BHAM-HEP/95-01
November 1995

THE UNIVERSITY
OF BIRMINGHAM

Measurements of R_b using Lifetime Tags

D.G. Charlton

Royal Society University Research Fellow

Abstract

Precise measurements of the Z partial decay width to $b\bar{b}$ have been made at LEP and SLC. The results are dominated by double lifetime tag measurements. Combination of the latest published and preliminary results, taking into account correlated sources of error, yields $R_b = 0.2205 \pm 0.0016$ if R_c is fixed to its Standard Model prediction. This value of R_b lies three standard deviations above the Standard Model expectation, for $m_{top} = 180 \pm 12$ GeV. If the value of R_c is also taken from experiment, $R_b = 0.2219 \pm 0.0017$ and $R_c = 0.1540 \pm 0.0074$ are obtained. These results together are consistent with the Standard Model at the 0.1% level.

(Invited talk given at the
International Europhysics Conference on High Energy Physics,
Brussels, 27 July - 2 August 1995)

School of Physics and Space Research

The University of Birmingham
Edgbaston
Birmingham
B15 2TT
United Kingdom

MEASUREMENTS OF R_b USING LIFETIME TAGS

D.G. CHARLTON

Royal Society University Research Fellow, School of Physics and Space Research, University of Birmingham,
P.O.Box 363, Birmingham B15 2TT, United Kingdom

Precise measurements of the Z partial decay width to $b\bar{b}$ have been made at LEP and SLC. The results are dominated by double lifetime tag measurements. Combination of the results, taking into account correlated sources of error, yields $R_b = 0.2205 \pm 0.0016$ if R_c is fixed to its Standard Model prediction. This value of R_b lies three standard deviations above the Standard Model expectation, for $m_{top} = 180 \pm 12$ GeV. If the value of R_c is also taken from experiment, $R_b = 0.2219 \pm 0.0017$ and $R_c = 0.1540 \pm 0.0074$ are obtained. These results together are consistent with the Standard Model at the 0.1% level.

1 Introduction

The partial decay width of the Z^0 to $b\bar{b}$, $\Gamma_{b\bar{b}}$, is particularly interesting because the $Z^0 b\bar{b}$ vertex corrections differ from those for other quarks and leptons. Diagrams such as those shown in Fig. 1 give $\Gamma_{b\bar{b}}$ a different dependence on the top mass from those of the other quark widths. Further, beyond the framework of the Standard Model, it is possible that indications of new physics might be seen first in $\Gamma_{b\bar{b}}$ because new physics coupling to massive particles might affect this vertex more than others.

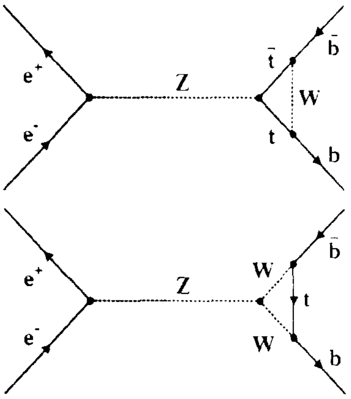

Figure 1: Diagrams contributing specially to the $Z^0 b\bar{b}$ vertex

The Z^0 to $b\bar{b}$ width is also the most experimentally accessible of the hadronic decay widths, because of the high mass and long lifetime of b hadrons. In practice, measurements are made of the fraction of hadronic events at the Z^0 peak which contain primary $b\bar{b}$ pairs. This is practically identical to the quantity

$$R_b \equiv \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})} \qquad (1)$$

differing only by a very small photon-exchange correction. The measurements are dominated by lifetime tagging approaches. The discussion here focusses on these analyses.

