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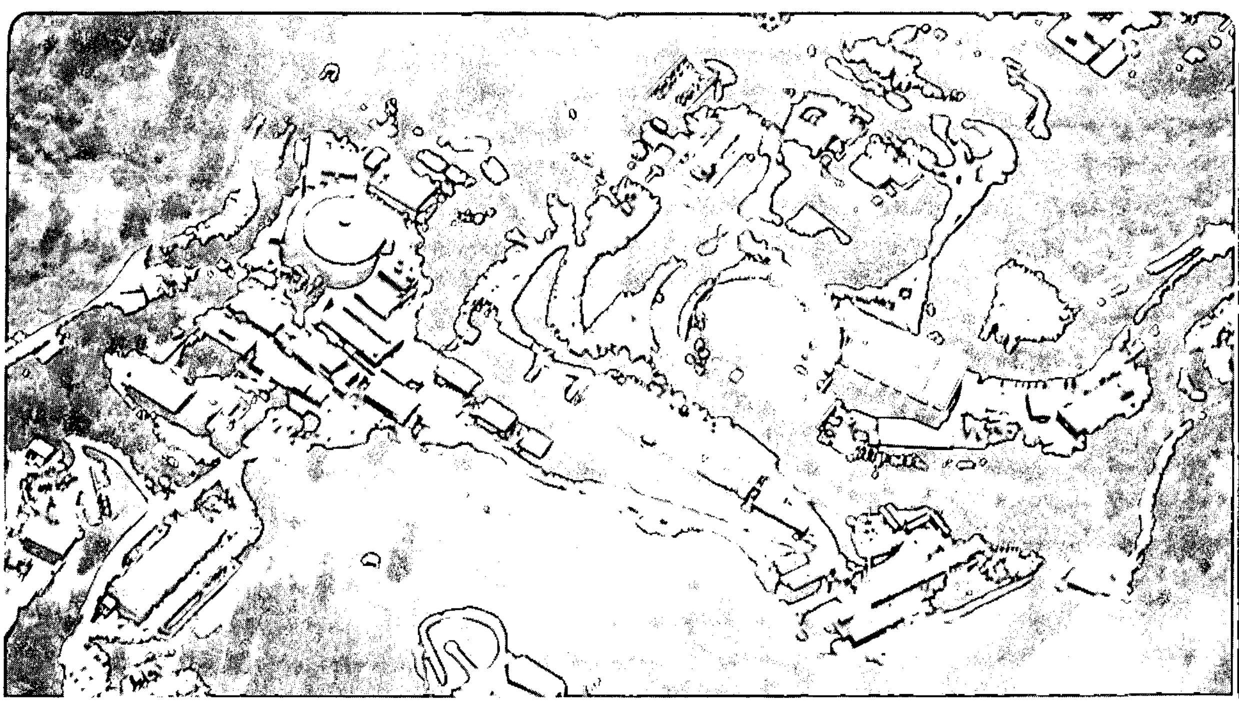

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Status of α_s Measurements*

Invited talk given at XXVIII Rencontres de Moriond

Electroweak Interactions and Unified Theories

Les Arcs, France, March 13-20, 1993

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Abstract

I review the current determinations of α_s. Attention is given to the theoretical uncertainties inherent in most determinations. All current determinations are consistent with an average of $\alpha_s(M_Z) = 0.119 \pm 0.005$. Prospects for reduction of the errors in the future are discussed.

Source	$\alpha_s(M_Z)$	error source
$R(e^+e^-)$	0.129 ± 0.017	Expt
$\Gamma(Z)$	0.128 ± 0.009	Expt
R_τ	0.121 ± 0.011	Theory
DIS	0.113 ± 0.006	Theory
LEP Jets	0.121 ± 0.008	Theory
$W + jets$	$0.123 \pm .027$	Theory
Υ	0.108 ± 0.010	Theory
Lattice	$0.105 \pm 0.004(?)$	Theory

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1 Introduction

There are many experiments and theoretical calculations that are used to determine the strong coupling constant α_s. In this talk I shall discuss the following processes; the total hadronic cross section in e^+e^- annihilation; the hadronic width of the Z; semi-leptonic tau decay; event shapes in e^+e^- annihilation; $W + jets$ in $p\overline{p}$ collisions; charmonium and bottomonium; and a few others. I shall not discuss the important results from Deep Inelastic Scattering; a full discussion of these can be found in the talk of Virchaux.[1]

