resulting in $\alpha_s(M_{Z'}) = 0.118 \pm 0.002$ (stat + syst). Both these results are subject to further completion and verification; they are therefore considered to be preliminary and are not included in this summary.

The results for $\alpha_s(Q)$, given in the 3\textsuperscript{rd} row of Table \[3\], are presented in Fig. \[11\]. These results are evolved from the energy scale $Q$, i.e. the typical energy scale of the hard scattering process under study, to the reference energy scale $M_{Z'}$, by using the QCD 4-loop beta-function with 3-loop matching at quark pole masses $M_b = 4.7 \text{ GeV}$ and $M_c = 1.5 \text{ GeV}$ \[32\], resulting in the values of $\alpha_s(M_{Z'})$ given in the 4\textsuperscript{th} row of Table 1. These values of $\alpha_s(M_{Z'})$ are displayed in Fig. \[11\]. The distribution of all $\alpha_s(M_{Z'})$ results is shown in
a scatter plot of $\alpha_s(M_{Z0})$ versus its quoted error, $\Delta\alpha_s$, and in a frequency distribution of $\alpha_s(M_{Z0})$ (Figure 12).

The world average value of $\alpha_s(M_{Z0})$ and its overall uncertainty as well as the corresponding QCD curves shown in Figs. 10 and 11 will be discussed in the following section.

5.2 World Average and Overall Uncertainty of $\alpha_s(M_{Z0})$

In order to average the results of $\alpha_s(M_{Z0})$, a weighted mean of the quoted central values is calculated, for all results as well as for subsamples as listed in Table 1. The weight of a measurement is taken to be the inverse of the square of its total error.

The central value $\bar{\alpha}_s(M_{Z0})$ does not depend on details of the weighting method; no significant differences are found if, for instance, the simple and unweighted mean is taken. Also, and more important, there are no significant differences between values of $\bar{\alpha}_s(M_{Z0})$ calculated from different subsamples of the data: the averages from the high- and the low-energy data as well as those from $e^+e^-$ annihilation, from DIS and from $p\bar{p}$ colliders agree well with each other and with the overall average of $\bar{\alpha}_s(M_{Z0}) = 0.119$, within the respective errors (irrespective of how those errors are defined; see the discussion below).

While the central value $\bar{\alpha}_s(M_{Z0})$ is remarkably stable and well defined,
the determination of its overall uncertainty, $\Delta \alpha_s$, depends very much on the detailed definition of what this uncertainty should be, and how it should be calculated. There are several reasons for this situation:

The errors of most $\alpha_s$ results are dominated by theoretical uncertainties, which are estimated using a variety of different methods and definitions. The significance of these non-gaussian errors is largely unknown. Furthermore, there are large correlations between different results, due to common theoretical uncertainties, as e.g. in the case of various event shape measurements in $e^+e^-$ annihilations. Nothing is known, however, about possible correlations between $\alpha_s$ determinations from different processes, such as DIS and $e^+e^-$ annihilations, or between different procedures and observables used within the same class of processes.

Therefore, in the past, the value of $\Delta \alpha_s$ was often “guess-timated”, and/or a variety of mathematical methods was applied to obtain a reasonable estimate. Some of these methods will be applied and discussed in the following; the results are summarised in Table 1:

- For illustrational purposes only, an overall error is calculated assuming that all measurements are entirely uncorrelated and all quoted errors are gaussian. The results are displayed in the 3rd column of Table 1.
- The simple, unweighted $r.m.s.$ of the mean value of all measurements is calculated and shown in the 4th column, labelled “simple rms”.
- Assuming that each result of $\alpha_s(M_Z)$ has a rectangular-shaped rather
Table 1: Average values of $\alpha_s(M_{Z0})$ plus averaged uncertainties, for several methods to estimate the latter, and for several subsamples of the available data.

