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R_b, R_c Measurements at SLD and LEP-I [1]

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Abstract

This report summarizes the measurements of R_b, R_c at SLD and LEP-I. These measurements are sensitive probes of the Z^0 couplings to heavy quarks, which provide precision tests of the Standard Model of electroweak interactions at ~0.3% and ~2% level respectively.

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1 Introduction

The abundant production of Z^0's at the $e^+e^- \to Z^0$ resonance peak provides an ideal opportunity for tests of the SM through precision electroweak measurements, where possible new physics could manifest themselves through radiative corrections. In particular, the heavy quark production fractions in Z^0 hadronic decays, $R_b = \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to Hadrons)}$ and $R_c = \frac{\Gamma(Z^0 \to c\bar{c})}{\Gamma(Z^0 \to Hadrons)}$ are observables with clean theoretical interpretations. The relatively democratic production of all quark flavors in the Z^0 decays combined with our ability to tag b and charm hadron decays, offer the possibility to test the Z^0 coupling to the individual quark flavors at high precision.

The measurements reviewed in this report are from the ALEPH,DELPHI, L3 and OPAL experiments at LEP, and the SLD experiment at SLC. The LEP experiments each accumulated 4.4M Z^0's from the LEP-I runs during 1989-1995. SLD has accumulated a total of 450K Z^0's from 1992 to 1998. These measurements rely on good capabilities in heavy quark identification using silicon vertex detectors. The characteristics of the LEP/SLD vertex detectors and the the event primary vertex (PV) resolution are summarized in Table.1.

Experiment	LEP	SLD
Detector type	Double−sided Silicon−strips	CCDs
Inner radius	6.3cm	2.7cm
Spatial resolution	8 μm	4 μm
High-P $\sigma_{impact}(r\phi)$	15 μm	8 μm
High-P $\sigma_{impact}(rz)$	25 μm	10 μm
Mult.Scat. σ_{impact}	$\frac{60-110\,\mu m}{P}$	$\frac{30\,\mu m}{P}$
<Beam Spot>	σ_y=10 μm	$\sigma_{x,y}$=4 μm
Event by event PV	$\sigma_{x,z}$=50 μm	σ_z=12 μm

Table 1: The Vertex Detector parameters and primary vertex resolution at LEP/SLD.

2 R_b Measurements

2.1 Measurement methods

The modern R_b measurements generally adopt the double tag technique to reach the interesting precision of $<\sim 1\%$. Events are divided into two hemispheres and a b-tag algorithm is applied to each hemisphere. The measured hemisphere tag rate and event double tag rate allow the extraction of both R_b and the b-tag efficiency ϵ_b from the data. Only the small background tagging efficiencies for uds and charm hemispheres, ϵ_{uds}, ϵ_c, and the b-tag hemisphere correlation need to be estimated using Monte Carlo (MC). R_c is also taken as the SM value.

It is essential to develop a high efficiency and high purity b-tag to enable the double tag scheme to achieve the necessary statistical and systematic precision. One commonly used tag is the hemisphere impact parameter probability tag first established by ALEPH [1] which is still used in the current ALEPH [2], DELPHI [3] and L3 [4]