The value of $\alpha_s(\mu)$ depends upon a renormalization scheme and a value of μ where is it evaluated. The μ dependence is given by the following equation:-

$$\mu\frac{\partial\alpha_s}{\partial\mu} = -\frac{\beta_0}{2\pi}\alpha_s^2 - \frac{\beta_1}{8\pi^2}\alpha_s^3 - \ldots,$$

where $\beta_0 = 11 - \frac{2}{3}n_f$, $\beta_1 = 102 - \frac{38}{3}n_f$.Here n_f is the number of light quark flavors. The dots on the right hand side indicate higher order terms. The coefficients of these terms (β_2 *etc.*) are dependent upon the the renormalizations scheme. It is convenient to define Λ in such a way that the μ dependence of $\alpha_s(\mu)$ can be parameterized, *viz*

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln\frac{\mu^2}{\Lambda^2_{\overline{MS}}}}\left[1 - \frac{\beta_1 \ln(\ln\frac{\mu^2}{\Lambda^2_{\overline{MS}}})}{\beta_0^2 \ln\frac{\mu^2}{\Lambda^2_{\overline{MS}}}}\right]$$

This acts as the definition of $\Lambda_{\overline{MS}}$, the $\overline{MS}$ subscript denotes the modified minimal subtraction scheme [2] and is dropped in the following. Λ depends on n_f; it must change discontinuously as μ is increased across a flavor threshold [3]. Experiments at LEP are above the b quark threshold and hence quote $\Lambda^{(5)}$; those in deep inelastic scattering usually quote $\Lambda^{(4)}$. Note that $\Lambda^{(4)} \sim 1.54\Lambda^{(5)}$ for the range of Λ that is indicated by experiment. The variation of $\alpha(\mu)$ with μ implies that experiments at small values of μ where $\alpha(\mu)$ is larger are more sensitive than ones at large μ. For example, $\alpha(6GeV) = 0.200 \pm 0.032$ (a 16% error) corresponds to $\alpha(M_Z) = 0.117 \pm 0.012$ (a 10% error). However such experiments are usually subject to more of the theoretical uncertainties that we now discuss.

The first of these uncertainties is the scale at which $\alpha_s(M)$ is evaluated. A shift in the scale is equivalent to a change in the coefficient of the next to leading order (NLO) term in the perturbative expansion of result for the process in question.

$$\frac{\alpha_s(M)}{\alpha_s(Q)} = 1 + \frac{\beta_0}{4\pi} \ln(Q^2/M^2)\alpha_s(Q)$$

As a result of this, only calculations done to next to leading order in α_s are useful for attempts to determine α_s. In principle, if a process is calculated to all orders in perturbation theory, the result will be independent of the choice of M; the change simply reshuffles the relative size of each term in the perturbative series. In practice, since processes are only calculated to some finite order, an ambiguity due to the choice of M is unavoidable. There are various theoretical schemes that have been proposed to determine the "best" value for M. Once can choose M so that the coefficient of the highest order term is zero (fastest apparent convergence) [4]; such that the derivative of the perturbative expression with respect to M is zero (minimal sensitivity) [5]; or use the so-called effective charge scheme [6]. Alternatively one could treat M as a parameter and choose it to get the best fit to the data. If any of these options leads to a value of M that is far from the typical energy scale of the process, it is an indication that the theoretical expression is unreliable. It is necessary to assign a systematic error to the extracted value of α_s to take into account the ambiguity associated with the choice of M. What range of M is to be allowed in making this estimate? It has become usual to vary M by a factor of 4 and use the resulting change in α_s to ascribe the error. This is likely to be a lower bound on the true error.

It will be clear from the above that the error associated with the choice of M is correlated with the error connected with unknown higher order terms. If the perturbation series is known to at least 3 terms, then one can attempt to understand the size of this error by fitting the full expression as well as the expression with the highest order term omitted. The differing values of α_s obtained can then be used to get an estimate of the systematic error. At present this method can only be applied to measurements of the Z width, tau semileptonic branching ratio and the total cross-section in e^+e^- annihilation.