2 Experimental Method: Double Tagging

With the high statistics available at the Z^0, competitive measurements of R_b now all employ the "double-tagging" technique. This consists of dividing each event into two thrust hemispheres, and separately looking for a b tag in each hemisphere. The number of tagged hemispheres, N_t, and the number of events with both hemispheres tagged, N_{tt}, can be written:

$$\begin{aligned} N_t &= \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c) \qquad (2) \\ N_{tt} &= C_b \epsilon_b^2 R_b + \epsilon_c^2 R_c + \epsilon_{uds}^2 (1 - R_b - R_c) \qquad (3) \end{aligned}$$

where ϵ_b, ϵ_c and ϵ_{uds} are the efficiencies for tagging hemispheres in $b\bar{b}$, $c\bar{c}$ and lighter-flavour events, respectively, and the correlation C_b is close to 1 (analogous correlations for charm and lighter flavours can be neglected). Equations 2 and 3 can be solved for R_b and ϵ_b if ϵ_c, ϵ_{uds} and C_b are known. The method has the major advantage that it is independent of the modelling of b hadron decays, although at the cost of statistical precision, dominated by N_{tt} in this method. Remaining systematic errors arise from the knowledge of ϵ_c, ϵ_{uds} and C_b obtained from lower energy measurements and through Monte Carlo modelling.

3 Lifetime Tags

With the precise silicon vertex detectors of the LEP and SLC experiments, tagging b hadrons by their long lifetimes is the most effective way of achieving high purity, high efficiency samples. Two different lifetime tagging algorithms are used by the experiments in the R_b analyses.

A tag based on the joint probability for obtaining the impact parameters seen in a hemisphere, under the assumption of no lifetime in that hemisphere, was originally developed by ALEPH[1] for the R_b measurement. It has also been adopted by DELPHI[2] and SLD[3]. The probability density function for each reconstructed track to have a given impact parameter, in the event of no lifetime in that hemisphere, is obtained from data. The joint probability that all tracks in the hemisphere have no lifetime information is constructed, and small values are used to tag b events. The performance of this tag, as obtained by SLD, is shown in Fig. 2.

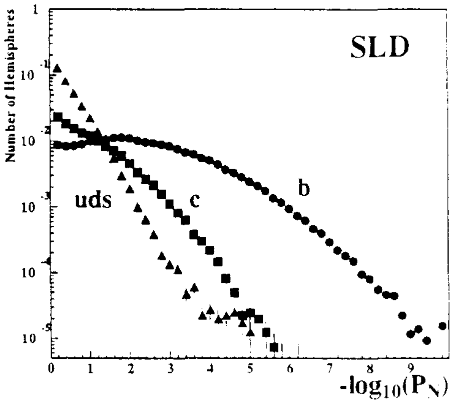

Figure 2: Expected distributions of $-\log(P_N)$ for SLD for b, c and lighter events, where P_N is the joint probability that the tracks in one event hemisphere all come from the primary vertex

OPAL use a different algorithm[4], which employs secondary vertex reconstruction in each jet of an event. Vertices qualify as b tags if the reconstructed decay length divided by its error is greater than 8. OPAL use a statistical subtraction of vertices reconstructed with negative decay lengths to reduce resolution uncertainties.

The performance of the tagging algorithms in the different detectors, as used for the R_b measurements, is summarised in Table 1. Since OPAL[4] allow either a secondary vertex or a high-p_t lepton to tag a hemisphere, the combined figures are quoted. The b hemisphere purities lie above 90% – crucial for keeping systematics from background low. The b tagging efficiencies are nonetheless excellent, above 20%, so that the loss of statistical precision resulting from the use of the double-tagging method is acceptable.

Table 1: Summary of Lifetime Tag Performances

	ϵ_b	b purity
ALEPH	26%	96%
DELPHI	21%	92%
OPAL*	23%	94%
SLD	31%	94%

(* the OPAL numbers include also lepton tags)

4 Correlations in Tagging Efficiencies

There are several types of effects which can introduce correlations in the tagging efficiencies between the hemispheres of an event. Those estimated to be of most importance include: the radiation of gluons, correlating the momentum of b and $\bar{b}$ quarks in the event and so their tagging efficiency, or in extreme cases causing both b and $\bar{b}$ quarks to travel into the same hemisphere; geometrical correlations in tagging efficiency, for example at the ends of the vertex detector acceptance; and the primary vertex information, which is shared between the two hemispheres of the event.