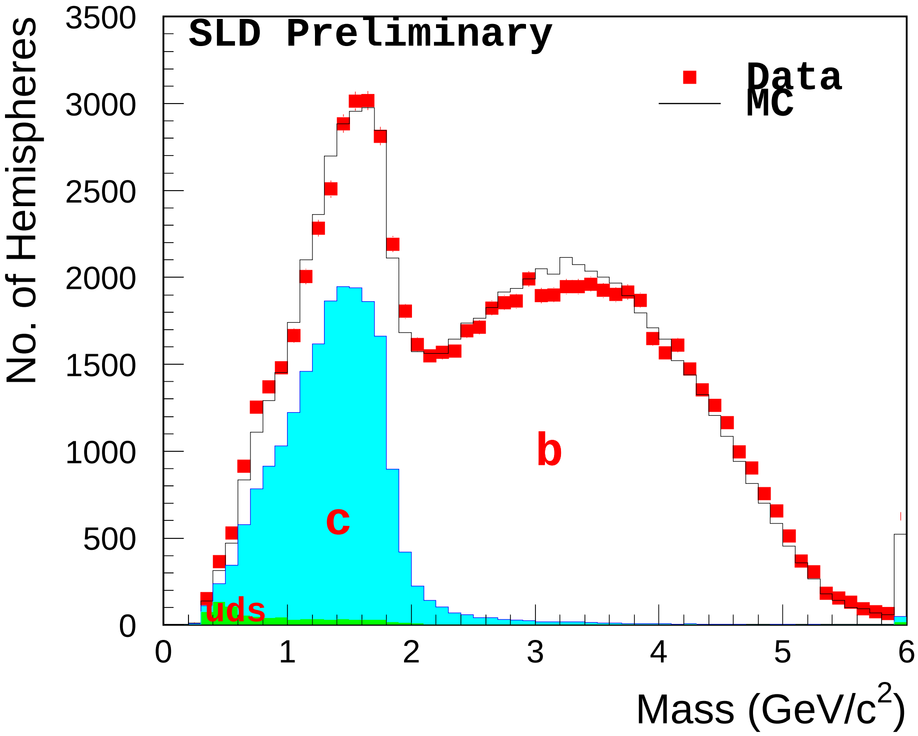

Figure 1: The P_t-corrected vertex mass distributions compared between data and MC for the current SLD R_b analysis.

measurements. A major improvement in b-tag purities for most of the current analyses is to incorporate vertex mass information to further suppress the charm background, as first introduced by SLD [6]. The SLD implementation also used the precise vertex flight direction to estimate a P_T correction from the missing neutrals to achieve a 'P_T corrected' vertex mass tag (see Fig.1) with boosted efficiency as well as the desired $\sim$98% b-purity.

Another modern development in the R_b analyses is to combine various discrimination variables to enhance the b-tag performance. One such approach is the multivariant analysis introduced by DELPHI [8], and are used by both DELPHI[3] and ALEPH[2] in their current analyses. Both implementations use 5 different tags constructed from a set of observables using lifetime, decay kinematics, event shape and lepton information. A more compact form of multi-variable tag is to combine the information using Fisher discriminant (DELPHI[3]) or neural network (NN) (OPAL[5],SLD[7]) to construct a single discriminating variable and still follow the simple double tag analysis. The OPAL[5] and L3[4] analyses have included high P_T lepton tags as a separate tag and used a simple 'OR' combination with the lifetime tags.

2.2 New Preliminary Results

At ICHEP-2000, all LEP R_b results are final for publications and essentially unchanged for the last two years. The only new preliminary result is from SLD [7], which is updated to include the last 150K Z^0's not previously used. An improved b-tag is

Experiment	ALEPH	DELPHI	L3	OPAL	SLD
b-tag method	multivar.	multivar.	impact+ℓ	vtx-NN+ℓ	vtx-mass NN
b-tag efficiency	19.6%	29.5%	23.7%	20.9%	61.8%
b-tag purity	98.5%	98.5%	84.0%	97.9%	98.3%
$\delta R_b \times 10^{-5}$					
statistics	87	67	150	112	94
$\epsilon_c, \epsilon_{uds}$ physics	39	25	218	74	44
Hemisphere correlation	36	28	116	71	23
$g \to b\bar{b}$	38	27	11	25	22
$g \to c\bar{c}$	22	8	13	17	18
Detector effects	46	13	43	25	42
Event selection	7	9		33	70
Internal (MC stat. etc.)	47	33	81	59	14
$\delta R_c \pm 0.005$	10	12	108	35	17

Table 2: The R_b measurement b-tag performance and measurement uncertainty comparison. Tagging performance numbers refer to the main vertex/lifetime tags only.

applied to data and MC from a recent new reconstruction. The new b-tag uses a neural network to optimize the track to vertex association, and a second neural network to construct a $c - b$ separation variable, incorporating vertex decay length, multiplicity and momentum information in addition to the P_T corrected vertex mass. This tag variable provides b-tag at one extreme and also a high performance c-tag at the other extreme. The b-tagging efficiency and purity achieved for the bulk 350K Z^0 data from the 97-98 run are 61.8% and 98.3% respectively.