In addition to the theoretical errors associated with the perturbative expansion, there are others associated with non-perturbative corrections. These corrections are generically of the order $(\Lambda/M)^n$ relative to the perturbative terms. Hence they are much less important for processes at high energies (such as the hadronic width of the Z) than at low energy (such as the semi-leptonic width of the tau). There are several ways of dealing with these effects and the systematic errors on α_s associated with them. One can parameterize them in some way and then fit to the data. This is done by Virchaux [1] in his analysis of deep inelastic scattering where a contribution of the form $f(x)/Q^2$ is added to the perturbative structure function $F_2(x, Q^2)$. Alternatively one can attempt to estimate them as is done in the case of semi-leptonic tau decay.

Measurements of α_s from exclusive processes such as the jet rates in e^+e^- annihilation depend on models that describe the evolution of the perturbative final state of quarks and gluons into that of hadrons seen by the experiment. These models, in the form of Monte-Carlo event generators, are parameterizations of the non-perturbative effects.

2 Total cross section in e^+e^- annihilation and hadronic Z width

In the approximation of a single photon in the s-channel (valid at low values of $\sqrt{s}$ appropriate to the PEP/PETRA energy range), the total hadronic rate in e^+e^- annihilation is given by:-

$$R = \frac{(\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{11}{3}\Big[1+(1+\frac{12m_b^2}{11\pi s})\frac{\alpha_s(\sqrt{s})}{\pi}+1.411(\frac{\alpha_s(\sqrt{s})}{\pi})^2-12.76(\frac{\alpha_s(\sqrt{s})}{\pi})^3+\cdots$$

At LEP formula is different due to V and A couplings of Z.

$$R_Z = \frac{\Gamma(Z \to hadrons)}{\Gamma(Z \to e^+e^-)} = R_{EW}\Big[1+1.05\frac{\alpha_s(\sqrt{s})}{\pi}+(0.9\pm0.1)(\frac{\alpha_s(\sqrt{s})}{\pi})^2-13(\frac{\alpha_s(\sqrt{s})}{\pi})^3+\cdots\Big]$$

Here R_{EW} is the result from the electro-weak theory, calculated in the limit $\alpha_s = 0$. The error arises from the top quark contribution to the process $Z \to q\overline{q}$ that appears at two loops.

A recent fit to all of the data in the energy range $5-61$ GeV, [7] having fixed M_Z and $sin^2\theta_w$ at their values determined at LEP yields

Energy Range	5-61 GeV	14-61 GeV
$\alpha(34GeV)$	0.157 ± 0.018	0.193 ± 0.026

Note that the two values corresponding to the different energy ranges differ by more than 1-σ. If M_Z is allowed to float the fit gives

Energy Range	5-61 GeV	14-61 GeV
$\alpha(34GeV)$	0.134 ± 0.022	0.179 ± 0.034
M_Z	88.7 ± 1.1GeV	89.8 ± 1.4 GeV

The values of M_Z are significantly below the correct value. Note that the theoretical errors in this case are less than the experimental errors. Note that the QCD perturbation series is well convergent

$$R(34GeV) \sim \frac{11}{3}(1. + .05 + 0.0033 - 0.0016).$$

In order to combine this result with the other values of α_s discussed here, I have to choose which of the above values to use. I have chosen to use the value from the full energy range viz $\alpha_s(34GeV) = 0.157$. but have inflated the error to ± 0.036 to take account of the differences between the extracted values.

From the experimental value $R_Z = 20.85 \pm 0.07$ we obtain $\alpha_s(M_Z) = 0.130 \pm 0.011 \pm 0.004 \pm 0.002$ where the errors are experimental, due to m_t and m_b respectively. A combined fit to all of the electroweak parameters [8] gives $\alpha_s(M_Z) = 0.128 \pm 0.009(expt.) \pm 0.002(m_h)$. If the order α_s^3 term is dropped, the extracted value of α_s decreases by 0.003. The extracted value is dominated therefore by experimental errors and a more precise determination of the hadronic width of the Z would result in a smaller error on α_s.

3 Semi-Leptonic Tau decay

The semi-leptonic branching ratio of the tau (R_τ) is an inclusive quantity. It is related to the contribution of hadrons to the imaginary part of the W self energy ($\Pi(s)$), just as R is related to the imaginary part of the photon self energy. However it is more inclusive than R since it involves an integral

$$R_\tau \sim \int_0^{m_\tau^2} \frac{ds}{m_\tau^2}(1 - \frac{s}{m_\tau^2})^2 \,\mathrm{Im}(\Pi(s))$$

which can be written as

$$R_\tau \sim \frac{1}{2\pi i}\int_{|s|=m_\tau^2} \frac{ds}{m_\tau^2}(1 - \frac{s}{m_\tau^2})^2 \Pi(s)$$

$$R_\tau = 3.058(1 + \frac{\alpha_s(m_\tau)}{\pi} + 5.2(\frac{\alpha_s(m_\tau)}{\pi})^2 + 26.4(\frac{\alpha_s(m_\tau)}{\pi})^3 + a\frac{m^2}{m_\tau^2} + b\frac{m\psi\overline{\psi}}{m_\tau^4} + c\frac{\psi\overline{\psi}\psi\overline{\psi}}{m_\tau^6} + \cdots)$$

