

HEAVY QUARK MASS EFFECTS AND IMPROVED TESTS OF THE FLAVOUR INDEPENDENCE OF STRONG INTERACTIONS*

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ABSTRACT

A review is given of latest results on tests of the flavour independence of strong interactions. Heavy quark mass effects are evident in the data and are now taken into account at next-to-leading order in QCD perturbation theory. The strong-coupling ratios $\alpha_s^b / \alpha_s^{uds}$ and $\alpha_s^c / \alpha_s^{uds}$ are found to be consistent with unity. Determinations of the b -quark mass $m_b(M_Z)$ are discussed.

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1 Motivation

In order for Quantum Chromodynamics (QCD) to be a gauge-invariant renormalisable field theory it is required that the strong coupling between quarks (q) and gluons (g), α_s , be independent of quark flavour. This basic *ansatz* can be tested directly in e^+e^- annihilation by measuring the strong coupling in events of the type $e^+e^- \rightarrow q\bar{q}g$ for specific quark flavours. Whereas an absolute determination of α_s using such a technique is limited, primarily by large theoretical uncertainties, to the 5%-level of precision [1], a much more precise test of the flavour-independence can be made from the ratio of the couplings for different quark flavours, in which most experimental errors and theoretical uncertainties cancel. Precise measurements of this type have been made using data collected at the Z^0 resonance by the SLC and LEP collaborations, and are reviewed here.

However, the emission of gluon radiation in $b\bar{b}$ events is expected to be modified relative to that in $q_i\bar{q}_i$ ($q_i = u+d+s$) events due to the large b -quark mass, and such an effect must be taken into account in the test of flavour independence of the strong coupling. Recently three groups have completed calculations of 3-jet observables in $Z^0 \rightarrow b\bar{b}$ events complete at next-to-leading order in QCD perturbation theory [2, 3, 4, 5]. Comparison of the rates for $Z^0 \rightarrow b\bar{b}g$ and $Z^0 \rightarrow q_i\bar{q}_i g$ hence allows measurement of the mass* of the b -quark at the Z^0 scale, $m_b(M_Z)$. Finally, given recent excitement in the electroweak sector concerning the values of the quantities R_b and A_b , it seems worthwhile to provide a complementary cross-check of the strong dynamics of the b -quark.

2 Strategy

The analysis strategy is, in principle, straightforward: one chooses infra-red- and collinear-safe observables to measure in $b\bar{b}$, $c\bar{c}$ and $q_i\bar{q}_i$ events, and compares the results

*Use of the modified minimal subtraction renormalisation scheme [6] is implied throughout.

with the QCD predictions, taking mass effects into account. However, there are at least two possible approaches: 1) input the best knowledge of the b -mass taken from independent measurements, *eg.* in the Υ system, and test the flavour-independence of the strong coupling; 2) *assume* the flavour-independence, and determine the b -mass from the data. One or the other of these approaches has been followed in the results reported here.

The basic experimental method is common to both cases. One first selects $e^+e^- \rightarrow$ hadrons events, and applies a flavour-tagging algorithm to select samples of events of different primary quark flavour, represented by the indices i and j . One measures the 3-jet observable(s) X in the different tagged-flavour event samples, and, in order to cancel sources of common systematic error, forms the *ratios* X^i/X^j . Before these can be compared with the relevant QCD calculations, they must be corrected for: the effects of detector acceptance and resolution; the bias of the flavour tag to select preferentially 2-jet rather than 3-jet events; the flavour compositions; and hadronisation effects. These corrections are very important, and the associated uncertainties must be taken into account in the estimation of the systematic errors [7, 8, 9].

3 Flavour Tagging

The three new contributions reviewed here have used complementary methods for the separation of events of different primary quark flavour, and the systematic uncertainties are therefore at least partly uncorrelated. All methods rely on the large decay multiplicity and long lifetime of B hadrons as a discriminator of $b\bar{b}$ against $c\bar{c}$ and $q_l\bar{q}_l$ events.