2.3 Systematics and Result Summary

With the R_b measurements now reaching an impressive precision of ~0.5% for even individual measurements, it is crucial to ensure that the systematic evaluation is convincing. The breakdown of the R_b measurement errors are listed in Table 2.

For most of the correlated systematic errors, there is generally a consistent evaluation among the measurements following the standard procedure [9]. The uncertainties due to physics modeling for $\epsilon_c, \epsilon_{uds}$ are extensively checked and yield good consistency between measurements. The rather complex hemisphere correlation systematic evaluation has been subject to intense scrutiny, especially in the areas of primary vertex and QCD gluon radiation effects. The discussions in the OPAL publication [5] is particularly detailed. The general finding is that the MC typically describes the correlation fairly well, although it is difficult to be convinced that all possible significant sources are investigated.

A major common systematic source is the uncertainty in the $g \to c\bar{c}$, $g \to b\bar{b}$ rates which can cause a primary light quark event to be tagged. There are quite few recent measurements on both $g \to c\bar{c}$ [10, 11] and $g \to b\bar{b}$[12]. These results are tabulated in Table 3. The measurements are well within the range of uncertainty assumed by the standard procedure [9]. The $g \to QQ$ rates would at first sight imply a more significant problem for R_b. The generally low tagging efficiency for the heavy hadrons from gluon splitting, which are mostly at low momentum, reduces the R_b systematic sensitivity to this effect.

Expt.	$g \to c\bar{c}$ $(\times 10^{-2})$	$g \to b\bar{b}$ $(\times 10^{-3})$
ALEPH	$3.23 \pm 0.48 \pm 0.53$	$2.77 \pm 0.42 \pm 0.57$
DELPHI		$2.1 \pm 1.1 \pm 0.9$ $3.3 \pm 1.0 \pm 0.8$
L3	$2.45 \pm 0.29 \pm 0.53$	
OPAL	$3.20 \pm 0.21 \pm 0.38$	$3.07 \pm 0.53 \pm 0.97$
SLD		$2.84 \pm 0.61 \pm 0.59$
LEP Std	3.19 ± 0.46	2.51 ± 0.63

Table 3: The $g \to c\bar{c}, g \to b\bar{b}$ measurements compared to the current standard recommendations from the LEP HF group.

The detector systematics mainly cover tracking resolution and efficiency effects. The MC track impact parameters are typically 'smeared' to accommodate unsimulated vertex detector misalignment effects. Although this random smearing tend to bring MC to agree with data overall, the underlying effects are typically local and can affect tracks coherently going through the same detector region in a jetty environment. The treatment for the resolution effect among the experiments unfortunately vary significantly, reflecting very different levels of subjective judgments. Given the fact that underestimated tracking resolution systematic was the main culprit driving the previously high R_b result in 1995-1996, this is perhaps an area which should deserve more attention for better confidence in the systematics.

A possible surprise in systematics is in the event selection flavor bias which has received relatively little attention. The theoretical calculations [13] indicate that the use of the running quark mass compared to the pole mass or massless quark for the 3 or 4 jet rate calculations can have significant effects for b events. This can affect R_b measurements through event selection bias or hemisphere correlation. This specific source of systematics is so far only evaluated by SLD explicitly, which currently assigned an event selection bias systematic for this effect as large as all other systematics combined.

The current R_b measurement results are listed in Fig.2. All measurements are in good agreement with the SM and the combined world average of 0.21651 ± 0.00069 is consistent with the SM expectation of 0.2158 for the currently known top quark mass.