The correlations are estimated with a mixture of data and Monte Carlo studies, differently by the different collaborations. A common technique used to evaluate whether a source of correlation is well understood is to measure the tagging efficiency as a function of an event variable reflecting a possible efficiency correlating effect: for example, the position of the thrust axis in the detector for geometrical correlations, or the thrust value for momentum correlations. Since tagged hemispheres are dominated by correct b tags, this procedure allows the correlations to be estimated directly in the data, with relatively minor corrections for background. The correlations obtained can be checked against Monte Carlo simulation to ensure that the correlating effects are well modelled, and to derive an estimate of the residual systematic error. The typical sizes of the correlations, re-expressed in terms of the variable $\rho = (C_b - 1)\epsilon_b/(1 - \epsilon_b)$ are -1% to -2% for the impact parameter lifetime tag, around +0.2% for the decay length tag.

5 Systematic Uncertainties

The main systematic uncertainties affecting the precise lifetime tag R_b measurements are shown in Table 2. These measurements together dominate the current experimental precision on R_b (Fig. 3). Aside from detector effects, which are essentially uncorrelated between the experiments, the main systematics arise from efficiency correlations, discussed above, and various aspects of charm

Table 2: Summary of main systematic uncertainties on the precise lifetime tag R_b measurements[1,2,3,4]. "Detector effects" include Monte Carlo statistics.

	ALEPH	DELPHI	OPAL	SLD
detector effects	0.0015	0.0009	0.0012	0.0025
eff. correlation	0.0016	0.0011	0.0007	0.0010
c fractions	0.0009	0.0016	0.0009	0.0013
c decay mult.	0.0006	0.0010	0.0010	0.0018
c lifetimes	0.0005	0.0006	0.0004	0.0003
c fragmentation	0.0001	0.0005	0.0008	0.0012
gluon splitting	0.0003	0.0003	0.0005	0.0004
light quarks	0.0002	0.0006	0.0003	0.0001
total systematic	0.0026	0.0027	0.0022	0.0037
statistical	0.0022	0.0017	0.0014	0.0040

modelling.

Since the lifetimes of different weakly-decaying c hadrons vary substantially, the lifetime tagging probabilities of the different species also varies a lot. This introduces an uncertainty on $R_{\rm b}$ via $\epsilon_{\rm c}$. The production fractions employed have been taken from CLEO and ARGUS measurements[5] at 10.55 GeV, assuming no significant energy dependence between there and the Z^0. The decay branching ratios have been taken from the world averages[6]. The uncertainties on the low energy measurements of the c production fractions are used to derive the $R_{\rm b}$ errors. Measurements have now also been made at LEP of these production fractions times branching ratios[7]. The results are of similar precision to those at lower energy, and are consistent, indicating that the assumption of energy independence between 10.55 and 91 GeV is reasonable. In future, LEP measurements can be used to improve further this source of uncertainty.

The charged decay multiplicity produced in c hadron decays affects the tagging efficiency, because high decay multiplicities are tagged preferentially, since they are typical in b hadron decays. The charged decay multiplicity distributions for the weakly decaying c mesons D^0, D^- and D_s^+ are taken from a measurement by MARK III[8]. That analysis included tracks from $K^0 \to \pi\pi$ decay, which are usually not included in the secondary vertex or impact parameter probability at LEP: a further error arises from this difference. There are no measurements of the topological decay branching ratios for weakly decaying c baryons: they are instead taken from Monte Carlo predictions, with a large error (unimportant because of the shorter c baryon lifetimes).

Remaining systematics in the charm sector arise from the knowledge of c lifetimes, and of c fragmentation. Experimental measurements of these quantities, however, continue to improve, and new measurements are consistent with, and more precise than, the older averages[6] used in the derivation of results here.

An systematic error also arises from the production of heavy quarks in the parton shower, rather than directly from Z^0 decay. These secondary heavy quarks are not included in the definition of $R_{\rm b}$, and must be considered separately because they have different tagging efficiencies to primary heavy quarks. The rate of $c\bar{c}$ production by this process in Z^0 decays has recently been measured by OPAL[9]. The measured rate is consistent with, and slightly higher than, the predictions of parton shower and other Monte Carlo programs[10].