DELPHI has employed a method based on the probability P that all tracks in an event originate from the primary e^+e^- interaction point (IP) [7]; $q_l\bar{q}_l$ events tend to have a high probability value, and $b\bar{b}$ events a low one. Requiring $P \leq 0.005$ ($P > 0.2$) tags a $b\bar{b}$ ($q_l\bar{q}_l$) event sample with efficiency (ϵ) and purity (Π) of 55% and 85% (80%

and 80%) respectively.

OPAL has employed a method based on the number N_{sig} of ‘significant’ tracks, *i.e.* those whose impact parameter deviates significantly from the IP [8]; $q_l\bar{q}_l$ events tend to have few such tracks, and $b\bar{b}$ events several. Requiring $N_{sig} \geq 5$ ($N_{sig} = 0$) tags a $b\bar{b}$ ($q_l\bar{q}_l$) event sample with $\epsilon, \Pi = 23\%, 96\%$ ($35\%, 86\%$) respectively.

SLD has employed a method based on the mass, M_{vtx} , and momentum, P_{vtx} , of secondary decay vertices reconstructed using the 300M-pixel CCD vertex detector [9]. $q_l\bar{q}_l$ events rarely contain reconstructed secondary decay vertices, and these typically result from strange particle decays and are of low mass. Conversely, $b\bar{b}$ events typically contain high-mass vertices. Requiring $M_{vtx} > 1.8 \text{ GeV}/c^2$ tags a $b\bar{b}$ event sample with $\epsilon, \Pi = 62\%, 90\%$ respectively. Requiring no vertex and $N_{sig} = 0$ tags a $q_l\bar{q}_l$ event sample of $\epsilon, \Pi = 56\%, 91\%$ respectively.

In addition, both OPAL and SLD have tagged a third sample enriched in primary $c\bar{c}$ events. OPAL has explicitly reconstructed D^* candidates with $\epsilon, \Pi = 2\%, 55\%$ respectively. The low efficiency is due mainly to the intrinsically low D^* decay branching ratios into convenient tagging modes. SLD has utilised the correlation between vertex mass and momentum to distinguish $c\bar{c}$ from $b\bar{b}$ events by requiring $M_{vtx} < 1.8 \text{ GeV}/c^2$ and $P_{vtx} > 5 \text{ GeV}/c$. This yields a tagged sample with higher $\epsilon, \Pi = 19\%, 64\%$, and, equally importantly, low bias against 3-jet events.

4 Test of Flavour Independence

Having measured the ratios X^i/X^j for event flavour samples i and j , and made the corrections discussed in Section 2, the flavour-independence of strong interactions can be tested via

$$\frac{X^i}{X^j} = \frac{A^i(X)\alpha_s^i + B^i(X)(\alpha_s^i)^2}{A^j(X)\alpha_s^j + B^j(X)(\alpha_s^j)^2} \quad (1)$$

where A and B are the perturbatively-calculated leading- (LO) and next-to-leading order (NLO) coefficients, respectively, for observable X . In the case of $b\bar{b}$ (and $c\bar{c}$)

events these coefficients depend on the quark mass, and, for a given input mass value, can be calculated [5]. Eq. 1 can then be solved to obtain the ratio α_s^i/α_s^j . This has been done in new contributions from DELPHI, OPAL and SLD, using b -mass values of $m_b(M_Z) = 2.67 \pm 0.27$, $M_b = 5.0 \pm 0.5$ and $m_b(M_Z) = 3.0 \pm 0.5$ GeV/ c^2 , respectively (see Section 5). Using the Durham (D) jet-finder with a jet resolution parameter value $y_c = 0.02$, DELPHI has measured the 3-jet-rate ratio $R_3^{bl} \equiv R_3^b/R_3^{uds}$. Using the calculations of Ref. [2] they obtained [7]:

$$\frac{\alpha_s^b}{\alpha_s^{uds}} = 1.007 \pm 0.005(\text{exp.}) \pm 0.007(\text{frag.}) \pm 0.005(\text{theor.}) \quad (2)$$