| sample     | $\alpha_s(M_{Z0})$ | uncert. | simple rms | rms box | opt. corr. | overall | correl. |
|------------|---------------------|---------|------------|---------|------------|---------|---------|
| all        | 0.1193              | 0.0012  | 0.0044     | 0.0059  | 0.0049     | 0.71    |
| $\Delta \alpha_s \leq 0.008$ (18) | 0.1193  | 0.0013  | 0.0038     | 0.0052  | 0.0042     | 0.64    |
| $\Delta \alpha_s \leq 0.006$ (7)     | 0.1190  | 0.0016  | 0.0033     | 0.0041  | 0.0030     | 0.49    |
| $\Delta \alpha_s \leq 0.004$ (2)     | 0.1190  | 0.0021  | 0.0028     | 0.0022  | 0.11       |
| only $e^+e^-$ (15)                    | 0.1210  | 0.0016  | 0.0045     | 0.0059  | 0.0052     | 0.77    |
| only DIS (8)                          | 0.1175  | 0.0025  | 0.0029     | 0.0053  | 0.0061     | 0.80    |
| only $p\bar{p}$ (3)                   | 0.1156  | 0.0057  | 0.0053     | 0.0072  | 0.0088     | 0.69    |
| $Q \leq 10$ GeV (9)                   | 0.1184  | 0.0016  | 0.0029     | 0.0045  | 0.0038     | 0.69    |
| $Q \geq 30$ GeV (14)                  | 0.1199  | 0.0020  | 0.0047     | 0.0062  | 0.0060     | 0.69    |

than a gaussian probability distribution, all resulting weights (the inverse of the square of the total error) are summed up in a histogram, and the resulting r.m.s. of that distribution is quoted as “rms box”[16]..

- A correlated error is calculated from the error covariance matrix, assuming an overall correlation factor between all measurements. The correlation factor is adjusted such that the total $\chi^2$ is one per degree of freedom [33]. The resulting errors and correlation factors are given in the last two columns of Table 1 (labelled “optimised correlation”).

All of the methods defined above have certain advantages but also obey inherent problems. The “simple rms” indicates the scatter of all results around their common mean, but does not depend on the individual errors quoted for each measurement. The “box rms”, which takes account of the individual errors and of their non-gaussian nature, was criticised to be too conservative an estimate of the overall uncertainty of $\alpha_s$. The “optimised correlation” method is closest to a mathematically appropriate treatment of correlated errors, however - in the absence of a detailed knowledge of these correlations - over-simplifies by the (unphysical ?) assumption of one overall correlation factor, identical to all pairs of measurements. Moreover, the $\chi^2$ calculated from the covariance matrix does not have, if correlations are present, the same mathematical and propabilistic meaning as in the case of uncorrelated data. In the extreme, $\chi^2$ may even be negative.

With these reservations in mind, all three methods do provide some estimate of $\Delta \alpha_s$. Apart from systematic differences in the size of $\Delta \alpha_s$, they all depend on the significance of the data included in the averaging process: in all cases, $\Delta \alpha_s$ is largest if all data are included, and tend to smaller values if the
averaging is restricted to results with errors $\Delta \alpha_s \leq \Delta \alpha_s^{(max)}$, i.e. if only the most significant results are used to calculate $\overline{\alpha_s}(M_{Z^0})$ and $\Delta \overline{\alpha_s}$.

Figure 13: Dependence of $\Delta \overline{\alpha_s}$ on the selection of results with errors $\Delta \alpha_s(M_{Z^0}) \leq \Delta \alpha_s^{(max)}$.

This can be seen from Table 1 where $\overline{\alpha_s}(M_{Z^0})$ and $\Delta \overline{\alpha_s}$ are also shown for three subsets of data with $\Delta \alpha_s \leq 0.008$, 0.006 and 0.004. The decrease of $\Delta \overline{\alpha_s}$ as a function of $\Delta \alpha_s^{(max)}$ is graphically shown in Figure 13. All three estimates of $\Delta \overline{\alpha_s}$, the “simple rms”, the “box rms” and the “optimised correlation”, decrease from initial values of 0.004 ... 0.006, if all $\alpha_s$ results are taken into account, to about 0.003 if only the most “precise” results are included. Only at the very extreme, taking the two results with the smallest quoted errors, the “optimised correlation” method yields an overall error of less than 0.003. Note that, despite the dependence of $\Delta \overline{\alpha_s}$ on the choice of $\Delta \alpha_s^{(max)}$, the overall average $\overline{\alpha_s}(M_{Z^0})$ does not depend on this selection!