Here a, b, and c are dimensionless constants and m is a light quark mass. The term of order $1/m_\tau^2$ is a kinematical effect due to the light quark masses. The non-perturbative terms are estimated using sum rules [9]. In total they are estimated to be -0.007 ± 0.004 [10]. This estimate relies on there being no term of order Λ^2/m_τ^2 (note that $\frac{\alpha_s(m_\tau)}{\pi} \sim (\frac{0.5GeV}{m_\tau})^2$). Recently arguments have been advanced [12] questioning the absence of the $1/m_\tau^2$ terms. If valid, such arguments would invalidate the use of this process to extract α_s. The dominant dimension-6 ($\sim 1/m_\tau^6$) term has a large cancellation between the vector and axial vector contributions (the separate contributions are 0.0012 and -0.0019).

If the non-perturbative terms are omitted from the fit, the extracted value of $\alpha_s(m_\tau)$ decreases by ~ 0.02. Using the average of the LEP experiments [11] for R_τ of 3.64 ± 0.08 gives $\alpha_s(m_\tau) = 0.36 \pm 0.04$ using the experimental error alone.

A similar analysis can be performed for the vector hadronic current using the data for $e^+e^- \to$ *hadrons*. [13]. The resulting value of α_s depends quite strongly on the value of $\sqrt{s}$ where the fit is performed. The detailed results depend of the form assumed for the e^+e^- data but the conclusion does not. Varying $\sqrt{s}$ from 1.6 to 2.1 GeV results in shifts of $\alpha_s(m_\tau)$ of ± 0.06. The extracted value of the non-perturbative terms is not consistent with those expected from the sum rules. Note however that in the tau decay result there is a substantial cancellation of the vector and axial vector non-perturbative terms.

For $\alpha_s(m_\tau) = 0.36$ the perturbative series for R_τ has the form $R_\tau \sim 3.058(1.+.114+0.073+0.043)$. The size (estimated error) of the non-perturbative term is 20% (7%) of the size of the order α_s^3 term. The perturbation series in not very well convergent; if the order α_s^3 term is omitted the extracted value of $\alpha_s(m_\tau)$ increases by 0.05. Combining the uncertainties gives $\alpha_s(M_\tau) = 0.36 \pm 0.10$, or $\alpha_s(M_Z) = 0.121 \pm 0.011$

One can attempt to determine the non-perturbative contributions directly from the tau decay data by forming moments [14]

$$R_{mn}(m_\tau^2) = \int_0^{m_\tau^2} ds(1 - \frac{s}{m_\tau^2})^m (\frac{s}{m_\tau^2})^n Im(\Pi(s))$$

While, one cannot hope to reproduce many of the moments with a formalism that does not incorporate the resonances, π, ρ, a_1, that dominate the hadronic final state, this form enables more information to be extracted from the data and may give increased confidence in the theoretical estimates of the non-perturbative terms.

4 Event shapes in e^+e^- annihilation

The study of the hadronic final states in e^+e^- annihilation can be used to determine α_s [15]. All of these determinations are based on the ability of perturbative QCD to calculate the structure of such final states. For example, the ratio $3 - jet/2 - jet$ is proportional to α_s. There are many different variables that can be used to perform the analysis. Among them are the jet mass computed from the energies and angular separation of 2 particles $y_{ij} = E_i E_j (1 - \cos\theta_{ij})/s$ [16]. If $y_{ij} \leq y_{cut}$, the two particles are combined into a pseudo-particle and the procedure iterated until no more combinations are possible. The event will them have a well defined number of jets (pseudo-particles); the relative fraction of n-jet final states will then depend on y_{cut} and α_s and can be fitted to a QCD prediction. Alternatively, one can iterate until only 3 clusters remain and then look at the distribution in $y_3 = min(y_{ij})$. Another variable is the thrust distribution defined by $T = max(\sum_i |\overline{p_i}\cdot\overline{n}| / \sum_i |\overline{p_i}|)$, where the sum runs over all particles and the unit vector $\overline{n}$ is varied. Perturbative calculations are currently available to order α_s^2 for the shape variables used in fitting.