OPAL has measured ratios of the distributions of the event shape observables D_2 , $1-T$, M_H , B_T , B_W and C . Using the calculations of Ref. [4] they obtained [8]:

$$\frac{\alpha_s^b}{\alpha_s^{uds}} = 0.988 \pm 0.005(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.011(\text{theor.}) \quad (3)$$

$$\frac{\alpha_s^c}{\alpha_s^{uds}} = 1.002 \pm 0.017(\text{stat.}) \pm 0.025(\text{syst.}) \pm 0.009(\text{theor.}) \quad (4)$$

SLD has measured ratios of the 3-jet rates, R_3 , for a wide range of y_c values, for jets defined using the E, E0, P, P0, Durham and Geneva (G) iterative clustering schemes. Using the calculations of Ref. [3] they obtained [9]:

$$\frac{\alpha_s^b}{\alpha_s^{uds}} = 1.004 \pm 0.018(\text{stat.})_{-0.031}^{+0.026}(\text{syst.})_{-0.029}^{+0.018}(\text{theor.}) \quad (5)$$

$$\frac{\alpha_s^c}{\alpha_s^{uds}} = 1.036 \pm 0.043(\text{stat.})_{-0.045}^{+0.041}(\text{syst.})_{-0.018}^{+0.020}(\text{theor.}) \quad (6)$$

All results are consistent with unity, *i.e.* no flavour dependence of the strong coupling. The SLD result has larger experimental errors as it is based on a data sample comprising approximately 150k Z^0 events, compared with the roughly 2.8M and 4.4M event samples used by DELPHI and OPAL, respectively. The SLD analysis is currently being updated with the additional 400k events collected between 1996 and 1998 with the new vertex detector, and the resultant experimental precision is expected to be competitive with that achieved by the LEP experiments. Interestingly the three

collaborations quote rather different theoretical uncertainties (Eqs. 2-6). This may be due to the facts that DELPHI used only one observable (see next section) and implicitly assumed $\alpha_s^c = \alpha_s^{uds}$, that different conventions were used for assigning the uncertainty, and that different procedures were used by OPAL and SLD for averaging over the ensemble of observables. In order to compare results meaningfully and form a world average it would be desirable to reach consensus on these issues. The results for $\alpha_s^b/\alpha_s^{uds}$ are illustrated in Fig. 1. They are also in agreement with older results (not shown) incorporating mass effects at LO only [1].

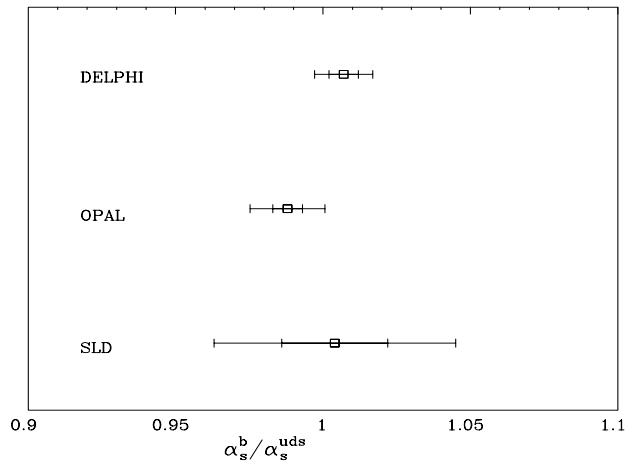


Figure 1: Summary of new measurements of $\alpha_s^b / \alpha_s^{uds}$ determined using quark mass effects calculated at NLO.