On first sight it seems logical to restrict the determination of $\overline{\alpha_s}(M_{Z^0})$, and especially of $\Delta \overline{\alpha_s}$, to the most significant data, if inclusion of insignificant measurements enlarges $\Delta \overline{\alpha_s}$. Taken to the extreme, one may even be tempted to quote the one result which carries the smallest quoted error as the final world average value of $\alpha_s(M_{Z^0})$ and $\Delta \overline{\alpha_s}$. However, the errors on $\alpha_s(M_{Z^0})$ estimated in individual studies are, in general, lower limits because unknown and additional systematic effects can only increase the total error. Small systematic errors of single measurements may well be due to ignorance, over-optimism and/or neglect of certain error sources, which may be difficult to judge. Indeed, the errors of the two results with the smallest errors quoted, $\alpha_s$ from $\tau$-decays and from heavy quark bound states using lattice gauge theory, were often criticised as being overly optimistic.
In this sense, averaging over a number of well understood and commonly accepted measurements of reasonable precision is a safe basis to estimate \( \alpha_s(M_Z) \) and \( \Delta \alpha_s \). While there is still a large degree of flexibility to choose the final data set and the procedure to estimate \( \Delta \alpha_s \), the choice to select results with \( \Delta \alpha_s(M_Z) \leq 0.008 \) and to determine \( \Delta \alpha_s \) using the “optimised correlation” method seems reasonable and to be neither overly optimistic nor pessimistic. The final world average of \( \alpha_s(M_Z) \) is therefore quoted to be, c.f. Table 1 and Figure 13,

\[
\alpha_s(M_Z) = 0.119 \pm 0.004 .
\]

The central values of 19 out of the 27 measurements listed in Table 2, or equivalently 70%, are inside this error range of \( \pm 0.004 \), thus being compatible with the expectation of a “one standard deviation” interval.

If the result of \( \alpha_s \) which is based on lattice gauge theory is omitted in the averaging process, \( \alpha_s(M_Z) \) and \( \Delta \alpha_s \) increase to \( 0.120 \pm 0.005 \). The same is true if the result of the reanalysis of muon deep inelastic scattering data is used instead of the one listed in Table 2.

Note that the value of \( \Delta \alpha_s = 0.004 \) is a factor of two larger than the one quoted in the latest edition of the Review of Particle Physics. The smaller value of 0.002 quoted there corresponds to a (slightly enlarged) r.m.s. assuming all measurements to be totally uncorrelated; an assumption which seems, in view of the results discussed above, unrealistic.

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\(^c\) The increase of \( \Delta \alpha_s \) is due to an artifact of the “optimised correlation” method which may increase the overall correlation factor (and thus, the overall error) if individual measurements are closer to their common mean.
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Table 2: World summary of measurements of $\alpha_s$. Underlined entries are new or updated since summer 1997 (DIS = deep inelastic scattering; GLS-SR = Gross-Llewellyn-Smith sum rules; Bj-SR = Bjorken sum rules; (N)NLO = (next-)next-to-leading order perturbation theory; LGT = lattice gauge theory; resum. = resummed next-to-leading order).