6 Energy Dependence of the $b\bar{b}$ Fraction

Photon-exchange contributions mean that the cross-section ratio $\sigma(e^+e^- \to b\bar{b})/\sigma(e^+e^- \to \text{hadrons})$ is slightly lower than $R_{\rm b}$ (by 0.0003) and that it varies slightly with centre-of-mass energy. The value of this ratio has been measured ±2 GeV off the Z^0 peak by OPAL[4] and DELPHI[2]. The results are found to be consistent with expectation, which is a shift of just $\sim -0.3\%$.

7 Results of the Measurements

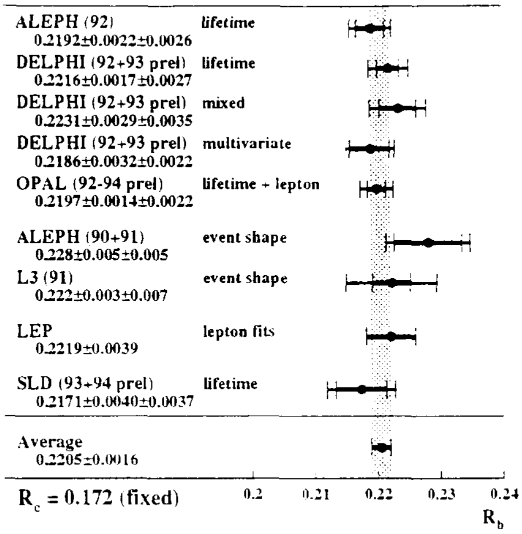

Figure 3: Latest results for $R_{\rm b}$, in the case where $R_{\rm c}$ is fixed to its Standard Model value of 0.172.

The latest results on $R_{\rm b}$ are shown in Fig. 3. New for this conference are the preliminary numbers from DELPHI, OPAL and SLD. Apart from the lifetime analyses, there are results from ALEPH and L3 using event shape tags; from DELPHI using a multivariate analysis with reduced charm modelling uncertainties; from DELPHI using a "mixed" analysis of lepton spectra and a lifetime tag; and from all of the LEP experiments using fits to lepton p and p_t spectra[11]. The results all depend to some extent on the value of $R_{\rm c}$ assumed: this dependence is considered in the averaging procedure, discussed next.

8 Combined Heavy Quark Electroweak Results

A consistent combination of the different heavy quark electroweak results is not trivial. The analyses often measure more than one parameter at a time, and depend in different ways on external input assumptions and ranges. The averaging procedure developed by the LEP heavy flavour electroweak working group, takes these correlating effects into account, by providing standard ranges for systematic parameter variation, and requiring that each result gives a full breakdown of systematic errors. A χ^2-minimisation is used to find the final averages, employing the full covariance matrix between the input measurements. The procedure gives directly the full covariance matrix of the final averaged electroweak parameters.

Various simple checks are made to ensure the reliability of the method.

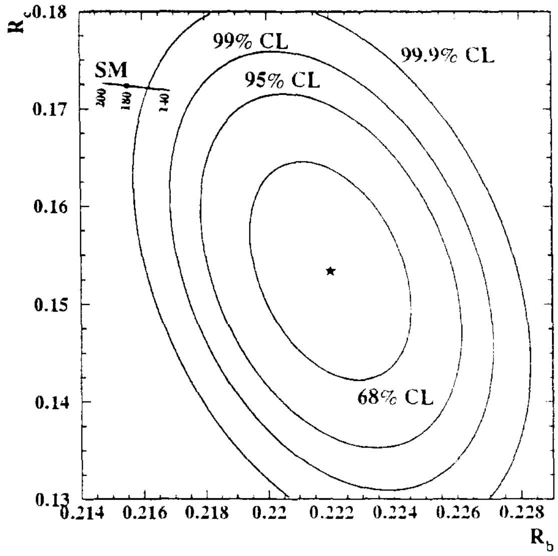

Figure 4: Combined result for R_b and R_c compared to Standard Model prediction for a range of top masses.