5 Heavy Quark Mass Effects

The effects of a non-zero b -quark mass are clearly visible in the data. For example, the SLD measured ratios R_3^{bl} are shown in the bottom of Fig. 2(a). For the E, E0, P and P0 algorithm cases R_3^{bl} lies significantly above unity (note that all the data points are highly correlated with one another), whereas for the D and G algorithms R_3^{bl} lies just below unity. For a b -mass value of $m_b(M_b) = 3.0 \pm 0.5 \text{ GeV}/c^2$ the expected [3] QCD values of R_3^{bl} are shown as the short lines below the data points in Fig. 2(a) with the

arrows pointing towards *lower* mass. The calculations are clearly in good agreement with the data. Unfolding these data using Eq. 1 yields the results for $\alpha_s^b / \alpha_s^{uds}$ shown at the bottom of Fig. 2(b) and discussed in the previous section.

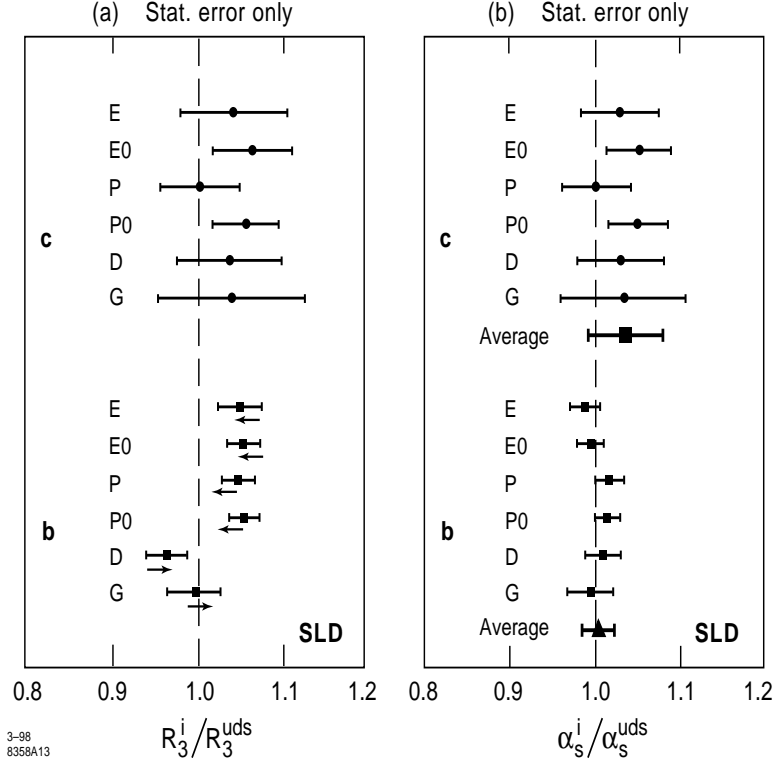


Figure 2: R_3^i / R_3^{uds} and $\alpha_s^i / \alpha_s^{uds}$ measurements for $i = c, b$.

One sees, therefore, a b -mass effect that is jet-algorithm dependent, with $R_3^{bl} \geq 1$ for the JADE family of algorithms and $R_3^{bl} \leq 1$ for the D and G algorithms, and which is reproduced beautifully by the NLO calculations. Qualitatively similar effects were found for the observables used in the OPAL study [8]. This can be understood simply in terms of two competing physical origins. 1) The non-zero b -mass tends to cause a phase-space suppression of gluon emission relative to the massless quark case. 2) For a given kinematic configuration, the large b -mass tends to enhance the invariant mass of a local quark-gluon pair relative to the massless quark case. Since the JADE family of jet algorithms is based on a clustering metric that is closely related to invariant mass,

for fixed y_c the two partons are more likely to be resolved as separate jets when the quark is massive, implying $R_3^{bl} \geq 1$. By contrast, the clustering metric used in the Durham and Geneva algorithms is less sensitive to this kinematic effect, the phase-space suppression dominates, and $R_3^{bl} \leq 1$. For increasing values of y_c one expects both effects 1) and 2) to diminish in importance, and $R_3^{bl} \rightarrow 1$. This is indeed observed, as illustrated in Fig. 3 from DELPHI, which shows $R_3^{bl}(y_c)$ for the D case.