In practice the data fitting is not so straightforward [17]. The perturbative result does not usually give a good description of the data. In the case of the thrust distribution at LEP, the perturbative result describes the data to 10% only in the range $T \lesssim .925$. The perturbative final state of quarks and gluons must be passed through a Monte-Carlo event generator that produces a final state of hadrons. There is subtle interplay between the perturbative QCD and the showering Monte-Carlos. The corrections are typically 10% at LEP energies and are much larger at PEP/PETRA where substantial data have been accumulated. At LEP, the distribution in the difference $\Delta T = T_{partons} - T_{hadrons}$ is approximately gaussian with $\sigma = 0.01$[18]. The fragmentation parameters of these Monte-Carlos are tuned to get agreement with the observed data. Recently an attempt has been made to use data at PEP, TRISTAN and LEP, to get a consistent fit to the fragmentation parameters and determine α_s [19].

The scale M at which $\alpha_s(M)$ is to be evaluated is not clear. The invariant mass of a typical jet (or $\sqrt{sy_{cut}}$) is probably a more appropriate choice than the e^+e^- center of mass energy. If the value is allowed to float in the fit to the data, the data tend to prefer values of order $\sqrt{s}/10$ [17] the exact value depends on the variable that is fitted. The dominant uncertainties arise from the choice of M and from the freedom in the fragmentation Monte-Carlos. An average of many variables and all the LEP experiments [22] gives $\alpha_s(M_Z) = .119 \pm 0.006$. The situation might improve if perturbative calculations to order α_s^3 became available.

The perturbative QCD formulae can break down in special kinematical configurations. For example, the thrust distribution contains terms of the type $\alpha_s \ln^2(1-T)$. The higher orders in the perturbation expansion contains terms of order $\alpha_s^n \ln^m(1-T)$. For $T \sim 1$ the perturbation expansion is unreliable. The terms with $n \leq m$ can be summed to all orders in α_s [18]. The resummed results give better agreement with the data at large values of T [21]. Such resummed results are not available for all of the shape variables [20], but fits using those available yields a LEP average of $\alpha_s(M_Z) = 0.124 \pm 0.006$ [22]. Some caution should be exercised in using these resummed results because of the possibility of overcounting; the showering Monte-Carlos that are used for the fragmentation corrections also generate some of these leading log corrections. The errors in the values of $\alpha_s(M_Z)$ from these shape variables are totally dominated by the theoretical uncertainties associated with the choice of scale and the effects of hadronization Monte-Carlos. It is gratifying that the shift from the result using the unresummed formulae is less than the error. I think that it is prudent to average these results and increase the error somewhat. I therefore conclude that $\alpha_s(M_Z) = 0.121 \pm 0.008$.

5 Bound states of heavy quarks.

The total decay width of the Υ is predicted by perturbative QCD [23]

$$R_\mu = \frac{\Gamma(\Upsilon \to hadrons)}{\Gamma(\Upsilon \to \mu^+\mu^-)} = \frac{10(\pi^2-9)\alpha_s^3(M)}{9\pi\alpha_{em}^2}(1+\frac{\alpha_s}{\pi}(-19.4+\frac{3\beta_0}{2}(1.162+\ln(\frac{2M}{M_\Upsilon}))))$$

Data are available for the Υ, Υ', Υ'' and Ψ. The result is very sensitive to α_s and the data are sufficiently precise ($R_\mu(\Upsilon) = 32.5 \pm 0.9$) [24] that the theoretical errors will dominate. There are theoretical corrections to this simple formula due to the relativistic nature of the $Q\overline{Q}$ system; $v^2/c^2 \sim 0.1$ for the Υ. They are more severe for the Ψ. There are also non-perturbative corrections of the form Λ^2/m_Υ^2; again these are more severe for the Ψ. A fit to Υ, Υ', and Υ'' [25] gives $\alpha_s(M_Z) = 0.108 \pm 0.001(expt)$. The results from each state separately and also from the Ψ are consistent with each other. There is an uncertainty of order ± 0.005 from the choice of scale; the error from v^2/c^2 corrections is a little larger. I conclude that $\alpha_s(M_Z) = 0.108 \pm 0.010$ is a fair representation of the total error including the possibility of non-perturbative corrections.