3 R_c Measurements

The measurement of R_c also requires an efficient and pure charm tag to achieve good precision. This has turned out to be a more challenging task than tagging b's. Exclusive charm reconstruction is a clean tag, but the usable branching fractions are somewhat limited and the reconstruction random combinatorial background is also not negligible. The charm hadrons produced in b decays adds further complication. The charm hadrons have shorter lifetimes and smaller decay charged multiplicities compared to the B hadrons, which make the inclusive charm tagging difficult. Without a clean

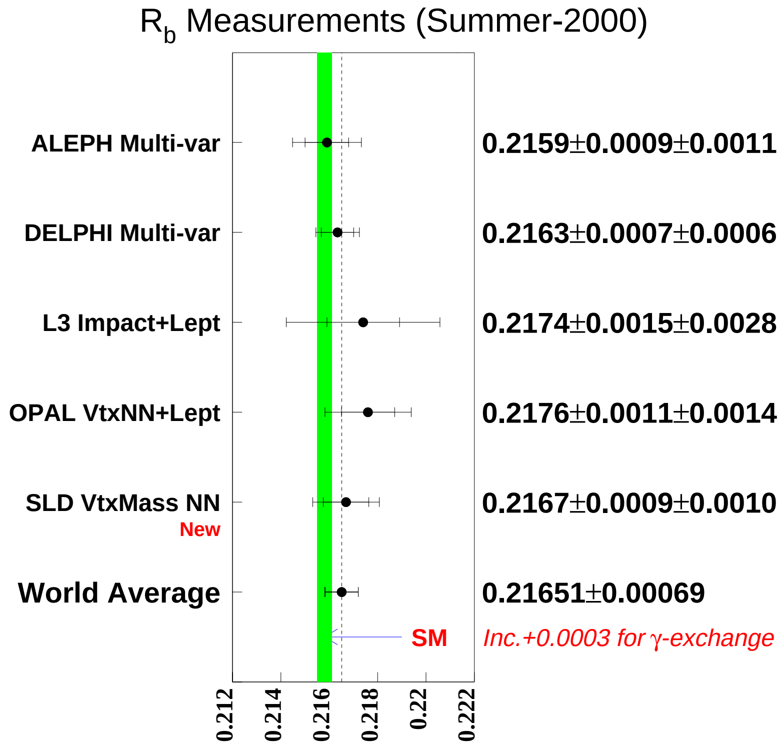

Figure 2: R_b^0 measurement results. The inner and outer error bars represent statistical and total errors respectively.

and high efficiency inclusive charm tag at LEP, the R_c measurement techniques are therefore rather diverse:

Lepton Spectrum Analysis: A specialized analysis by ALEPH [14] fits the lepton P, P_T spectra after subtracting $b\bar{b}$ contributions using lepton spectra in hemispheres opposite a b-tag. The main systematics sources are the MC simulation of the $c \to \ell$ branching ratio and spectrum.

Charm Counting: All primary charm hadron decay chains will eventually involve a weak decay via D^0, D^+, D_s or Λ_c (and a very small fraction of Ξ_c, Ω_c). R_c can be measured [16, 15, 11] from the sum of production cross sections of the these four charm hadrons using fully reconstructed decays of well-known modes. The systematic limitation come from charm fragmentation simulation and charm decay branching ratio uncertainties.

Exclusive/Inclusive $D^{(*)}$ Cross Tags: Another widely used technique at LEP is the exclusive/inclusive D^* cross tag [14, 15, 17] which partially calibrates the tagging efficiencies from data. The analysis uses a fully reconstructed $D^{*+} \to D^0\pi^+$ charm tag or a b-tag in one hemisphere, to calibrate a more inclusive charm tag in the other hemisphere by identifying the transition pions π_* from the $D^{*+} \to D^0\pi_*^+$ decays without exclusive D^0 reconstruction. The production fractions $f(c \to D^{*+}X)$ and $f(b \to D^{*+}X)$ are extracted from data together with R_c. The main systematic sources are background subtraction, c/b separation, and $\mathrm{Br}(D^0 \to K^-\pi^+)$ error.