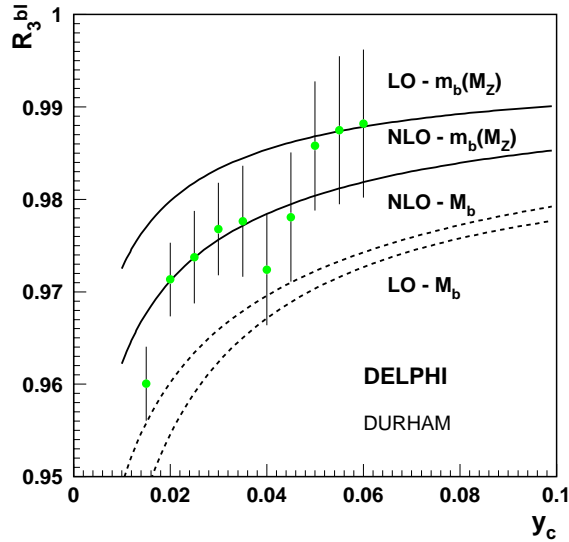


Figure 3: R_3^{bl} vs. y_c compared with QCD calculations using M_b and $m_b(M_Z)$ (see text).

Also shown in Fig. 3 are curves representing the LO and NLO QCD calculations [2] for two choices of the b -mass based on Υ data: the pole mass M_b ($=4.6 \text{ GeV}/c^2$) and the corresponding *running* mass $m_b(M_Z)$ ($=2.8 \text{ GeV}/c^2$). The NLO prediction with $m_b(M_Z)$ clearly provides the best description of the data, and DELPHI has fitted it to the data point at $y_c = 0.02$ by allowing the b -mass $m_b(M_Z)$ to vary. They obtained [7]:

$$m_b(M_Z) = 2.67 \pm 0.25(\text{exp.}) \pm 0.34(\text{frag.}) \pm 0.27(\text{theor.}) \text{ GeV}/c^2 \quad (7)$$

This result is illustrated in Fig. 4, where it is plotted at the energy scale $\mu = M_Z$ and compared with the value [7] $m_b(M_{\Upsilon/2}) = 4.16 \pm 0.14 \text{ GeV}/c^2$. The comparison yields:

$$m_b(M_Z) - m_b(M_{\Upsilon/2}) = -1.49 \pm 0.52 \text{ GeV}/c^2 \quad (8)$$

which is consistent with the expected QCD running, shown by the band in Fig. 4.

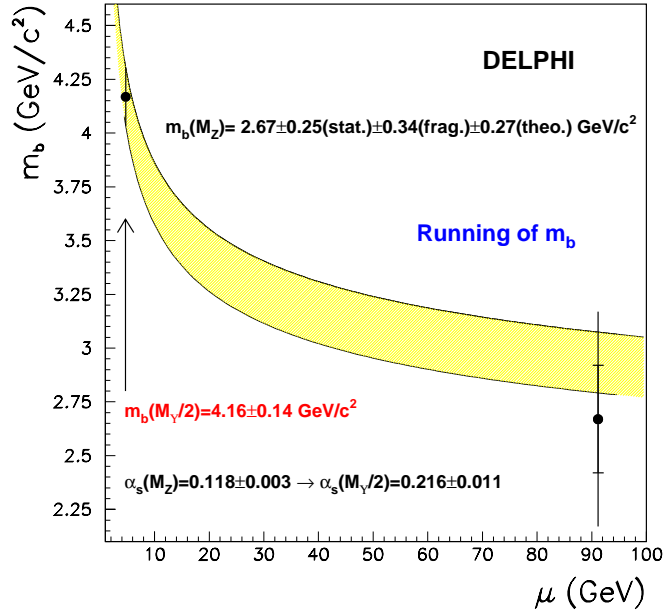


Figure 4: The running of the b -mass with energy scale.