Lattice gauge theory calculations can be used to calculated the energy levels of a $Q\overline{Q}$ system and then extract α_s. The FNAL group [26] uses the splitting between the 1S and 1P in the charmonium system ($m_{h_c} - (3m_\psi + m_{\eta_c})/4 = 456.6 \pm 0.4$ MeV). The splitting is almost independent of the charm quark mass and is therefore dependent only on Λ. The calculation does not rely on perturbation theory or on non-relativistic approximation. The main errors are systematic associated with the finite lattice spacing (a) and quenched approximation used in the calculation. The extrapolation to zero lattice spacing produces a shift in Λ of order 5% and is therefore quite small. The quenched approximation is more serious. No light quarks are allowed to propagate and hence the extracted value of Λ corresponds to the case of zero flavors. $\alpha_s(M)$ is evolved down from the scale (~ 2.3 GeV) of the lattice used to the scale of momentum transfers appropriate to the charmonium system ($\sim$ 700 MeV). The resulting coupling is then evolved back up with the correct number of quark flavors. This produces a shift in $\alpha_s(5GeV)$ of order 25%, with a claimed uncertainty of 7%. The FNAL group quotes $\alpha_s(5GeV) = 0.174 \pm 0.012$. This error could be an underestimate as the perturbative running of $\alpha_s(M)$ has to be used at small M. Calculations based on the Υ spectrum using non relativistic lattice theory give $\alpha_s(5GeV) = 0.170 \pm 0.012$ [27]

6 Other results

The transverse momentum distribution of the W in $p\overline{p}$ collisions has been calculated beyond leading order in α_s [28] and can therefore be used to determine α_s. The UA2 collaboration measured the ratio [29]

$$R_W = \frac{\sigma(W + 1jet)}{\sigma(W + 0jet)}$$

The result depends on the algorithm used to define a jet and the dominant systematic errors due to fragmentation and corrections for underlying events (the former causes jet energy to be lost, the latter causes it to be increased) are connected to the algorithm. UA2 quote $\alpha_s(M_W) = 0.123 \pm 0.018(stat) \pm 0.017(syst)$ The scale at which $\alpha_s(M)$ is to be evaluated is not clear. A change from $M = M_W$ to $M = M_W/2$ causes a shift of 0.01 in the extracted $\alpha_s(M_Z)$. I have increased the quoted error to take this into account.

Measurements of the photon structure functions at e^+e^- colliders can also constrain Λ. Hopes that the photon structure function might be exactly calculable in perturbative QCD are no longer believed; there are substantial non perturbative components [30] The analysis is therefore similar to that of the proton structure function. No new data are available; the existing data are consistent with $\Lambda^{(4)} = 90 - 280$ MeV [31].

The UA1 collaboration [32] have used the measured $b\overline{b}$ cross-section in $p\overline{p}$ collisions to extract $\alpha_s(M_Z) = 0.136 \pm 0.025$. I am somewhat skeptical of this result since the perturbative cross-section for $b\bar{b}$ production has substantial scale dependence at next-to leading order and is increased by almost a factor of two over the lowest order prediction [33]. The gluon distribution used in this fit does not predict the correct $b\bar{b}$ rate at CDF [34]. Recently it has been claimed that the two data sets can be made consistent if the gluon distribution is suitably chosen [35]. It would be interesting to see by how much the extracted value of α_s is changed by this gluon distribution.

7 Summary

The various values of $\alpha_s(M_Z)$ are summarized in the table in the abstract. In the cases where the errors are dominantly theoretical, I have used my judgement based on the discussion above in setting the error. The table indicates, for each measurement, the dominant source of error. In forming an average, I have not included the number from lattice gauge theory because of the difficulty in reliably estimating the error. I have assumed that the errors on the other measurements are uncorrelated. Since most of the uncertainties are theoretical (a notable exception is the value from the Z width), the current situation will not improve without improved calculations. For some processes, we are at the limit of theoretical uncertainty without improvement in the uncertainties of the the non-perturbative terms. Full order α^3 Altarelli-Parisi evolution equations may help to reduce the scale uncertainties in the results from Deep Inelastic scattering. Similarly full order α_s^3 for the event shapes in e^+e^- annihilation could bring us to the point where the residual uncertainties due to the hadronization Monte-Carlos dominate.

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