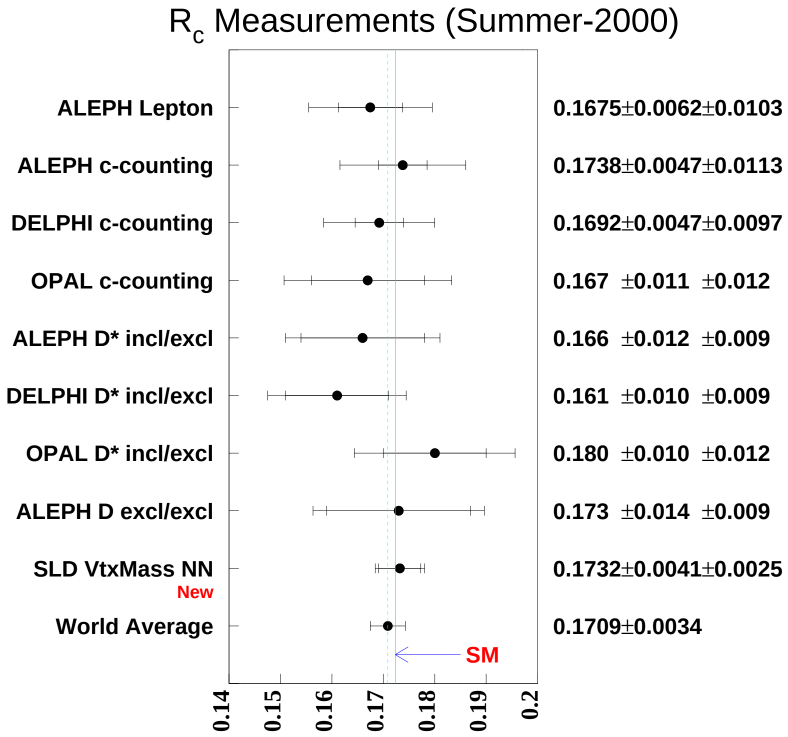

Figure 3: R_c measurement results. The inner and outer error bars represent statistical and total errors respectively.

Inclusive Vertex Double Tag: The SLD measurement of R_c [7] is the only true high efficiency inclusive double tag measurement. The inclusive vertex charm tag is a product of the same neural network $c-b$ separation tag as described in section 2.2. The essence of $c-b$ separation power can be seen from Fig.1 where the low mass region is already clearly dominated by charm. The operating point of the hemisphere charm tag gives a $b:c:uds$ composition of 15.6:83.8:0.6 and a charm-tag efficiency of 17.4%. The key successes is the strong suppression of uds background. This measurement is not only statistically most precise, it has also achieved the lowest systematic as the charm region b,c tag efficiencies are all measured from data similar to an R_b analysis.

The various R_c measurements are compared in Fig.3. The world average of $R_c = 0.1709 \pm 0.0034$ is in good agreement with the SM prediction of 0.1723 at the present precision. The main reason for the shift of the LEP R_c measurements toward the confirmation of the SM since the 'R_b, R_c crisis' in 1995-1996 is that the D^{*+} production fraction $f(c \to D^{*+})$ is now measured at LEP and noticeably lower than the previously assumed values based on low energy measurements by CLEO and ARGUS.

4 Conclusions

The continuous effort of the last 9 years at LEP and SLD have yielded precision tests of the standard model for the $Zb\bar{b}, Zc\bar{c}$ couplings through R_b and R_c measurements, reaching impressive levels of precision at $\pm 0.34\%$ for R_b and $\pm 2\%$ for R_c. The results are in good agreement with the SM predictions. The heavy flavor tagging techniques pushed by these measurements have far reaching effects for many other measurements at present and in the future.

On behalf of the LEP and SLD collaborations, I would like to thank the CERN and SLAC accelerator departments for their dedicated effort on LEP and SLC to make these measurements possible.

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