| Process                          | $Q$ [GeV] | $\alpha_s(Q)$ | $\alpha_s(M_{Z^0})$ | $\Delta\alpha_s(M_{Z^0})$ | Theory |
|---------------------------------|-----------|---------------|---------------------|---------------------------|--------|
| DIS [pol. strict. fts.]        | 0.7 - 8   | 0.120 ± 0.010 | +0.004              | +0.009                    | NLO    |
| DIS [Bj-SR]                     | 1.58      | 0.375 ± 0.062 | 0.121 ± 0.005      | 0.005                     | NNLO   |
| DIS [GLS-SR]                    | 1.73      | 0.295 ± 0.092 | 0.114 ± 0.010      | 0.005                     | NNLO   |
| $\tau$-decays                   | 1.78      | 0.339 ± 0.021 | 0.121 ± 0.003      | 0.001                     | NNLO   |
| DIS [\nu; F2 and F3 ]          | 5.0       | 0.215 ± 0.016 | 0.119 ± 0.005      | 0.002                     | NLO    |
| DIS [$\mu$; F2]                | 7.1       | 0.180 ± 0.014 | 0.113 ± 0.005      | 0.003                     | NLO    |
| DIS [HERA, F2]                  | 2 - 10    | 0.120 ± 0.010 | 0.005               | 0.009                     | NLO    |
| DIS [HERA, \nu; jets]          | 10 - 100  | 0.118 ± 0.009 | 0.003               | 0.008                     | NLO    |
| DIS [HERA, ev. shapes]         | 7 - 100   | 0.118 ± 0.007 | 0.001               | −0.006                    | NLO    |
| Q$^2$ states                    | 4.1       | 0.223 ± 0.009 | 0.117 ± 0.003      | 0.000                     | LGT    |
| $T$ decays                      | 4.13      | 0.220 ± 0.027 | 0.119 ± 0.008      | 0.001                     | NLO    |
| e$^+e^-$ (p$\bar{p}$ → had.)   | 10.52     | 0.20 ± 0.06   | 0.130 ± 0.029      | −0.029                    | NNLO   |
| e$^+e^-$ (ev. shapes)           | 22.0      | 0.161 ± 0.016 | 0.124 ± 0.006      | 0.005                     | resum  |
| e$^+e^-$ (\nu; had.)           | 34.0      | 0.146 ± 0.031 | 0.123 ± 0.021      | 0.005                     | NNLO   |
| e$^+e^-$ (ev. shapes)           | 35.0      | 0.145 ± 0.012 | 0.123 ± 0.008      | 0.002                     | resum  |
| e$^+e^-$ (ev. shapes)           | 44.0      | 0.139 ± 0.010 | 0.123 ± 0.008      | 0.003                     | resum  |
| e$^+e^-$ (ev. shapes)           | 58.0      | 0.132 ± 0.008 | 0.123 ± 0.007      | 0.003                     | resum  |
| pp → bX                         | 20.0      | 0.145 ± 0.018 | 0.113 ± 0.011      | 0.007                     | NLO    |
| pp, pp → γX                     | 24.2      | 0.137 ± 0.017 | 0.111 ± 0.012      | 0.006                     | NLO    |
| σ(pp → jets)                    | 30 - 500  | 0.121 ± 0.009 | 0.001               | 0.009                     | NLO    |
| e$^+e^-$ (p→e$^+e^-$ had.)     | 91.2      | 0.122 ± 0.005 | 0.122 ± 0.005      | 0.004                     | NNLO   |
| e$^+e^-$ (ev. shapes)           | 91.2      | 0.122 ± 0.006 | 0.122 ± 0.006      | 0.001                     | resum  |
| e$^+e^-$ (ev. shapes)           | 133.0     | 0.111 ± 0.008 | 0.117 ± 0.008      | 0.004                     | resum  |
| e$^+e^-$ (ev. shapes)           | 161.0     | 0.105 ± 0.007 | 0.114 ± 0.008      | 0.004                     | resum  |
| e$^+e^-$ (ev. shapes)           | 172.0     | 0.102 ± 0.007 | 0.111 ± 0.008      | 0.004                     | resum  |
| e$^+e^-$ (ev. shapes)           | 183.0     | 0.109 ± 0.005 | 0.121 ± 0.006      | 0.002                     | resum  |
| e$^+e^-$ (ev. shapes)           | 189.0     | 0.109 ± 0.006 | 0.122 ± 0.007      | 0.003                     | resum  |