The averages are performed including the latest b and c partial width and asymmetry measurements from both LEP and SLD[11,12]. The results obtained are:

$$
\begin{aligned}
R_b &= 0.2219 \pm 0.0017 \\
R_c &= 0.1540 \pm 0.0074 \\
A_{FB}^{b,0} &= (9.97 \pm 0.31)\% \\
A_{FB}^{c,0} &= (7.29 \pm 0.58)\% \\
A_{FB,pol}^{b} &= 0.841 \pm 0.053 \\
A_{FB,pol}^{c} &= 0.606 \pm 0.090
\end{aligned}
\qquad (4)
$$

and also $Br(b \to \ell) = (11.12 \pm 0.23)\%$, $Br(b \to c \to \ell^{+}) = (7.76 \pm 0.36)\%$ and $\bar{\chi} = 0.1145 \pm 0.0061$. The χ^2 probability for the overall fit is 80%. The correlations between the measured parameters in Equations 4 are all below 15%, except for that between R_b and R_c, which is -35%. The average R_b and R_c values are shown in Fig. 4. When the fit is repeated with R_c fixed to its standard model value of $R_c = 0.172$, a value $R_b = 0.2205 \pm 0.0016$ is obtained.

The standard model prediction shown in Fig. 4 is obtained from the ZFITTER program version 4.9, which includes radiative corrections as derived by the working group on precision calculations for the Z resonance[13]. The value of R_b predicted is $R_b = 0.2155 \pm 0.0005$ for a top mass of 180±12 GeV.

9 Conclusion

The precision of individual measurements of R_b using lifetime tags has reached the 1.2% level. Combination of the latest preliminary and published results from LEP and SLD, taking into account correlated errors, gives a 0.7% measurement, if the value of R_c is taken to have its Standard Model value. The central result obtained lies three standard deviations above the Standard Model prediction. If R_c is also determined from experiment, the value of R_b disagrees more with the expectation. Whether this deviation is due to unforeseen experimental problems, invalid input assumptions, or physics beyond the standard model, is a question which hopefully will be answered by the final analyses of the full LEP I data sample which should be completed in the next year or two.

Acknowledgments

The preparation of the averages presented here is a laborious task requiring patience and care. It was done by the members of the heavy-flavour LEP electroweak working group, together with members of the SLD heavy flavour working group. Thanks belong to them all, in particular T. Behnke, K. Mönig and P.S. Wells from LEP and Su Dong and H.A. Neal jr. from SLD. My thanks also to the OPAL R_b experts, J.R. Batley and M. Morii.

References

1. ALEPH Collaboration, D. Buskulic et al., *Phys. Lett.* **B313** (1993) 535.
2. DELPHI Collaboration, paper eps0570 contributed to this conference; DELPHI Collaboration, P. Abreu et al., *Zeit. Phys.* **C66** (1995) 323.
3. SLD Collaboration, paper eps0222 contributed to this conference.
4. OPAL Collaboration, paper eps0278 contributed to this conference; OPAL Collaboration, R. Akers et al., *Zeit. Phys.* **C65** (1995) 17.
5. ARGUS Collaboration, H. Albrecht et al., *Zeit. Phys.* **C52** (1991) 353;CLEO Collaboration, D. Bortoletto et al., *Phys. Rev.* **D37** (1988) 1719.
6. Particle Data Group, K. Hikasa et al., *Phys. Rev.* **D45** (1992) S1.
7. M. Hauschild, these proceedings.
8. MARK III Collaboration, D. Coffman et al., *Phys. Lett.* **B263** (1991) 135.
9. OPAL Collaboration, R. Akers et al., *Phys. Lett.* **B353** (1995) 595.
10. M.H. Seymour, *Nucl. Phys.* **B436** (1995) 163.
11. P. Perret, these proceedings.
12. T. Behnke, J. Huber, A. Passeri, these proceedings.
13. "Reports of the Working Group on Precision Calculations for the Z Resonance", Eds. D. Bardin, W. Hollik and G. Passarino, CERN yellow report 95-03; D. Bardin, these proceedings.