DELPHI has updated its study recently [10] with an improved flavour tag, and has also employed the new Cambridge jet-finding algorithm [11]. The corresponding dependence of R_3^{bl} on y_c is shown in Fig. 5. In this case, although the NLO calculation with $m_b(M_Z)$ describes the data best, the NLO and running mass effects do not seem as pronounced as in the Durham case, and both the LO calculation with $m_b(M_Z)$ and the NLO calculation with M_b are also consistent with the data.

The running b -mass has also been studied [12] using the SLD data shown in Fig. 2. The calculations described in Ref. [3] have been performed, for the six jet algorithms

and y_c values used, for $m_b(M_Z)$ values in the range $2.0 \leq m_b(M_Z) \leq 4.0 \text{ GeV}/c^2$. The results are illustrated in Fig. 6, where the curves are cubic polynomial interpolations between the calculations at discrete mass values. It can be seen that the $m_b(M_Z)$ -dependence has a different form for each algorithm, with a positive slope for the E, E0, P and P0 cases, and a negative slope for the D and G cases. By comparing these curves with the SLD data, shown as horizontal bands, for each algorithm one can read off the value of $m_b(M_Z)$ that is preferred, represented by the vertical lines.

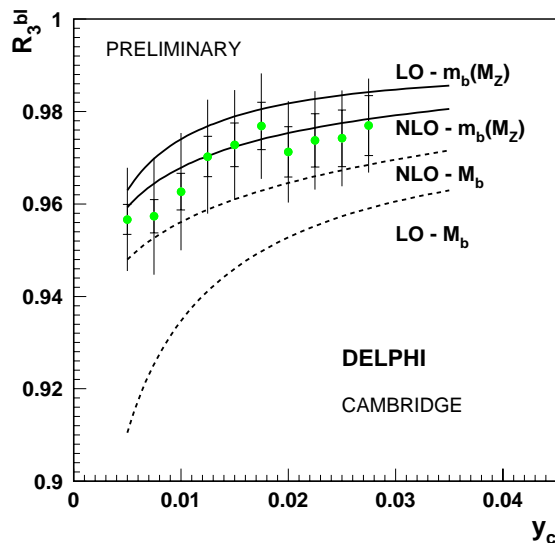


Figure 5: R_3^{bl} vs. y_c compared with QCD calculations using M_b and $m_b(M_Z)$ (see text).

It is worth reemphasising that the SLD results shown are highly correlated among the six jet algorithms since the same data sample was used and the observables are intrinsically correlated. It is therefore interesting that no single b -mass value fits the data corresponding to all six algorithms. The r.m.s. scatter of the central values is $\Delta m_b(M_Z) = \pm 0.49 \text{ GeV}/c^2$, which is comparable with the DELPHI total error on $m_b(M_Z)$ using just the Durham algorithm. The origin of this scatter is unclear, but it is

certainly plausible that it results from higher-order QCD effects that are, by definition, not included in the NLO calculation, and which can *a priori* be of different sign and magnitude for different observables. In addition, the considerable dependence [9] on jet algorithm of the size of the hadronisation uncertainties on R_3^{bl} translates [12] into uncertainties on $m_b(M_Z)$ as large as ${}^{+0.5}_{-1.7}$ GeV/ c^2 .

A weighted average over the results from the six jet algorithms yields a preliminary result:

$$m_b(M_Z) = 3.23^{+0.56}_{-0.72}(\text{stat.})^{+0.81}_{-1.28}(\text{syst.})^{+0.28}_{-1.05}(\text{theor.}) \pm 0.49(\text{r.m.s.}) \text{ GeV}/c^2 \quad (9)$$

This is consistent with Eq. 7, and the r.m.s. has been conservatively included as an additional uncertainty. (For this reason the r.m.s. over the six $\alpha_s^b / \alpha_s^{uds}$ results discussed in the previous section was included as an uncertainty on the SLD average value, Eq. 5). Finally, it should be noted that effects due to the c -quark mass are expected to be much smaller than those due to the b -mass, *i.e.* at the level of 1% or less on R_3^c / R_3^{uds} . Such effects are much smaller than the current experimental errors, and are difficult to observe; see Fig. 2 and Refs. [8, 9].

6 Summary and Conclusions

Recent results on tests of the flavour independence of strong interactions and heavy quark mass effects from DELPHI, OPAL and SLD have been reviewed. Three theoretical groups have recently completed calculations of 3-jet observables, including quark mass effects, complete at next-to-leading order in perturbative QCD. These calculations have been used enthusiastically by the experimentalists in the flavour-independence studies, as well as to determine the b -quark mass at the Z^0 scale.

The values of the strong coupling ratios, $\alpha_s^b / \alpha_s^{uds}$ and $\alpha_s^c / \alpha_s^{uds}$, extracted using the different NLO calculations, are in good agreement with one another, with the previous results incorporating mass effects only at LO, and with unity. There is hence no evidence for any anomalous flavour-dependent effects. Though the measurements of

b-quark mass at M_Z

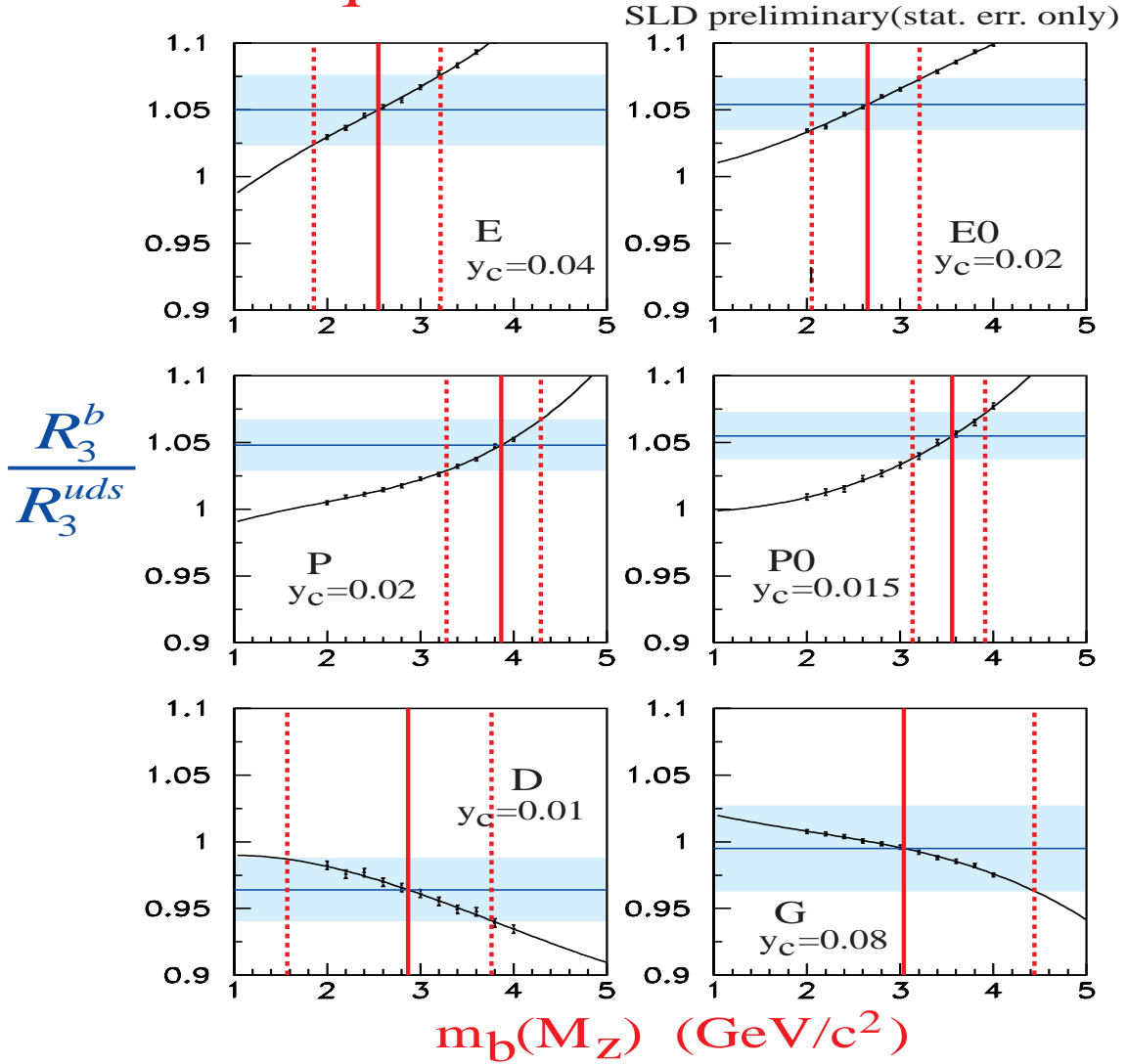


Figure 6: SLD R_3^b/R_3^{uds} measurements compared with the $m_b(M_Z)$ -dependence of the NLO calculation (see text).

$\alpha_s^b / \alpha_s^{uds}$ are approaching the per cent level of precision, there are fewer measurements of $\alpha_s^c / \alpha_s^{uds}$, and these are limited in precision currently to the 5% level; more and better measurements would be welcomed. It would also be desirable to achieve a consensus on the treatment of experimental and theoretical systematic uncertainties by the different collaborations, so that the data could be combined sensibly to obtain meaningful world average values and errors.

The DELPHI and SLD data have been used to determine $m_b(M_Z)$ and consistent values are obtained. A strong jet-algorithm dependence of $m_b(M_Z)$ has been observed, as well as large hadronisation uncertainties for some jet algorithms. DELPHI is currently investigating use of the new Cambridge jet algorithm, and the recent large SLD data sample collected with the new vertex detector will be included in an analysis optimised for the study of $m_b(M_Z)$.

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References

- [1] For a recent review, see *eg.* P.N. Burrows, 'Results on α_s and QCD from (and Above) the Z^0 ', Proc. XVII International Conference on Physics in Collision, Bristol, England, June 25-27 1997, p. 221.
- [2] G. Rodrigo, A. Santamaria, M. Bilenky, Phys. Rev. Lett. **79** (1997) 193.
- [3] W. Bernreuther, A. Brandenburg, P. Uwer, Phys. Rev. Lett. **79** (1997) 189;
A. Brandenburg, P. Uwer, Nucl. Phys. **B515** (1998) 279.
- [4] P. Nason, C. Oleari, Phys. Lett. **B407** (1997) 57.
- [5] M. Bilenky, these proceedings.
- [6] W.A. Bardeen, A.J. Buras, D.W. Duke, T. Muta, Phys. Rev. **18** (1978) 3998;
D.W. Duke, Rev. Mod. Phys. **52** (1980) 199.
- [7] DELPHI Collab., P. Abreu *et al.*, Phys. Lett. **B418** (1998) 430.
- [8] OPAL Collab., contributed paper: ICHEP98 295.
- [9] SLD Collab., K. Abe *et al.*, SLAC-PUB-7660; to appear in Phys. Rev. D; contributed paper: ICHEP98 253.
- [10] DELPHI Collab., contributed paper: ICHEP98 152.
- [11] Yu.L. Dokshitzer *et al.*, J. High Energy Phys. 08:001 (1997).
- [12] A. Brandenburg, P.N. Burrows, N. Oishi, P. Uwer, SLAC-PUB-7915 (1998); in preparation.

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